

Bathymetry and Sediment Geochemistry of Lake Hazen (Quttinirpaaq National Park, Ellesmere Island, Nunavut)

G. KÖCK,¹ D. MUIR,² F. YANG,² X. WANG,² C. TALBOT,² N. GANTNER³ and D. MOSER⁴

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ABSTRACT. Arctic lakes can provide a long-term perspective on environmental change, including trends in long-range atmospheric transport and deposition of contaminants, inferred from studies of sediment cores. In this study, we conducted the first detailed bathymetric survey of Lake Hazen (Quttinirpaaq National Park, Ellesmere Island, Nunavut), the world's largest lake north of 74° latitude. With these data we were able to determine optimal locations for sediment coring and to collect and analyze profundal sediment cores. A bathymetric map of Lake Hazen was developed on the basis of 362 spot soundings obtained with GPS-coupled sounding equipment placed directly on the ice combined with additional soundings from a small boat. The deepest point in the lake (81°49.5' N; 70°42.8' W) was found to be 267 m deep. The lake volume was estimated to be $5.14 \times 10^{10} \text{ m}^3$, about 10% larger than previous estimates. Using estimates of the discharge of Lake Hazen from the Water Survey of Canada, we estimated the water retention time to be 89 years. Sediment cores were dated using ^{210}Pb and ^{137}Cs . Sedimentation rates at the deep point, estimated using the Constant Rate of Supply model for excess ^{210}Pb , were relatively high ($1260 \text{ g m}^{-2}\text{yr}^{-1}$) in the period 2005–1963 and lower ($650 \pm 100 \text{ g m}^{-2}\text{yr}^{-1}$) in horizons dated to 1950–1880. The majority of elements measured in sediment (24 of 29 consistently above detection limits), as well as organic carbon, showed less than 20% variation in concentrations in the top 10 cm (compacted depth), which represent deposition over approximately 140 years. Geochemical characteristics of the sediment suggest that erosional inputs from annual glacial melting are the major source of essentially all elements and that anthropogenic inputs from long-range transport of toxic metals such as mercury and lead are very low.

Key words: bathymetry, sediment, metals, depth sounding, lake volume, water residence time, radiometric, dating

RÉSUMÉ. Les lacs de l'Arctique peuvent fournir une perspective à long terme en matière de changement environnemental, notamment en ce qui a trait aux tendances relatives au transport atmosphérique et au dépôt de contaminants sur de longues périodes, tendances inférées à partir d'études de carottes de sédiments. Dans le cadre de la présente étude, nous avons effectué le premier levé bathymétrique détaillé du lac Hazen (parc national Quttinirpaaq, île d'Ellesmere, Nunavut), le plus grand lac de la planète situé au nord de 74° de latitude. Grâce aux données prélevées, nous avons réussi à déterminer les meilleurs emplacements pour le prélèvement de carottes de sédiments de même que pour la collecte et l'analyse de carottes de sédiments profonds. Une carte bathymétrique du lac Hazen a été dressée en fonction de 362 sondages obtenus au moyen de matériel d'appareils phoniques dotés de GPS placés directement sur la glace et supplémentés par des sondages recueillis à partir d'un petit bateau. Le point le plus profond du lac (81°49,5' N; 70°42,8' O) a été trouvé à 267 m de profondeur. Le volume du lac a été évalué à $5,14 \times 10^{10} \text{ m}^3$, soit 10 % de plus que les évaluations précédentes. À l'aide d'estimations du déversement du lac Hazen obtenues auprès de la Division des relevés hydrologiques du Canada, nous avons évalué que la durée de rétention de l'eau était de 89 ans. La datation des carottes de sédiments a été faite à l'aide de ^{210}Pb et de ^{137}Cs . Les taux de sédimentation au point profond, estimés en s'appuyant sur le modèle CRS (Constant Rate of Supply) pour l'excédent ^{210}Pb , étaient relativement élevés ($1260 \text{ g m}^{-2}\text{an}^{-1}$) pour la période allant de 2005 à 1963, et moins élevés ($650 \pm 100 \text{ g m}^{-2}\text{an}^{-1}$) pour la période de 1950 à 1880. La majorité des éléments mesurés dans les sédiments (24 sur 29 étaient uniformément au-dessus des seuils de détection) ainsi que dans le carbone organique ont produit une variation de concentrations de moins de 20 % dans les 10 cm supérieurs (profondeur compactée), ce qui représente des dépôts s'échelonnant sur environ 140 ans. Les caractéristiques géochimiques des sédiments laissent présumer que les matières d'érosion découlant de la fonte glaciaire annuelle constituent la source principale de sensiblement tous les éléments, et que les matières anthropiques provenant du transport à grande distance de métaux toxiques, tels que le mercure et le plomb, sont très faibles.

¹ Austrian Academy of Sciences, Dr. Ignaz Seipel-Platz 2, A-1010 Vienna, Austria and Institute of Zoology, University of Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria; guenter.koeck@oeaw.ac.at

² Environment Canada, Water Science and Technology Directorate, 867 Lakeshore Road, Burlington, Ontario L7R 4A6, Canada

³ Department of Environmental Biology, University of Guelph, Guelph, Ontario N1G 2W1, Canada; present address: Water & Climate Impacts Research Centre, Environment Canada, University of Victoria, Victoria, British Columbia V8W 3R4, Canada

⁴ VINCA Institut für Naturschutzforschung und Ökologie GmbH, Giebergasse 6/7, A-1090 Vienna, Austria

Mots clés : bathymétrie, sédiment, métaux, mesure des profondeurs, volume lacustre, temps de séjour de l'eau, radiométrique, datation

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INTRODUCTION

Lake Hazen, situated in Quttinirpaaq National Park on the northern tip of Ellesmere Island (Nunavut) stretches east-northeast (81°40' N, 72°58' W) to west-southwest (81°56' N, 68°55' W). With a surface area of approximately 540 km², it is the tenth largest Arctic lake and the world's largest lake north of 74° latitude (Parks Canada, 2009). Given the size and location of Lake Hazen, its study could provide a long-term perspective on environmental change, including trends in long-range atmospheric transport and deposition of contaminants, inferred from studies of sediment cores. However, since measurements of depth, inflows, and outflows remain very limited, accurate information on lake characteristics, such as water volume and residence time, is not available (Clark, 2007; ILEC, 2007). Lake bathymetry information collected during the International Geophysical Year in 1958 is incomplete, and further studies of lake bathymetry have been recommended (Clark, 2007).

Descriptions of the geographical and physical characteristics of the lake, as well as its biolimnology and the regional climate, are provided in the World Lakes Database (ILEC, 2007) and by Clark (2007) and Parks Canada (2009). Lake Hazen is fed by multiple glacial inflows and is drained only by the 29 km long Ruggles River, which flows from the southeastern shore into Chandler Fjord on the northeastern coast of Ellesmere Island. The lake lies at 159 m a.s.l. (Parks Canada, 2009). The area of the Lake Hazen basin is estimated to be 4900 km² (Babaluk et al., 2001; Clark, 2007).

Situated on the Paleozoic rocks of the Hazen Plateau, and protected from the main flow of air from the polar basin onto the Queen Elizabeth Islands by the glacier-covered Garfield Range (rising to more than 2500 m a.s.l.) to the north, the lake experiences a milder summer climate than anywhere else on northern Ellesmere Island (Clark, 2007). The area around the lake has been described as a thermal oasis within a polar desert (France, 1993): summer temperatures can rise above 20°C, resulting in a relatively high vegetation cover and locally abundant wildlife compared to either the barren Hazen Plateau or the surrounding mountain ranges (Savile and Oliver, 1964; France, 1993). The lake is covered by ice for about 10 months a year and retains partial ice cover in most summers (Clark, 2007; ILEC, 2007).

The lake is extremely oligotrophic (Babaluk et al., 1999, 2009; Keatley et al., 2007), with no macrophytes and low phytoplankton and zooplankton productivity (McLaren, 1964; ILEC, 2007). Thirty-four species of benthic invertebrates have been reported from the lake (Oliver, 1963).

Arctic char, *Salvelinus alpinus*, is the only fish species found in Lake Hazen (Johnson, 1983; Reist et al., 1995).

There is evidence that the lake was used by Paleo-Inuit of the Independence I culture about 4000 years ago (McGhee, 1996). The lake was first explored and mapped in 1882 by the United States Lady Franklin Bay Expedition led by Adolphus W. Greely (Greely, 1886), which was carried out within the framework of the First International Polar Year 1882–83 (McGhee, 1996; Dick, 2001). Valuable data were also gathered during the scientific program “Operation Hazen” carried out by the Defence Research Board of the Canadian Department of National Defence as part of Canada's contribution to the International Geophysical Year in 1957–58 (Hattersley-Smith, 1961, 1987, 1998).

Deane (1959:62), on the basis of 62 echo sounding traverses in 1958, suggested a maximum depth for the lake of 263 m and noted that the “main part of the lake shows a shallow, asymmetrical, U-shaped depression, with the deepest part about half-way between the centre of the lake and the north shore.” Muir et al. (1996), using the data from Deane's work, reported a maximum depth of 263 m, mean depth of 85 m, and approximate lake volume of 4.55×10^{10} m³. Sediment coring in 1990 at a site northeast of Johns Island in the deep zone identified by Deane (1959) was conducted to a maximum depth of 254 m (G. Brunskill, Australian Institute of Marine Science, Townsville, Queensland, pers. comm. 2006).

Although the basic geology and geomorphology of the Lake Hazen basin are reasonably well known, the lake bottom remains virtually unstudied. During Operation Hazen, studies were made of bedrock geology (Christie, 1958) and geomorphology (Smith, 1961) of the Lake Hazen basin. A report by the Geological Survey of Canada (1981) summarized knowledge of mineral deposits and noted the presence of coal, amber, and soapstone in the Hazen basin, as well as the potential for metallic minerals and oil and gas. Early lake surveys noted coal seams at lake level but did not collect bottom sediments (Deane, 1959). The first detailed analysis of lake sediment was done on cores collected in 1990 by a Fisheries and Oceans Canada team led by Gregg Brunskill. Results on sedimentation rate and mercury concentrations and fluxes were subsequently published (Lockhart et al., 1998). Sediment core profiles of polyaromatic hydrocarbons (Lockhart et al., 1992) and PCBs (Muir et al., 1996) have also been reported. Outridge et al. (2002) reported the historical profile of Pb and ²⁰⁶Pb/²⁰⁷Pb and ²⁰⁸Pb/²⁰⁷Pb isotope ratios in “core A” collected by the Fisheries and Oceans team. The presence of other metals (Cd, Cu, Ni, Co, V, Zn, Mn, As, Al, and Fe) was also determined (W.L. Lockhart, Freshwater Institute, Winnipeg Manitoba,

unpubl. data). Microscopic examination of the core material showed granules of coal and amber. In addition, one core underwent preliminary paleolimnological analysis for diatom microfossils (Douglas et al., 1992).

Our long-term goal was to use the sediments and Arctic char from Lake Hazen to study trends of contaminants such as metals and important anthropogenic chemicals released from urban areas in North America, Europe, and Asia and transported to the Arctic in the atmosphere. The results for temporal trends of mercury, cesium, potassium, selenium, and thallium in Lake Hazen char have been published elsewhere (Gantner et al., 2009). We wished to obtain sediment cores to update earlier paleolimnological studies. But given the lake depth and lack of georeferenced depth information, sediment coring was problematic. Thus the objectives of our study were first to characterize the bathymetry of Lake Hazen as a basis for sediment coring at the deepest point of the lake and to estimate lake volume to support hydrological studies, and then to examine profiles of a suite of elements, as well as organic carbon and nitrogen, in profundal sediments. The study was part of a collaboration between Environment Canada, the University of Innsbruck, and the Austrian Academy of Sciences.

MATERIALS AND METHODS

Measurement of Lake Bathymetry

Depth measurements in Lake Hazen were made through the ice in May 2004 and June 2005. Measurements began in the north-central part of the lake east of Parks Canada's camp because this was previously reported as the deep area, although only a few soundings were available and these only with visual locations rather than exact latitude and longitude (Deane, 1959). Snowmobiles and a sled (komatik) were used for travel and transport of the equipment on the ice-covered lake. Spot soundings were obtained through the ice cover using a Lowrance LCX-15MT GPS/sounder and a dual-frequency, 200/50 kHz pole-mounted transducer. The method that worked best was to clear the snow from the ice, chip a shallow trench (approximately 5×15 cm and 2 cm deep) in the ice using an ice chisel, fill it with water, and place the transducer in the water. Holes were drilled through the ice, and soundings were made in the water at various times to verify the operation of the sounder.

In August 2006 and August 2010, additional soundings were made in open-water areas from a small boat. In 2006, 35 depth soundings were made in the area between Hazen Camp and Johns Island using a Vexilar LPS-1 handheld sonar and Garmin III GPS. In 2010, we used a Lowrance LCX-15MT GPS/sonar system mounted on the same small boat to obtain an additional 112 soundings over an area of approximately 30 km² southwest of Johns Island and along the north shore. Several of the soundings in 2010 were conducted at the same sites as in 2005 and 2006 and agreed within ± 1 m.

Because of the irregular distribution of our spot soundings, we decided to use a kriging method for the interpolation of the bathymetric map. To produce a reliable surface that accurately reflects the depth measurements, an ordinary point kriging algorithm, which produces exact interpolations, was used (Journel, 1989; Cressie, 1991). The interpolation was based on 250 spot soundings from 2004 and 2005 and additional data points from 2006 and 2010. The calculations were done with the Surfer 7.0 software (Golden Software, Golden, Colorado) using the default options. The map was produced using ARC-GIS 9.0 software (ESRI, Redlands, California).

Hydrometric Data

The discharge of Lake Hazen has been monitored since 1996 by the Water Survey of Canada (Environment Canada, Yellowknife) at a gauging station set up on the Ruggles River. Summer flows (m³ sec⁻¹) were measured in 1996, in 1997, and for limited times in July 1998 and 1999. For 2002 and 2004–10, a more detailed set of estimated discharge data is available. From these preliminary data, made available by L. McGregor and M.K. Jones (Water Survey Branch, Yellowknife, Northwest Territories, pers. comm. 2010), we estimated average monthly discharge (± 1 SD) for October to May and average biweekly flow for the high-flow period from June to September. From these estimates, the total discharge was estimated (m³/year). Water residence time was calculated as the discharge/lake volume. The error for the residence time was calculated as the square root of $((SD \text{ volume}/\text{volume})^2 + (SD \text{ annual discharge}/\text{discharge})^2)$.

Sediment Core Collection and Analysis

Cores were obtained with a KB (Kajak-Brinkhurst) type corer (Kajak et al., 1965; Brinkhurst et al., 1969) using acrylic plastic tubes 6.7 cm and 10 cm diameter. The sediment ranged from soft silts for the top 10 cm to a stiffer soft-clay base. Cores were extruded under hydraulic pressure and sectioned at 0.5 cm (top 10–20 cm) and at 1 cm intervals for lower horizons, using a stainless steel sheet. Sediments from the 10 cm diameter cores were placed in glass jars (pre-rinsed with acetone and then hexane; caps lined with aluminum foil) or in polyethylene plastic (Whirl-Pak[®]) bags. Sediments were held in a plastic cooler and subsequently stored at 4°C in a walk-in refrigerator.

Samples from the top 15 cm of the 6.7 cm diameter sediment core were freeze-dried, ground, and analyzed by both alpha- and gamma-counting. Subsamples of each section were treated using a variation on the Eakins and Morrison (1978) polonium distillation procedure. ¹³⁷Cs was analyzed by gamma spectroscopy for 47 hours/sample by the radiodating lab at the Paleoecological Environmental Assessment and Research Laboratory (PEARL, Queen's University) using a digital, high-purity germanium spectrometer (DSPEC, Ortec instruments). Further details on gamma counting by PEARL can be found in Michelutti et al. (2008). To check gamma

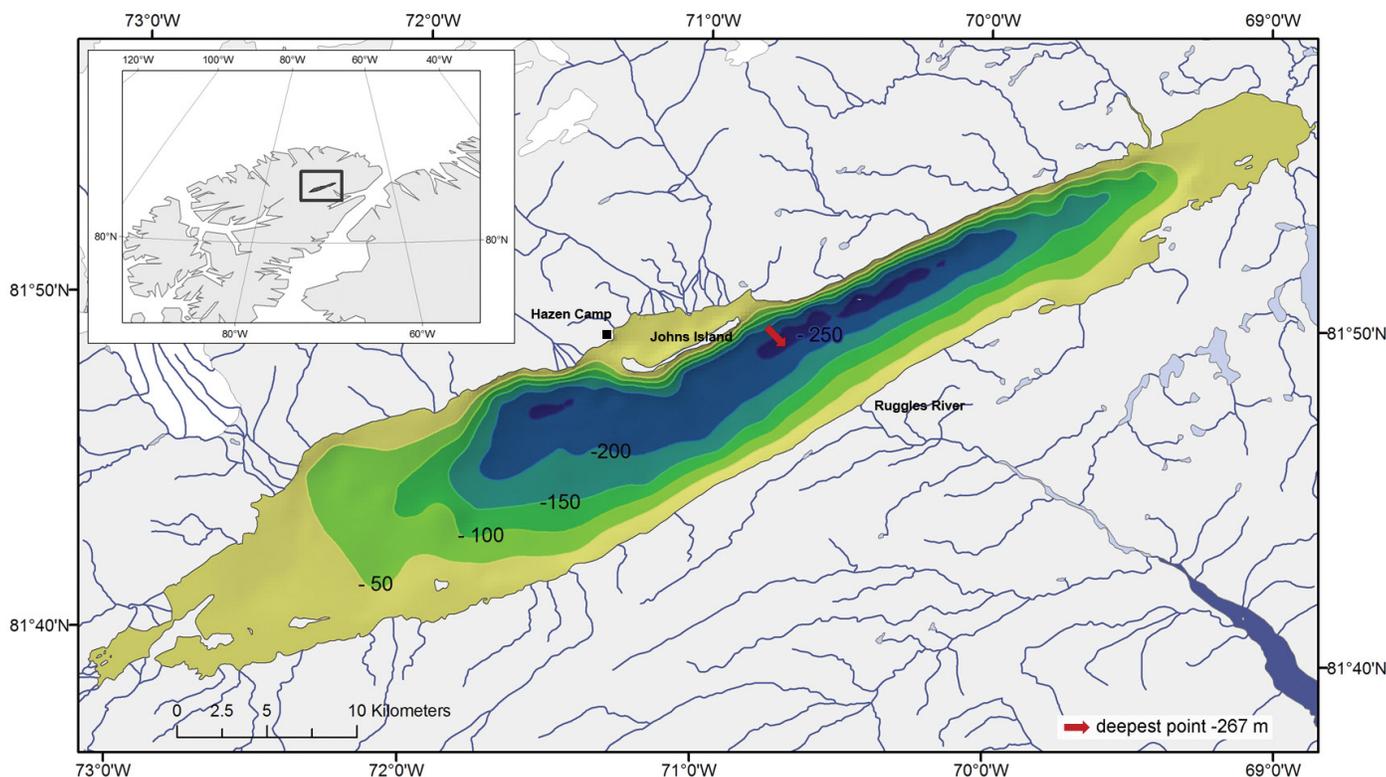


FIG. 1. Bathymetric map of Lake Hazen (depth contours in meters). The map is based on kriging interpolation of 362 depth measurements. Arrow indicates approximate location of deepest point.

counting accuracy, the 3.0–3.5 cm sample was reanalyzed three months later, and results were within 15.2% for ^{137}Cs . Sedimentation rates and dates were estimated from the unsupported ^{210}Pb results using the Constant Rate of Supply (CRS) model (Oldfield and Appleby, 1984).

Freeze-dried sediments from the same core were analyzed for Al, Ba, Cr, Cu, Fe, Mn, P, Sr, V, Zn, Ca, Mg, Na, and K by ICP-Atomic Emission Spectroscopy (AES). Multi-element analysis for 18 additional trace elements (As, Be, Bi, Cd, Co, Ga, La, Li, Mo, Ni, Pb, Pt, Pd, Rb, Rh, Sb, Tl, and U) was conducted by ICP-Mass spectrometry, while mercury was analyzed by atomic absorption spectroscopy (AAS). Total organic carbon (TOC), inorganic carbon (TIC), and organic nitrogen (TON) were determined by CHN (Carbon, Hydrogen, Nitrogen) analyzer.

Certified sediment reference materials (NRC MESS-3 and NIST RM 8704) were used to ensure accuracy. Results for certified elements were consistently within $\pm 7\%$ of certified values. Method detection limits (MDL) were estimated for each analyte (Table 1). All the ICP-MS/AES/AAS and CHN analyses were performed at the National Laboratory for Environmental Testing (NLET, Burlington, Ontario). Additional details on analytical methods are provided in the supporting information in Muir et al. (2009).

For calculation of basic statistics, non-detects were replaced by $\frac{1}{2}$ the MDL. Correlations among elements and TOC, TIC, and TON were examined using a Pearson Correlation matrix, and significance was tested using Bonferroni probabilities (SystatSoftware, 2009).

RESULTS AND DISCUSSION

Lake Bathymetry

The bathymetric map of Lake Hazen (Fig. 1) was based on a total number of 362 spot soundings collected between 2004 and 2010. The deepest point, found northeast of Johns Island (at $81^{\circ}49.5' \text{ N}$; $70^{\circ}43.8' \text{ W}$), was 267 m deep, about 4 m deeper than reported by the only other depth survey (Deane, 1959). A large area south and east of Johns Island, for which no previous soundings existed, was found to be more than 250 m deep. The International Lake Environment Committee web site (ILEC, 2007) lists the maximum depth of Lake Hazen at 280 m, but without attribution. However, since our depth measurements in this deepest area of the lake were less than 100 m apart, the probability of finding a spot significantly deeper than our record is relatively low.

The precision of the map in Figure 1 is not uniform over the entire lake area. Assuming the deepest part to be northeast of Johns Island, as suggested by Deane (1959), we focused our initial measurements in that area. This approach led to an agglomeration of spot soundings beginning about 5 km west of Johns Island and the outflow of Ruggles River. Because of the huge distances (and thus long travel times) on the lake, fewer soundings were made along the shoreline and at the far distant north and south ends of the lake.

Control measurement through ice holes show that the “through the ice” sounding method works very well in

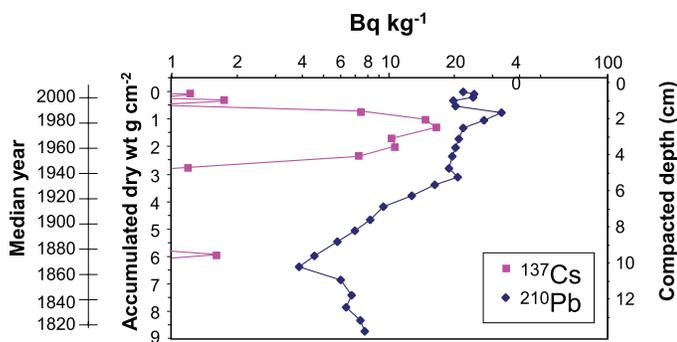


FIG. 2. Results of radiometric dating of ^{137}Cs and unsupported ^{210}Pb in a sediment core from the Lake Hazen deep point. Scales along the left vertical axis show accumulated dry weight versus dates of each sediment horizon, modeled using the CRS model for the exponentially declining portion of the ^{210}Pb profile. The scale for compacted depths is shown on the right vertical axis.

extreme conditions of 1.7 m ice thickness and water depths down to 267 m. However, the method is limited by the structure of the ice cover. On dark compact ice, it delivered high-quality results in a very short time of several seconds. When the ice surface contains a high amount of air bubbles or ridges due to melt/refreeze processes (in particular candled ice), the quality of the signal starts to decrease, leading to extended measurement time, measurement failure, or both. This pattern holds especially true in the case of advanced candled ice conditions, when much of the melt-water on the ice has drained through it. Because of the poor quality of the ice in early June 2005, a fairly high percentage of the soundings had to be done through drilled holes, which made the survey much more time-consuming than in 2004.

Although depth measurements can be made more efficiently using a boat with outboard motor and onboard sounding equipment, the “through the ice” method was chosen for several reasons. In most years, Lake Hazen does not become entirely ice-free during summer (Clark, 2007; ILEC, 2007). Given the extreme weather conditions and the size of the lake, commonly used boat-supported bathymetric work would require at least one large reliable boat with a powerful engine for safety reasons. However, budget limitations did not allow us to fly in such equipment. In addition, Parks Canada has placed limitations on the use of motorized equipment within Quttinirpaaq National Park. Even if financial and logistical barriers were overcome, allowing the airlift of such a boat to Lake Hazen, ice conditions would probably inhibit sounding work in most years. Furthermore, high winds are likely to hinder boat travel on the lake in open-water conditions. We were fortunate in 2006 and 2010 to find calm days on which to do additional soundings from the small boat. Overall, the “through the ice” method is more time-consuming, but it is safer and less dependent on weather conditions and was able to deliver a reasonable map for the given scientific goal. The precision of the bathymetric map of Lake Hazen will be increased in the future by adding more spots, particularly along the shoreline and at the far ends of the lake. The volume of the

lake based on our bathymetric interpolation is approximately $5.14 \times 10^{10} \text{ m}^3$ and the mean depth is 95 m; both figures are about 10% larger than previous estimates by Muir et al. (1996) based on data in the Deane (1959) report.

Estimated Ruggles River average discharge ranged from $2.6 \text{ m}^3 \text{ sec}^{-1}$ in May and early June to $85 \text{ m}^3 \text{ sec}^{-1}$ during the first two weeks of August. Estimated average annual discharge ($\pm 1 \text{ SD}$) was $0.573 \pm 0.419 \text{ km}^3$. The large SD was due to high year-to-year variation, particularly in the July and August flows. On the basis of this discharge and volume, the water residence time was estimated to be 89 ± 66 years. When more complete flow data from the Ruggles River become available, a more precise estimate of the water residence time of the lake will be possible.

Radiometric Dating of a Sediment Core

The sediment core collection site at the deep point was at a slightly deeper (267 m) and more northeasterly location than the one used in 1990 (254 m, $81^\circ 47' \text{ N}$; $71^\circ 30' \text{ W}$). The sediment had relatively low porosity, ranging from 91% at 0.0–0.5 cm to 73% at 10 cm depth. The profiles of ^{137}Cs and ^{210}Pb by gamma and alpha counting, respectively, are shown in Figure 2. A distinctive ^{137}Cs peak (16.8 Bq kg^{-1}) observed at 2.8 cm compacted depth was followed by a decline to less than 0.25 Bq kg^{-1} in samples below 5.0 cm. This peak was assumed to be representative of deposition from atmospheric nuclear testing, which began in the early 1950s (Robbins et al., 1978) and peaked in 1963 (Appleby, 2001). Several other minor peaks were observed, but these were very close to background of $0.3\text{--}1 \text{ Bq kg}^{-1}$.

The unsupported ^{210}Pb signal determined by alpha counting was relatively constant in the upper 2.0 cm ($20\text{--}32 \text{ Bq kg}^{-1}$) with a maximum at 1.85 cm, then declined exponentially to background at about 14 cm compacted depth (Fig. 2). The flat profile in the upper horizons implies relatively high recent sedimentation rates, while the steep decline indicates lower rates in older layers (Appleby, 2004). Applying the CRS model to the entire ^{210}Pb profile yielded dates for the horizons corresponding to maximum ^{137}Cs of 1980 to 1990 (data not shown) and therefore was not in good agreement with observations. However, because the ^{137}Cs profile clearly identified the 1963 horizon, the CRS model was applied using all of the unsupported ^{210}Pb results below 3 cm compacted depth (at 1.3 g cm^{-2}). The CRS model estimated high sedimentation rates ($1070 \pm 180 \text{ g m}^{-2} \text{ yr}^{-1}$) in horizons dated to the 1950s and 60s and lower sedimentation rates ($650 \pm 100 \text{ g m}^{-2} \text{ yr}^{-1}$) for earlier horizons (1950–1880) (Fig. 2). The dates of the upper horizons (2005–1963) were estimated assuming a single sedimentation rate over the four decades of $1260 \text{ g m}^{-2} \text{ yr}^{-1}$, which was based on the CRS model estimate for the horizon dated to 1963. The Constant Initial Concentration (CIC2) model, which assumes a constant initial concentration of unsupported ^{210}Pb and uses cumulative dry weight to account for sediment compaction (Robbins and Edgington, 1975), was also evaluated; however, the reversals of ^{210}Pb vs.

accumulated dry weight (Fig. 2) in some horizons violated the model assumptions. The Rapid Steady-state Mixing Model (RSSM) (Robbins, 1978), which is a modification of the CIC model, was also investigated, but it was difficult to apply to the entire ^{210}Pb profile because of the unusual subsurface profile of excess ^{210}Pb . Also the assumption of bioturbation by benthic organisms does not apply in Lake Hazen, which has very low productivity (Clark, 2007).

Lockhart et al. (1997, 1998) and Omelchenko et al. (2005) reported on the dating of two cores (Box Cores A and B) collected from Lake Hazen in 1990. Their ^{210}Pb profile for Box Core B was limited to 6 points because they used 1.25 cm sample intervals but nevertheless showed an overall exponential decline from about 30 Bq kg⁻¹ in the top 2 cm to 11 Bq kg⁻¹ at about 6 cm, a pattern similar to what we observed for the core from 2005. They assigned a date of 1964 for the 3.75–5.0 cm horizon, which agreed with the ^{137}Cs maximum of about 30 Bq kg⁻¹, and estimated an overall sedimentation rate of 498 g m⁻² yr⁻¹. For Box Core A, Omelchenko et al. (2005) reported a sedimentation rate of 1189 ± 60 g m⁻² yr⁻¹ based on the ^{137}Cs signal, which is in good agreement with the sedimentation rate of 1260 g m⁻² yr⁻¹ based on the CRS model for the same horizon in our 2005 core. However, applying the RSSM model, the same studies reported a sedimentation rate of 278 ± 24 g m⁻² yr⁻¹ in Box Core A (Omelchenko et al., 2005) and 498 g m⁻² yr⁻¹ in Box Core B (Lockhart et al., 1997). These lower rates may reflect the limited data available to fit the unsupported ^{210}Pb vs. accumulated dry weight because of the low sampling resolution (1.25 cm slices) with the box corer.

The ^{137}Cs peak in the present study includes the horizons from 3 to 5 cm with ^{137}Cs greater than 10 Bq kg⁻¹ and, although taken at a slightly deeper location in the same area sampled by Lockhart et al. (1997), it has a maximum at about the same depth as the box core collected in 1990. This similarity is surprising, because the intervening 15 years should have buried the ^{137}Cs further. Both maxima were at horizons with a similar accumulated dry weight of about 1.3 g cm⁻². The difference may reflect variability of deposition within the profundal area, as well as the differences in performance of the types of coring equipment (core vs. box) and in sampling resolution.

Sediment Core Trace Element Profiles

The top 30 slices from the sediment core, estimated to represent the past 135 years, were analyzed to assess concentrations of heavy metals and other elements. Of the 33 elements analyzed in the sediment samples, 29 were present at concentrations above the MDL in all horizons (Table 1). Mo, Rh, Sb, and Pt were near or at MDLs in most samples. TON was also very low (0.01–0.8%). Our main interests in terms of data interpretation were the extent to which concentrations were changing with depth and whether there might be anthropogenic enrichment. If the ratio of concentrations in recent horizons to those in pre-industrial horizons (the enrichment ratio, or ER) is greater than 1, then

anthropogenic enrichment has occurred. We have previously reported on the Hg profile in this core (Muir et al., 2009), as well as algal carbon and diatom abundance (Kirk et al., 2011).

Overall, there were limited changes in concentrations of most analytes with depth in the core. The majority of elements measured (24 of 29 consistently above the MDL), as well as TOC, showed less than 20% variation in concentrations in the 30 samples representing the top 15 cm. As, Cd, Na, Pd, and Mn had greater variation, ranging from 24% to 81% (Table 1). ERs ranged from 0.5 (As) to 1.4 (Ca), but most were in the 0.8–1.2 range (25/29), reflecting the low variation with depth.

Concentration profiles of selected elements, as well as TOC, in Lake Hazen sediment are plotted against the estimated median age of each horizon in Figure 3A–D. The elements with greatest ERs—Al, Li, V, and Ca—are shown in Figure 3A. They showed a slow but steady increase in concentration over time. Al was correlated with V ($p < 0.001$), but not with Ca or Li. Ca and Li were correlated with V ($p < 0.001$) (Table 1). Lithogenic elements Al and Mg were significantly positively correlated ($p < 0.05$) with many other elements (Table 1). Al was correlated with As, Mg, Cr, K, and Pb (Fig. 3B) as well as with Co, La, and Sb. Mg was significantly correlated ($p < 0.05$) with 11 elements (Al, Ba, Be, Ga, Cr, K, Na, P, Rb, Sr, Tl, Zn), the greatest number of correlations for any of the 29 elements (Table 1). Profiles for Ba, P, Rb, Sr, and Tl are presented in Figure 3C. The observed increase in Al, K, and Mg concentration implies increased erosional inputs from the catchment of clay-associated minerals (Hilton et al., 1985). The significant correlation of Al and Mg with many elements implies a common pathway and source.

TOC showed a 34% increase in the profile, with much of the increase coming after about 1940. TOC had significant negative correlations with As, Co, Pb, and U and positive correlations with Ca, Li, and Pd. The negative relationship with the metals such as Co and Pb, and the lack of correlation with clay mineral-related elements Al and Mg, suggest separate controls for the clay mineral and organic carbon inputs.

Fe concentrations showed some variation in horizons dated to the period 1870–1930, but were relatively constant in more recent horizons (Fig. 3D). Fe was significantly positively correlated ($p < 0.05$) with As, Co, Ni, Pb, Cu, P, and Zn. Some of these elements (for example, As, Co, Cr, and V) are known to be redox-sensitive and could undergo diffusive migration in a redox gradient in their reduced states because of higher solubility (Boyle, 2001). Others could form insoluble sulfides (Pb, Zn). However, no diagenetic accumulation just below the sediment surface was observed for Fe or Mn, in contrast to some other oligotrophic lake studies (Cornwell, 1986; Outridge et al., 2005; Wilson et al., 2008).

Overall, the elemental profiles imply natural sources dominated by erosional inputs from annual glacial melting and scouring of riverbeds. The sediment-coring site is

TABLE 1. Means, relative standard deviations, and ratios of recent to preindustrial concentrations in a sediment core from Lake Hazen.

Analyte	µg/g Dry weight			RSD ¹ %	MDL ² µg/g	ER ³	Correlation coefficients ⁴			
	Mean	Minimum	Maximum				Year	Al	Mg	Fe
Al	73640	55000	92000	12	< 1.0	1.201	0.531	–	0.703*	-0.062
As	13.9	9.00	24.0	30	< 0.1	0.502	-0.812*	-0.323	0.159	0.860*
Ba	395	291	595	18	< 1.0	0.821	-0.430	0.412	0.723*	0.584
Be	2.14	1.58	2.46	9	< 0.1	1.078	0.255	0.830*	0.696*	0.193
Bi	0.250	0.200	0.300	20	< 0.01	0.921	-0.297	0.080	0.473	0.472
Ca	3301	2300	3970	14	< 1.0	1.387	0.928*	0.600	0.238	-0.393
Cd	0.177	0.100	0.200	24	< 0.01	0.942	0.123	-0.005	0.051	0.019
Co	16.4	11.3	23.4	18	< 0.1	0.751	-0.490	-0.179	0.285	0.724*
Cr	86.2	69.0	107	10	< 1.0	1.114	0.335	0.941*	0.787*	0.050
Cu	35.1	28.0	44.0	14	< 1.0	0.797	-0.600	-0.082	0.482	0.705*
Fe	39630	30500	51300	13	< 1.0	0.809	-0.506	-0.062	0.434	–
Ga	20.5	15.5	24.4	10	< 0.1	1.106	0.264	0.878*	0.643*	0.080
Hg	0.063	0.045	0.077	11	< 0.01	1.035	0.020	-0.185	0.059	-0.011
K	18827	14600	24700	13	< 1.0	1.115	0.302	0.954*	0.766*	0.106
La	36.9	33.3	40.6	4	< 0.1	1.010	-0.106	0.466	0.550	0.242
Li	88.8	60.8	109	10	< 0.1	1.213	0.679*	0.719*	0.387	-0.125
Mg	8146	6080	10100	10	< 1.0	1.046	0.173	0.703*	–	0.434
Mn	729	299	3180	81	< 1.0	0.598	0.044	-0.027	0.214	0.224
Mo	0.695	< 0.50	2.00	66	< 0.5	–	-0.588	-0.470	-0.162	0.547
Na	804	510	1420	26	< 1.0	0.833	-0.343	0.477	0.696*	0.401
Ni	40.8	31.7	48.3	11	< 0.1	0.826	-0.529	0.019	0.525	0.790*
P	648	606	736	5	< 1.0	0.952	-0.369	0.375	0.749*	0.638*
Pb	28.0	21.4	34.9	15	< 0.1	0.776	-0.611*	-0.093	0.531	0.769*
Pd	0.189	0.13	0.23	12	< 0.01	1.088	0.017	0.197	0.497	0.536
Pt	0.010	< 0.01	0.010	34	< 0.01	–	0.712*	0.548	0.354	-0.172
Rb	105	77.4	130	12	< 0.1	1.089	0.161	0.865*	0.694*	0.158
Rh	0.004	< 0.002	0.009	63	< 0.002	–	-0.011	0.399	0.566	-0.008
Sb	0.092	< 0.10	0.200	32	< 0.1	–	-0.089	-0.415	-0.085	0.247
Sr	117	105	142	8	< 1.0	0.970	-0.233	0.544	0.722*	0.396
Tl	0.604	0.505	0.787	12	< 0.1	0.975	-0.182	0.662*	0.743*	0.350
U	1.853	1.47	2.43	15	< 0.1	0.783	-0.706*	-0.295	0.163	0.368
V	1010	82.0	132	12	< 1.0	1.263	0.736*	0.890*	0.405	-0.304
Zn	90.7	76.0	105	7	< 1.0	0.961	-0.142	0.446	0.904*	0.696*
	%	%	%	%						
TIC	0.096	0.005	0.410	104		1.904	-0.013	-0.078	-0.031	-0.129
TOC	1.41	0.99	1.82	15		1.340	0.462	0.462	0.021	-0.487
TON	0.237	0.005	1.00	106		0.094	-0.662	-0.194	0.108	0.425

¹ RSD = 100 × standard deviation/mean based on 30 samples (0–15 cm depth).

² Instrument detection limit.

³ ER = Mean for horizons dated 1986–2005 ÷ mean for horizons dated 1830–66. Dash indicates not calculated for elements with concentration below the method detection limits.

⁴ Pearson correlation coefficients. An asterisk (*) indicates significant ($p < 0.05$) correlations based on Bonferroni probabilities.

actually relatively close (4–7 km) to the Snow Goose and Abbé River inflows, which are fed by the Abbé and Roudel glaciers flowing out of the northern Ellesmere icecap. While most suspended particles from those rivers are probably deposited as sediment between the river delta and John's Island (Fig. 1), this large input could nevertheless influence the deep zone to the northeast. The relatively uniform elemental concentrations contrast with the ²¹⁰Pb profile (Fig. 2), which shows similar activities in the top 2 cm, implying mixing or a more rapid sedimentation rate in the past 30 years compared to lower horizons. Redistribution of sediment by slumping might explain the higher ²¹⁰Pb at 1.5–2.0 cm compacted depth; however, the lack of change in concentrations of major elements Al, Fe, K, and Ca (Fig. 3) suggests only gradual shifts in sedimentation and no change in the source of sedimenting particles. The estimated sedimentation rates of 1260 g m⁻² yr⁻¹ for the recent

horizons and 650 ± 100 g m⁻² yr⁻¹ for the period 1950–1880 are at the upper end of the range (10–1000 g m⁻² yr⁻¹) that we observed in 18 high-latitude lakes in Canada (Muir et al., 2009) and within the range observed by Appleby (2004) for lakes on Svalbard.

Toxic metals, Hg and Pb, have been determined in numerous high-latitude Arctic lake sediments (Bindler et al., 2001; Outridge et al., 2002, 2005; Michelutti et al., 2009; Muir et al., 2009; Cooke et al., 2010), and previous reports for these elements from Lake Hazen are reviewed briefly here. Outridge et al. (2002) found increasing concentrations of total Pb with depth in a core from Lake Hazen collected in 1990. The same trend was noted in the present study, and the ER for Pb was 0.776, indicating higher concentrations in the mid-1800s. Outridge et al. (2002) also found no shifts in Pb isotopes attributable to anthropogenic Pb inputs. The increase of concentrations with depth is unlike the pattern of

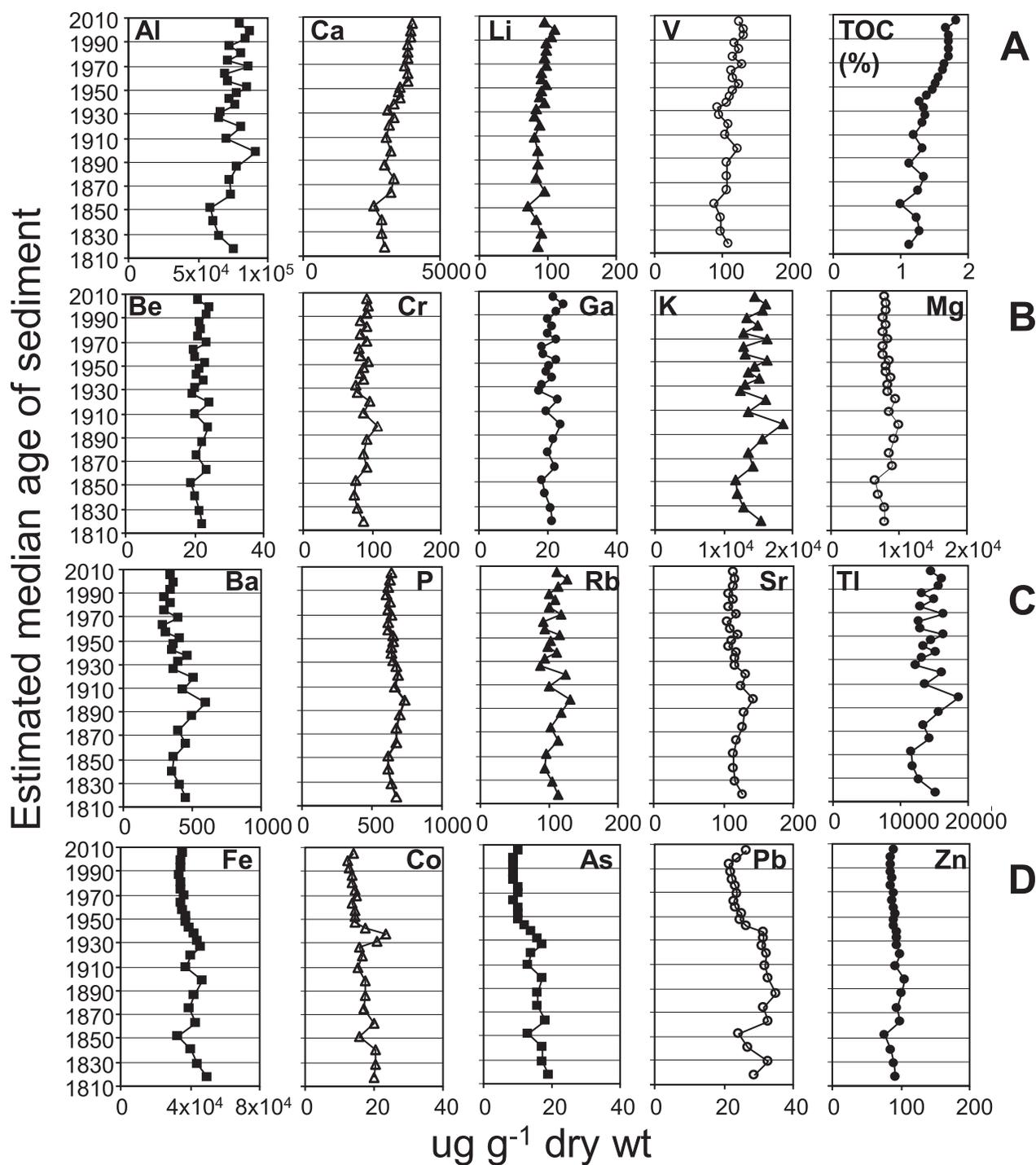


FIG. 3. Concentration profiles of selected elements in a Lake Hazen sediment core. (A) shows the elements with greatest enrichment ratios, while the remaining sections show elements significantly correlated with (B) aluminum, (C) magnesium, and (D) iron.

some lakes on eastern Baffin Island and western Greenland, where ERs higher than 1 have been reported, along with evidence from Pb isotope ratios of anthropogenic Pb inputs (Bindler et al., 2001; Michelutti et al., 2009). In the case of Hg, Muir et al. (2009) reported an uncorrected Hg flux ratio of 1.13 in Lake Hazen, which was low relative to most other Arctic sediment cores (average = 2.15, N = 18 lakes), but consistent with atmospheric deposition modeling, which predicted low anthropogenic fluxes at very high latitudes.

In conclusion, this study has developed the first bathymetric map of Lake Hazen, which will be valuable for future research on the lake. Lake characteristics such as mean depth and water residence time have now been more accurately estimated. The identification of the profundal zone allowed us to collect and analyze a sediment core from the deepest point in the lake and to infer sedimentation rates and geochemical characteristics of the sediment. The geochemical profiles suggest that Lake Hazen is responding

very slowly to climate change, as evidenced by increasing TOC and lithogenic elements, as well as by changing sedimentation rates. However, these trends are slow and do not appear to be as dramatic as some geochemical and biological shifts observed in smaller Arctic lakes and ponds in the Canadian Archipelago (Outridge et al., 2005; Smol, 2005).

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