Limnological Characteristics of 22 Lakes and Ponds in the Haughton Crater Region of Devon Island, Nunavut, Canadian High Arctic

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Abstract

The physical and chemical limnological characteristics of 22 lakes and ponds in the remote region of Haughton Impact Crater, Devon Island, Nunavut, Canada, were explored. Our overall goals were to gather baseline information for use in climate and environmental change monitoring programs in the High Arctic as well as to compare these observations to other limnological surveys conducted in high-latitude regions. Study sites were alkaline ($pH_{mean} = 8.3$), ultraoligotrophic ($TPU_{mean} = 3.7$ µg L^{-1}), and phosphorus limited. Major and minor ionic concentrations of most sites are comparable to other previously surveyed high arctic sites. Lakes and ponds in close contact with the impact-generated carbonate melt rocks associated with Haughton Crater were distinguished from the larger data set due to their elevated Mg^{2+}, SO_4^{2-}, Ba^{2+}, Sr^{2+}, and SiO_2 concentrations. Selenite ($CaSO_4 \cdot 2H_2O$) formations commonly associated with the lower levels of the carbonate melt sheets were identified as a likely source for the elevated SO_4^{2-} concentrations in these sites. Principal Components Analysis separated sites along a conductivity and nutrient gradient on the primary and secondary axes, respectively. This study serves as a baseline for a long-term monitoring program in the Haughton Crater region.

Introduction

The High Arctic is a distinct region of our planet, unique in the manner in which it supports life, responds to shifts in the climate, and in turn influences environments at lower latitudes. Characteristics such as low incoming solar radiation, small land mass (one-tenth the size of tropical regions), and high-albedo surfaces exacerbate the effects of global climate change in the High Arctic compared to lower latitudes (Roots, 1990; Rouse, 1993) and contribute to the region's environmental vulnerability. Furthermore, the effects of high arctic environmental change are not confined to this region because they are strongly tied to general oceanic and atmospheric circulation patterns and the modulation of global carbon budgets (Overpeck et al., 1997). For example, an increase in the average annual discharge of arctic freshwater input to the Arctic Ocean over the period 1936–1999 has been correlated with changes in both the North Atlantic Oscillation and global mean surface air temperature (Peterson et al., 2002). Given these elements, the High Arctic has become a critical reference area for global environmental change, and an area in need of long-term monitoring programs for effective study, analysis, and management.

Consistent and sustained monitoring of the High Arctic remains a challenge due to financial and logistical constraints; hence, ecological and environmental baseline data for much of this extreme region remain sparse. However, the large number of lakes and ponds found throughout the High Arctic can provide a means of establishing monitoring programs. These water bodies are particularly sensitive to environmental changes, including those operating on a global scale, which may or may not have been caused or accelerated by anthropogenic activities (Rouse et al., 1997; Douglas and Smol, 2000; Vincent and Hobbie, 2000). For example, climate warming may induce changes in hydrology or catchment vegetation, resulting in concentration shifts of light-attenuating compounds (e.g., colored dissolved organic carbon) in high arctic water bodies, leading to increased solar ultraviolet ray penetration, increased ion and nutrient influx triggering greater productivity levels, and alterations to overall aquatic biodiversity and food web structure

and dynamics (Douglas and Smol, 1999; Hobbie et al., 1999; Vincent and Hobbie, 2000). Thus, establishing baseline data for high arctic lakes and ponds and subsequent monitoring is critical to our understanding of the effects of future climate changes in this region.

Although the importance of high arctic lakes and ponds has been widely recognized, the collection of even basic limnological data in the High Arctic is still in its infancy (Rouse et al., 1997; Vincent and Hobbie, 2000). An increase in research activity over the past decade has begun to rectify this situation. Some examples of recent collection and analysis of Canadian high arctic limnological data include Douglas and Smol (1994), Antoniades et al. (2000), and Hamilton et al. (2000), all from Ellesmere Island, Nunavut; Michelutti et al. (2002b) on Victoria Island, Nunavut, and Lim et al. (in press) on Banks Island, Northwest Territories, both southwestern islands in the Canadian Arctic Archipelago; Michelutti et al. (2002a) on Axel Heiberg Island, Nunavut; Lim et al. (2001) on Bathurst Island, Nunavut; Ludlam (1996) on Cornwallis and Ellesmere Island, Nunavut; Joynt and Wolfe (2001) on Baffin Island, Nunavut; and Hamilton et al. (2001), who produced a limnological overview of 204 lakes from the Canadian Arctic Archipelago.

Even with this growing list of investigations, most of the High Arctic's lakes and ponds remain unexplored, including those found on Devon Island, Nunavut. Although some paleolimnological studies have been carried out on the island (e.g., Young and King, 1989; Gajewski et al., 1997; Ng and King, 1999), these have largely focused on selected lakes along the coast and in the Truelove Lowlands area.

Our sample sites are located in and around Haughton Crater because this study is part of a larger effort by the National Aeronautics and Space Administration/Search for Extraterrestrial Intelligence (Institute) (NASA/SETI) Haughton Mars Project (HMP) to map and characterize the biology and geology of this region of interest. Here we present an overview of the water chemistry data of 22 lakes and ponds from the Haughton Crater region of Devon Island, Nunavut (Fig. 1). Our objective was to conduct a comprehensive limnological survey of the Haughton Crater region that was comparable and complementary to
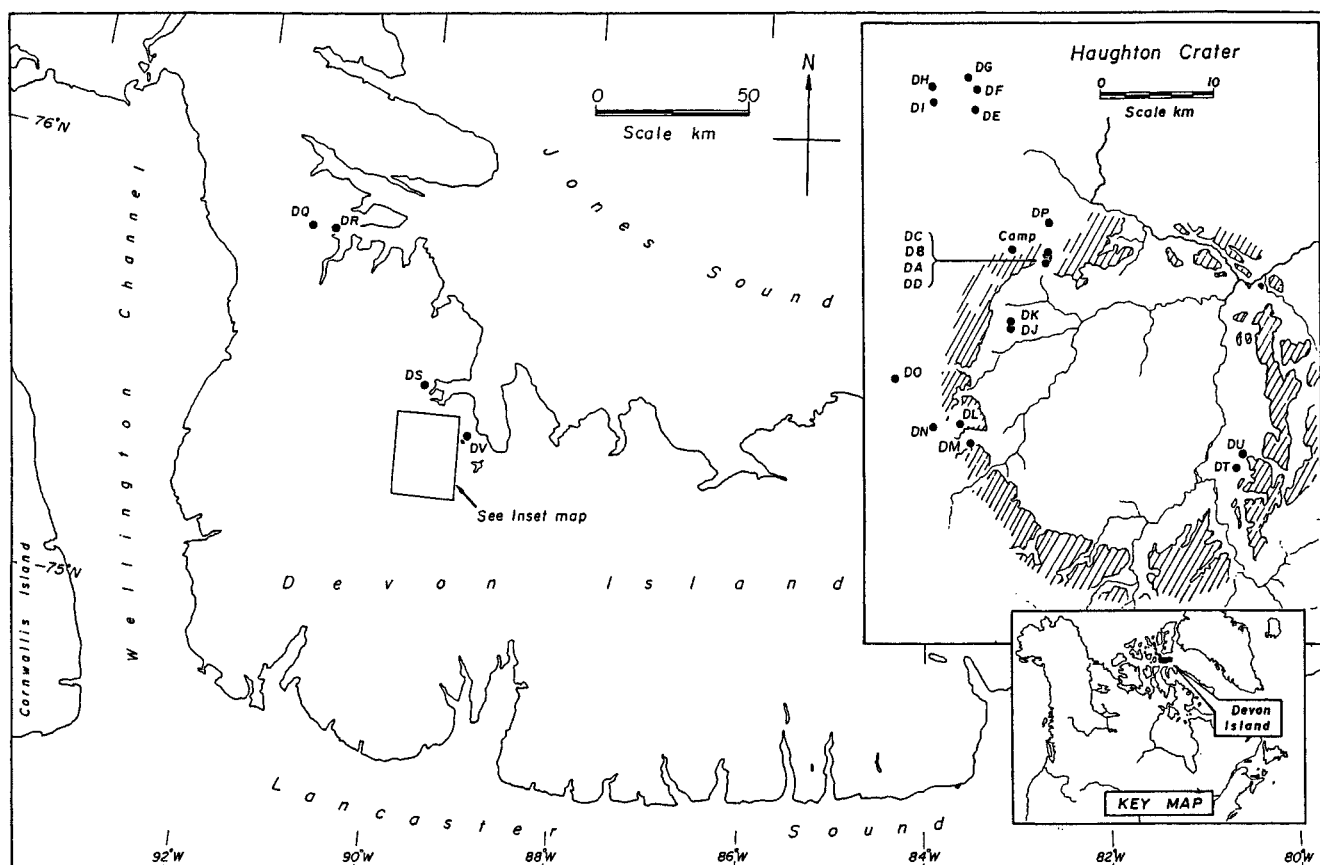
FIGURE 1. Map of Devon Island and the Haughton Crater region, with the location of the 22 lakes and ponds in this limnological study. Crater rim interpolated from 10-m contour intervals of 1:50,000 Canada NTS map No. 58 H/7.

surveys from other Canadian high arctic islands (e.g., Hamilton et al., 2001; Lim et al., 2001; Michelutti et al., 2002a, 2002b). Haughton Crater is a unique setting in the High Arctic that offers the opportunity to explore the effects of a meteorite impact on the limnology of the surrounding water bodies. This study contributes to the advancement of the growing limnological database from the Canadian High Arctic and will play a key role in future paleolimnological investigations for this region.

Site Description

Devon Island is located in the eastern sector of the Canadian Arctic Archipelago. It is the world's largest uninhabited island (approximately 66,800 km^2) and consists mostly of high plateau bordered in many places by sea cliffs and deep fiords (Thorsteinsson and Mayr, 1987). This plateau, drained mainly by short dendritic streams, is highest in the east, where it is approximately 1500 m a.s.l., and then gradually tilts down westward. The eastern portion of the island is distinguished by a large ice cap underlain by Precambrian crystalline rocks (Thorsteinsson and Mayr, 1987). The sites included in this study are located on the western portion of Devon Island, particularly the Haughton Crater area. This area is classified as Arctic Lowland, characterized by flat-lying sediments that become thicker northward, where they form smooth plateaus (Maxwell, 1980). Phanerozoic sedimentary succession outcrops in the western portion of the island overlie crystalline rocks that are exposed in the eastern portion of Devon Island (Thorsteinsson and Mayr, 1987). Most of the Phanerozoic succession consists of lower Paleozoic rocks, overlain unconformably by widely separated outliers of Mesozoic and Tertiary sediments (Thorsteinsson and Mayr, 1987) estimated at 1885 m in thickness based on seismic reflection profiling (Scott and Hajnal, 1988). Haughton Crater (75°22′N, 89°40′W) is

a circular impact structure 24 km in diameter that consists largely of much faulted lower Paleozoic (Ordovician-Silurian) carbonate formations overlain unconformably by what has been deemed to be impact breccia (up to 90 m thick in some areas) by Redeker and Stöffler (1988) or carbonate-rich impact-melt rocks by Osinski and Spray (2001). Shocked basement gneisses from Haughton Crater have been estimated at 23.4 ± 1.0 Ma through ^{40}Ar–^{39}Ar dating (Jessburger, 1988).

The Haughton Formation, which overlies the breccia in some distinct areas, is composed of up to 48 m of interbedded dolomite-rich lacustrine silt, fine sand, and mud (Hickey et al., 1988). These paleolake deposits contain a rich assemblage of pollen, plant macrofossils, and the only known record of early Neogene arctic vertebrates (Whitlock and Dawson, 1990). *Pinus*, *Picea*, *Tsuga*, *Larix*, *Betula*, *Alnus*, and *Corylus* were found to be the most abundant pollen types in the Haughton lacustrine remains (Hickey et al., 1988; Whitlock and Dawson, 1990) and are comparable to modern-day pollen distributions associated with mixed conifer-hardwood forests of eastern coastal North America. Herbaceous taxa are nearly absent, and Gramineae pollen are entirely absent. Since grasses began appearing in the southwestern portion of Canada during the early Miocene, the lack of grass pollen in the Haughton Formation stratigraphies suggests an early Miocene date consistent with the time span representing the limits of error of the date for the impact event (Hickey et al., 1988).

Like other high arctic sites, this region is characterized by a continuous permafrost layer. The western portion of Devon Island, including the area of Haughton Crater, is classified as a polar rock desert, or fellfield, and is characterized by cryic regosol, shallow soils without significantly developed genetic horizons (Maxwell, 1980). These soils are often characterized by arid features, including salt crusts, alkali flats, and carbonate accumulations, which serves to increase surficial pH up to 9.0 (Maxwell, 1980). Most of the Haughton Crater area is largely

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unvegetated, but portions are inhabited by herbaceous species such as *Oxyria digyna*, *Oxytropis arctica*, *Saxifraga oppositifolia*, and *Papaver lapponicum*, with the occasional presence of low-lying dwarf shrubs such as *Salix arctica*. Cockell et al. (2001) determined that the alluvial terraces in the Haughton Crater area had vegetation cover that ranged from 2 to 11%, whereas the breccia hills were less vegetated with a coverage range of 0.1 to 0.3%. Also found throughout the Haughton Crater region are several isolated microoases, demonstrating enhanced local fertility relative to their surroundings, with vegetation cover ranging from 15 to 73% on the breccia and 2 to 98% on the alluvial terraces (Cockell et al., 2001). Overall, these microoases are dominated by either graminoids and *Stellaria longipes* or bryophytes and *Draba corymbosa* (Cockell et al., 2001). Seepage and snow-free south-facing slopes, as well as sheltered valleys, are examples of distinct hydrological features that contribute to increased water and nutrient supply to specific areas, resulting in small regions of enhanced vegetation growth (Edlund and Alt, 1989). Although these oases are considered to be small-scale features, they may nonetheless have a significant impact on the limnology of nearby water bodies.

Annual mean daily temperature on Devon Island from the closest weather station (approximately 175 km from Haughton Crater) at Resolute, Cornwallis Island, Nunavut (74°43'N, 94°59'W) is −16.6°C (data were collected over the period of 1947 to 1990 and tabulated by Environment Canada [1990]). Mean July temperature, which is on average the warmest month of the year and the height of the ice-free growth season, is estimated at 4.0°C. Mean annual precipitation is 139.6 mm.

Materials and Methodology

SAMPLING AND ANALYTICAL METHODS

A total of 22 lakes (>2 m depth) and ponds (<2 m depth) were sampled via ground-based and helicopter-assisted transects around Haughton Crater, Devon Island, Nunavut, over the period 8–29 July 2000 (Fig. 1). Lakes are distinguished from ponds in this study because differences in their physical properties (e.g., depth, volume, extent of ice cover) affect their thermal and chemical inertia and probably their water chemistry as well. For example, ponds may experience greater impacts and fluctuations in their thermal and chemical regimes, whereas lakes may be more chemically stable due to their greater volumes. All lakes and ponds were unnamed and were thus assigned unofficial alphabetic designations of DA to DV (D = Devon). Sites were sampled over a short time frame (3 wk) in order to minimize variability due to seasonal fluctuations. A total of 39 limnological variables (both field and laboratory) were measured for each site.

Site DA was sampled again later in the field season (11 d after initial sampling on 11 July 2000) in three separate areas of the lake in order to observe possible seasonal changes and check for within-lake patchiness. These three data points, labeled DA-1, DA-2, and DA-3, were also measured for the full limnological suite and are included in Table 1, the Pearson correlation matrix (Table 2), and the PCA ordination (Fig. 2). Sample DA-3 was collected at the same geographical point of the lake as the original sample DA in order to have a direct source of comparison. These three data points will be referred to as "subsites" hereafter.

Sites were selected to cover as wide an environmental gradient as possible (e.g., proximity to sea, drainage characteristics, vegetation, elevation), with latitudinal and longitudinal data for each site being recorded using a handheld global positioning system (GPS). Approximate elevation values for each site were recorded from 1:50,000 topographic maps. Sampling procedures for this study followed routine techniques as described by Douglas and Smol (1994) and Pienitz et al. (1997) and are briefly detailed below.

Lake and pond temperatures were measured from approximately 0.3-m water depth at each site to the nearest 0.5°C using a handheld thermometer. Unfiltered water samples for major/minor ion analyses and samples for trace metal analyses were collected from approximately 0.3-m depth at each site using precleaned 250-mL Nalgene® bottles rinsed three times with sample site water prior to collection. Lake and pond (unfiltered) samples were collected at each site for total unfiltered phosphorus (TPU) using prewashed 250-mL glass bottles. Water samples for nutrient analyses of total chlorophyll *a,* particulate organic carbon (POC), particulate organic nitrogen (PON), and other minor nutrient constituents, along with pH and specific conductance (COND) measurements, were partitioned and prepared from 1-L Nalgene® bottles within hours of sample collection. Conductivity and pH readings for each site were also recorded from these unfiltered samples.

For some analyses, water samples were prepared by filtration, with the filtrate being collected in acid-rinsed 125-mL glass bottles for the subsequent analysis of total "dissolved" phosphorus (TPF), nitrite (NO_2), nitrate (NO_3), ammonia (NH_3), soluble reactive phosphate-phosphorus (SRP), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and total Kjeldahl nitrogen (TKN). Water samples were also filtered for POC, PON, and total chlorophyll *a* (CHLA-U) as an estimate of biomass.

All samples were stored in a cool, dark area for the duration of the field season and subsequently shipped to the National Water Research Institute in Burlington, Ontario, where all water chemistry analyses were conducted following standard protocols outlined by Environment Canada (1994a, 1994b).

STATISTICAL ANALYSES AND DATA SCREENING

Principal Components Analysis (PCA) was performed using the statistical program CANOCO v. 4 (ter Braak and Šmilauer, 1998) in order to detect dominant patterns and environmental relationships in the limnological data set (Jongman et al., 1987; ter Braak and Prentice, 1988). PCA was also utilized to identify outlier sites falling outside the 95% confidence limits as determined from the site score means. No sites were identified as being outliers, so all sample sites from the Haughton Crater region were included in these statistical analyses.

Those environmental variables that were recorded as being below the detection limit (limits ranged from $<0.0002\,\mathrm{mg\,L^{-1}}$ to $<0.2\,\mathrm{mg\,L^{-1}}$) in more than 50% of the study sites were removed from the data set used in the PCA. This resulted in the elimination of Be^{2+}, K^+, Cd^{2+}, Co^{2+}, Cr^{2+}, V^{2+}, Mo^{2+}, Mn^{2+}, Pb^{2+}, Ni^{2+}, Li^+, Ag^+, NO_2, NO_3NO_2, and NH_3. Therefore, from the original 39 measured variables, a total of 24 chemical and physical variables were included in the final active environmental data set (Table 1). Other variables that contained measurements below the detection limits in less than 50% of the sites were not removed from the data set but rather replaced with a value of half of the measured detection limit for that variable. The values that have been replaced in this manner have been boldfaced in Table 1. The TPU value for site DB was disregarded in our study due to an analytical lab error.

A Pearson correlation matrix with Bonferroni adjusted probabilities was used to distinguish pairs of significantly ($0.01 \geq P \leq 0.05$) correlated environmental variables (Table 2). The program CALIBRATE v. 0.3 (Juggins and ter Braak, 1992) was used to identify skewness in the distribution of each individual variable. All of the environmental variables except Ca, TPU, CHLA-U, and COND were normalized in order to reduce skewness by performing either log (x) (Na, SO_4, Cl, Al, Ba, Fe, Sr, SiO_2, DOC, DIC, POC, TPF, TKN, pH) or square root (Mg, Cu, Zn, SRPF, PON, TEMP) transformations. This transformed data set was used in both the PCA ordination and the Pearson correlation matrix.

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TABLE 1

Environmental data set for all collection points (n = 25) sampled in the Haughton Crater region. Measurements below the detection limit were replaced with a value of half the measured detection limit for each specific variable and are listed in bold typeface

Sites	Ca mg L^{-1}	Mg mg L^{-1}	Na mg L^{-1}	SO$_4$ mg L^{-1}	Cl mg L^{-1}	Al mg L^{-1}	Ba mg L^{-1}	Fe mg L^{-1}	Cu mg L^{-1}	Sr mg L^{-1}	Zn mg L^{-1}	SiO$_2$ mg L^{-1}	DOC mg L^{-1}	DIC mg L^{-1}	POC µG L^{-1}
DA	21.1	5.9	1.6	4.0	4.13	0.030	0.0020	0.022	0.008	0.0215	0.0020	0.82	2.8	16.9	164.0
DA-1	26.2	7.3	1.7	4.0	4.49	0.090	0.0025	0.062	0.002	0.0248	0.0020	0.80	1.6	17.9	265.0
DA-2	23.0	6.3	1.7	4.0	4.51	0.010	0.0019	0.004	0.005	0.0235	0.0010	0.81	1.2	19.8	242.0
DA-3	23.1	6.4	1.7	4.0	4.47	0.010	0.0019	0.005	0.002	0.0236	0.0010	0.80	1.9	19.9	299.0
DB	25.0	5.3	1.5	9.2	3.31	0.030	0.0023	0.034	0.004	0.0204	0.0020	0.48	1.5	17.0	187.0
DC	23.8	5.6	1.0	5.2	2.38	0.020	0.0033	0.011	0.003	0.0205	0.0020	0.57	1.8	16.9	528.0
DD	36.8	10.9	1.8	4.0	4.23	0.720	0.0060	0.766	0.011	0.0288	0.0040	0.47	1.9	18.2	564.0
DE	9.0	4.2	0.7	0.3	1.59	0.020	0.0005	0.038	0.005	0.0034	0.0030	0.10	1.5	9.4	208.0
DF	12.5	4.6	0.8	0.4	1.77	0.010	0.0005	0.005	0.004	0.0038	0.0050	0.11	2.7	11.0	319.0
DG	17.5	6.2	1.5	0.7	3.08	**0.005**	0.0006	0.005	0.001	0.0054	0.0010	0.19	4.2	15.7	245.0
DH	12.4	5.0	1.2	0.5	2.74	0.010	0.0005	0.005	0.001	0.0039	0.0030	0.08	2.0	12.0	168.0
DI	13.1	4.3	1.0	0.6	2.28	0.010	0.0012	0.066	0.006	0.0039	0.0020	0.09	1.7	11.9	222.0
DJ	28.0	6.5	1.2	13.0	2.89	0.020	0.0065	0.021	0.002	0.0255	0.0010	1.58	1.7	18.2	381.0
DK	29.6	6.2	0.8	21.5	1.82	0.090	0.0088	0.073	0.002	0.0279	0.0020	1.60	2.4	16.3	282.0
DL	25.3	7.2	1.8	1.2	4.67	0.010	0.0018	0.006	0.002	0.0137	0.0020	0.12	3.0	20.7	330.0
DM	19.8	6.1	0.6	0.6	1.34	0.030	0.0010	0.036	0.002	0.0105	0.0010	0.20	1.7	17.3	187.0
DN	18.2	5.3	0.7	0.3	1.51	0.010	0.0008	0.011	0.002	0.0056	0.0010	0.15	1.6	15.4	314.0
DO	18.2	3.3	0.8	0.2	1.64	0.010	0.0009	0.011	0.002	0.0068	0.0010	0.14	1.8	13.5	367.0
DP	11.2	6.7	1.0	0.3	2.37	0.010	0.0010	0.005	0.002	0.0054	0.0010	0.17	1.9	13.9	268.0
DQ	19.1	6.1	1.5	2.1	3.15	0.010	0.0046	0.006	0.001	0.0139	0.0020	0.33	2.1	17.5	219.0
DR	30.5	7.9	13.1	7.2	30.30	0.010	0.0109	0.077	0.004	0.0525	0.0070	1.00	7.4	22.8	773.0
DS	11.5	6.3	1.3	0.5	2.85	**0.005**	0.0005	0.001	0.001	0.0038	0.0020	0.11	1.2	12.9	199.0
DT	28.8	7.0	1.0	10.5	2.56	0.030	0.0236	0.021	0.002	0.0789	0.0010	1.23	1.6	22.4	294.0
DU	27.6	7.1	1.0	11.0	2.63	0.010	0.0300	0.004	0.002	0.0909	**0.0005**	1.44	1.7	22.3	299.0
DV	27.6	4.7	1.4	18.6	2.93	0.030	0.0217	0.019	0.002	0.9790	0.0010	0.37	1.3	17.5	270.0
Mean	**21.6**	**6.1**	**1.7**	**5.0**	**3.99**	**0.050**	**0.0054**	**0.053**	**0.003**	**0.0599**	**0.0020**	**0.55**	**2.2**	**16.7**	**303.8**
Median	**23.0**	**6.2**	**1.2**	**4.0**	**2.85**	**0.010**	**0.0019**	**0.011**	**0.002**	**0.0204**	**0.0020**	**0.37**	**1.8**	**17.0**	**270.0**
Maximum	**36.8**	**10.9**	**13.1**	**21.5**	**30.30**	**0.720**	**0.0300**	**0.766**	**0.011**	**0.9790**	**0.0070**	**1.60**	**7.4**	**22.8**	**773.0**
Minimum	**9.0**	**3.3**	**0.6**	**0.2**	**1.34**	**<0.01**	**0.0005**	**0.001**	**0.001**	**0.0034**	**<0.001**	**0.08**	**1.2**	**9.4**	**164.0**

** TN does not include NO$_3$NO$_2$ because all NO$_3$NO$_2$ values were below detection limit and negligible; therefore TN = TKN + PON.

Results and Discussion

PHYSICAL VARIABLES

Of the 22 sites sampled around the Haughton Crater area, 12 were ponds that typically freeze to the bottom, and 10 were characterized as lakes that maintain liquid water under the ice. With the exception of DQ and DR, these sites were focused within a 20-km radius of the HMP base camp (Fig. 1) and were all within a small elevation gradient ranging from sea level to approximately 240 m a.s.l. (Table 1).

Temperature (TEMP) values for all 25 data collection points ranged from 1.5°C to 15.0°C (mean = 7.0°C). Pond temperatures ranged from 3.0°C to 15.0°C, while lake temperatures ranged from 1.5°C to 13.0°C, with the three additional samplings of site DA later in the field season ranging from 9.0°C to 11.0°C. Like other high arctic sites (e.g., Lim et al., 2001, Michelutti et al., 2002b), the mean temperature for the sampled ponds (mean = 7.7°C) is higher than the mean temperature for the lakes (mean = 4.7°C). This difference is attributed to the greater heat capacity of lakes versus smaller, shallower water bodies such as ponds.

CHEMICAL VARIABLES

pH, Conductivity, and Major/Minor Ions

The pH values for the lakes and ponds in the Haughton Crater region did not vary greatly, ranging from 8.0 to 8.6 (mean pH = 8.3). The tight range in pH values was not surprising given that all of the sample sites were underlain by similar carbonate bedrock. Furthermore, the alkaline mean pH for the Haughton Crater region water bodies is similar to pH values from other lakes and ponds on Devon Island (Hamilton et al., 2001) and nearby islands with comparable surficial geology and/or bedrock such as Bathurst Island (Lim et al., 2001), Cornwallis Island (Douglas and Smol, 2000; Smol, unpublished data) and Ellesmere Island (Douglas and Smol, 1994; Antoniades et al., 2000).

Ponds DJ (pH = 8.5), DQ (pH = 8.6), and DR (pH = 8.5) had the highest recorded pH values (Table 1). Given that these sites are underlain by bedrock similar to that underlying all other sites in the study, this characteristic may be attributable to their respective levels of photosynthetic activity and their size. The bottom of each of these sites was lined by rocks covered with a thick cyanobacterial mat, which through photosynthetic activities may have contributed to the elevated pH levels. Subsites DA-1 (pH = 8.6), DA-2 (pH = 8.4), and DA-3 (pH = 8.4) increased slightly in pH compared to the initial collection at the lake (DA pH = 8.3). Once again, this slight increase may be attributable to an increase in overall lake productivity; however, given that this lake and all other Haughton Crater sites are well buffered, it is not surprising that the effects of biotic activity on lake alkalinity might be muted.

Conductivity levels ranged from 50 µS cm^{-1} to 185 µS cm^{-1}, with a mean of 97 µS cm^{-1} (Table 1). The minimum value of 50 µS cm^{-1} was recorded in lake DE, which was approximately 7 m in depth, was devoid of any vegetation both without and within its catchment area, and drained through dry, rocky felsenmere. The maximum conductivity value of 185 µS was recorded in pond DR, a small water body located near the sea at Thomas Lee Inlet (Fig. 1). Overall, this site had numerous

TABLE 1

(Extd.)

SRPF µG L⁻¹	TPU µG L⁻¹	TPF µG L⁻¹	TKN µG L⁻¹	PON µG L⁻¹	CHLA-U µG L⁻¹	TEMP °C	pH	COND µS	**TN µG L⁻¹	POC: CHLA-U	TN:TPU w/out DB	ELEV-ATION m a.s.l.	Sampling Date dd/mm/yy	LATI-TUDE °N	LONGI-TUDE °W	Lake (L)/ Pond (P)
0.7	2.1	1.0	77.0	16.0	0.40	3.0	8.3	95.0	93.0	410:1	44:1	90	11.07.00	75°26.06′N	89°46.98′W	L
0.3	4.3	2.8	103.0	24.0	**0.05**	11.0	8.6	100.0	127.0	5300:1	30:1	90	22.07.00	75°26.06′N	89°46.98′W	L
0.3	3.3	12.5	82.0	8.0	1.00	10.0	8.4	100.0	90.0	242:1	27:1	90	22.07.00	75°26.06′N	89°46.98′W	L
0.4	2.7	4.0	92.0	19.0	0.70	9.0	8.4	100.0	111.0	427:1	41:1	90	22.07.00	75°26.06′N	89°46.98′W	L
0.5	**0.1**	4.5	90.0	22.0	0.40	5.0	8.3	101.0	112.0	468:1	N/A	90	13.07.00	50 m away	from D-A	P
0.3	3.3	0.8	139.0	19.0	0.40	5.0	8.3	60.0	158.0	1320:1	48:1	90	13.07.00	75°46.34′N	89°46.47′W	P
0.4	4.6	2.8	104.0	24.0	0.90	7.0	8.4	98.0	128.0	627:1	28:1	90	13.07.00	75°26.91′N	89°46.99′W	P
1.0	1.7	1.7	91.0	20.0	1.50	1.5	8.1	50.0	111.0	139:1	65:1	190	14.07.00	75°29.58′N	89°52.11′W	L
0.2	8.4	3.8	81.0	18.0	0.60	2.0	8.1	54.0	99.0	532:1	12:1	190	14.07.00	75°29.72′N	89°53.05′W	L
0.3	1.9	3.3	84.0	18.0	1.10	5.5	8.1	83.0	102.0	223:1	54:1	190	14.07.00	75°29.91′N	89°54.02′W	L
0.2	1.4	3.5	109.0	19.0	0.60	2.0	8.2	64.0	128.0	280:1	91:1	190	14.07.00	75°29.63′N	89°57.23′W	L
0.4	3.5	2.1	83.0	18.0	**0.05**	4.0	8.0	62.0	101.0	4440:1	29:1	190	14.07.00	75°29.36′N	89°56.28′W	L
0.4	2.5	3.9	166.0	24.0	0.60	13.0	8.5	142.0	190.0	635:1	76:1	110	15.07.00	75°24.50′N	89°49.66′W	P
0.7	3.7	3.1	104.0	24.0	1.00	7.0	8.4	115.0	128.0	282:1	35:1	110	16.07.00	75°24.51′N	89°49.69′W	P
0.4	3.0	3.0	216.0	26.0	1.00	4.0	8.4	107.0	242.0	330:1	81:1	180	17.07.00	75°22.29′N	89°53.68′W	P
0.6	2.2	3.1	72.0	9.0	1.00	5.0	8.2	85.0	81.0	187:1	37:1	180	17.07.00	75°21.93′N	89°52.90′W	P
0.1	3.0	2.4	81.0	22.0	1.60	3.0	8.2	72.0	103.0	196:1	34:1	200	17.07.00	75°22.29′N	89°55.98′W	P
0.1	3.0	2.3	99.0	27.0	0.90	4.0	8.2	65.0	126.0	408:1	42:1	240	17.07.00	75°23.41′N	89°58.17′W	P
0.1	3.7	3.0	171.0	22.0	0.90	11.0	8.2	80.0	193.0	298:1	52:1	170	20.07.00	75°25.99′N	89°51.81′W	P
0.2	3.5	6.7	80.0	19.0	1.00	15.0	8.6	92.0	99.0	219:1	28:1	60	24.07.00	76°07.66′N	91°26.22′W	P
0.7	8.7	13.4	716.0	61.0	0.60	13.0	8.5	185.0	777.0	1288:1	89:1	0	24.07.00	76°00.03′N	91°04.25′W	P
0.5	8.1	4.4	112.0	23.0	0.60	5.0	8.2	75.0	135.0	332:1	17:1	200	24.07.00	75°35.96′N	89°45.02′W	L
0.9	4.0	3.3	81.0	31.0	1.50	9.0	8.4	145.0	112.0	196:1	28:1	120	29.07.00	75°21.68′N	89°29.52′W	L
0.5	5.2	3.6	88.0	13.0	0.10	13.0	8.4	145.0	101.0	2990:1	19:1	120	29.07.00	200 m away	from D-T	L
0.6	4.0	8.3	55.0	8.0	0.60	2.0	8.3	150.0	63.0	450:1	16:1	10	29.07.00	75°28.20′N	89°15.85′W	L
0.4	**3.7**	**4.1**	**127.0**	**21.4**	**0.76**	**7.0**	**8.3**	**97.0**	**148.4**	**888:1**	**43:1**	**130**				
0.4	**3.3**	**3.3**	**91.0**	**20.0**	**0.70**	**5.0**	**8.3**	**95.0**	**112.0**	**408:1**	**36:1**	**120**				
1.0	**8.7**	**13.4**	**716.0**	**61.0**	**1.60**	**15.0**	**8.6**	**185.0**	**777.0**	**5300:1**	**91:1**	**240**				
<0.20	**<0.20**	**0.8**	**55.0**	**8.0**	**<0.1**	**1.5**	**8.0**	**50.0**	**63.0**	**139:1**	**12:1**	**0**				

elevated environmental variables, including the maximum recorded values for Na^+, Cl^-, Zn^{2+}, and bicarbonate (HCO_3^-) ions (Table 1). Although the mean value for the sampled lakes (mean$_{lakes}$ = 92.4 µS) was less than the mean for the sampled ponds (mean$_{ponds}$ = 100.2 µS cm^{-1}), as is typically expected, the difference between these two values was not as distinct as has been commonly recorded in other high arctic surveys, where lake conductivity mean values are usually substantially lower then those for ponds (e.g., Michelutti et al., 2002b). Lakes DT, DU, and DV, in particular, contributed to raising the mean lake conductivity value. Specifically, sites DT (145 µS), DU (145 µS), and DV (150 µS), although large lakes, all had specific conductance values above the data set mean (mean$_{data\ set}$ = 97 µS cm^{-1}) (Table 1). The elevated conductivity value for site DV, a large lake visible on the 1:500,000 VFR Navigation Chart, can be attributed to its close proximity to the ocean (approximately 50 m from the coast; 10 m a.s.l.), which may have acted as a point source for incoming marine aerosols. Sites DT and DU, however, were not in close proximity to the sea. Their elevated conductivity levels may be due, in part, to their proximity to impact-generated carbonate breccia-melt hills, which form part of their catchment area (Fig. 2). Drainage through these hills has resulted in the elevated Ca^{2+} and bicarbonate concentrations at these sites relative to other lakes and ponds in the area. Other ionic constituents such as Mg^{2+}, SO_4^{2-}, Ba^{2+}, Sr^{2+}, and SiO_2, which, with the exception of Mg^{2+}, were all positively and significantly ($P \leq 0.01$) correlated to each other and COND (Table 2), were also higher than their respective means in these sites. Their elevated concentrations may similarly reflect drainage effects through the melt hills, which are largely comprised of dolomite, calcite, and Si-Mg-Al-rich glasses (Osinski

and Spray, 2001). Furthermore, tabular plates and prismatic formations of selenite ($CaSO_4 \cdot 2H_2O$), a transparent form of gypsum that is commonly associated with the lower levels of the carbonate melt sheets throughout Haughton Crater (Osinski et al., 2001), may have been in contact with the lakes, providing a source for the elevated sulfate levels in DT and DU. Although much of the incoming water into these sites presently comes from snow and spring icemelts, these water bodies may nevertheless have been in existence since the last glacial retreat from this area approximately 8 ka B.P. (Dyke, 1999). Therefore, a sufficient period of time may have elapsed to allow these lakes and ponds to interact with the local catchment, hence dissolving the selenite structures. Interestingly, ponds DJ and DK, the only other sampled sites lying next to carbonate melt hills similar to those flanking lakes DT and DU, also have elevated Mg^{2+}, SO_4^{2-}, Ba^{2+}, Sr^{2+}, and SiO_2 concentrations relative to the respective means (Table 1).

The concentrations of all major (Ca, Mg, Na, Cl, HCO_3 [DIC], SO_4) and minor (Ba, Sr) ions were within the natural ranges of Canadian inland surface waters (McNeely et al., 1979), although somewhat on the low end. The relative concentration of the cations was Ca > Mg > Na > Sr, with means of 21.6 mg L^{-1}, 6.1 mg L^{-1}, 1.7 mg L^{-1}, and 0.06 mg L^{-1} respectively, while that of the anions was HCO_3 > SO_4 > Cl, with means of 16.7 mg L^{-1}, 5.0 mg L^{-1}, and 4.0 mg L^{-1} respectively (Table 1). These relative concentrations for the Haughton Crater sites are similar to those reported by other high arctic limnological surveys such as Hamilton et al. (2001), Lim et al. (2001), and Michelutti et al. (2002a, 2002b). Pond DK and lake DV do not, however, follow the overall relative concentration order of HCO_3 > SO_4 > Cl, but rather show sulfate as their dominant anion followed by bicarbonate and chloride. As

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TABLE 2

Pearson correlation matrix for transformed environmental data with Bonferroni adjusted probabilities of the 22 sites and 3 subsites (DA-1, DA-2, DA-3) included in the PCA

	CA	MG	NA	SO4	CL	AL	BA	FE	CU	SR	ZN	SIO2	DOC	DIC	POC	SRPF	TPU	TPF	TKN	PON	CHALU	TEMP	pH	COND
CA	1.000																							
MG	**0.647**	1.000																						
NA	0.424	0.482	1.000																					
SO4	*0.827	0.431	0.362	1.000																				
CL	0.457	**0.530**	*0.991	**0.403**	1.0000																			
AL	**0.625**	**0.483**	−0.016	**0.441**	0.009	1.000																		
BA	*0.815	**0.439**	0.314	*0.868	0.345	0.388	1.000																	
FE	**0.533**	0.321	0.182	0.319	0.178	*0.823	0.331	1.000																
CU	0.235	0.210	0.176	0.116	0.203	**0.524**	0.058	**0.627**	1.000															
SR	*0.768	0.315	0.328	*0.84	0.352	0.364	*0.892	0.249	0.046	1.000														
ZN	0.018	0.166	**0.518**	−0.064	**0.483**	0.199	−0.117	0.383	**0.425**	−0.182	1.000													
SIO2	*0.784	**0.492**	0.328	*0.887	0.388	**0.392**	*0.789	0.276	0.116	*0.694	−0.155	1.000												
DOC	0.154	0.243	**0.620**	0.018	**0.587**	−0.143	0.040	0.142	0.050	−0.05	**0.538**	0.072	1.000											
DIC	*0.822	**0.647**	**0.500**	*0.713	**0.551**	0.198	*0.742	0.118	−0.044	*0.709	−0.222	*0.755	0.201	1.000										
POC	0.559	**0.417**	**0.469**	0.266	**0.462**	0.219	**0.414**	0.341	0.205	0.298	0.358	0.331	**0.416**	**0.398**	1.000									
SRPF	0.321	0.179	0.177	**0.498**	0.205	0.301	**0.425**	0.372	0.271	**0.413**	0.156	0.385	0.058	0.214	−0.073	1.000								
TPU	0.070	0.263	0.378	0.020	0.365	−0.102	0.171	−0.089	0.028	0.094	**0.482**	0.048	0.276	0.065	**0.472**	0.027	1.000							
TPF	0.229	0.209	**0.530**	0.268	**0.500**	−0.188	0.289	−0.134	−0.208	0.358	0.115	0.188	0.112	0.357	0.116	0.020	0.355	1.000						
TKN	0.217	0.373	*0.712	0.083	*0.708	−0.126	0.127	0.120	0.010	−0.014	**0.516**	0.145	**0.638**	0.270	**0.632**	0.037	**0.390**	0.228	1.000					
PON	0.224	0.282	**0.579**	0.044	**0.557**	0.025	0.134	0.280	0.015	−0.08	**0.552**	0.132	**0.588**	0.160	**0.579**	0.091	0.375	0.087	*0.792	1.000				
CHLAU	−0.108	−0.015	−0.246	−0.29	−0.271	−0.033	−0.162	−0.037	−0.138	−0.179	−0.119	−0.191	−0.006	−0.072	0.006	0.039	−0.192	0.048	−0.091	0.083	1.000			
TEMP	**0.455**	**0.592**	0.408	**0.451**	0.446	0.047	**0.522**	0.021	−0.167	0.297	−0.156	**0.653**	0.129	**0.648**	0.333	−0.045	0.209	**0.412**	0.370	0.280	−0.146	1.000		
pH	0.717	**0.597**	**0.486**	*0.682	**0.532**	0.345	**0.654**	0.176	−0.096	**0.571**	0.014	*0.739	0.092	*0.755	0.341	0.118	0.113	0.368	0.309	0.269	−0.119	*0.732	1.000	
COND	0.748	**0.497**	**0.598**	*0.771	**0.619**	0.168	*0.846	0.220	−0.053	*0.808	−0.02	*0.727	0.281	*0.793	0.397	0.449	0.259	0.559	0.397	0.320	−0.113	0.558	0.653	1.000
	CA	MG	NA	SO4	CL	AL	BA	FE	CU	SR	ZN	SIO2	DOC	DIC	POC	SRPF	TPU	TPF	TKN	PON	CHALU	TEMP	pH	COND

Note: **BOLD** and * indicate significant correlation $P < 0.05$ and $P < 0.01$, respectively.
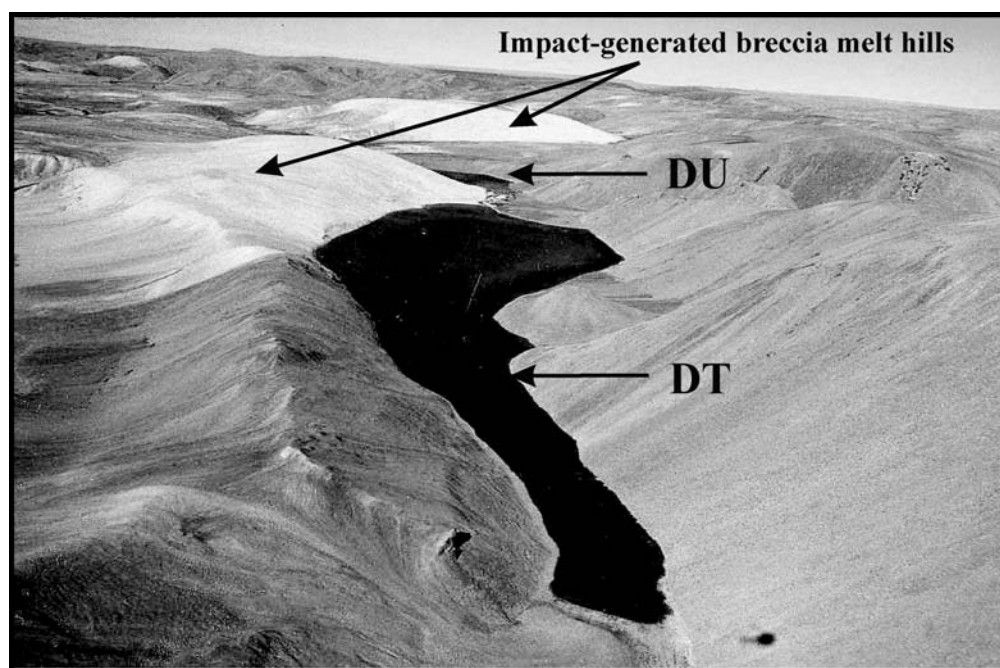
FIGURE 2. Photograph showing catchment area of lakes DT and DU.

discussed earlier, these two sites are in close contact with sulfate-bearing minerals and incoming marine aerosols, respectively, which most likely contributed to their elevated SO_4 levels relative to other sites.

Metals

Four metals (Al, Fe, Cu, and Zn) were considered in this study, as they had concentrations above their detection limit in over 50% of the sample sites (Table 1). With the exception of Fe, mean concentrations for each of these metals were within the natural ranges reported for Canadian inland waters (McNeely et al., 1979). The typical iron concentrations in aerated surface waters are listed as usually being less than 0.5 mg L^{-1}. The mean Fe value for the Haughton Crater sites is 0.05 mg L^{-1} (Table 1), which is comparable to those reported by Michelutti et al. (2002a, 2002b) for Axel Heiberg (Fe mean $= 0.03$ mg L^{-1}) and Victoria (Fe mean $= 0.02$ mg L^{-1}) Islands. The maximum values for Al (0.72 mg L^{-1}), Fe (0.77 mg L^{-1}), and Cu (0.011 mg L^{-1}) were all recorded in site DD, which is a small, possibly ephemeral pond, approximately 30 m from site DA (Fig. 1).

Carbon Measurements

Dissolved inorganic carbon (DIC) values in the Haughton Crater area ranged from 9.4 mg L^{-1} to 22.8 mg L^{-1} with a mean value of 16.7 mg L^{-1} (Table 1). This range and mean concentration for DIC is comparable to those recorded on other Canadian high arctic islands by Antoniades et al. (2000), Lim et al. (2001), and Michelutti et al. (2002a, 2002b). From a limnological sampling of 170 sites in the High Arctic, Hamilton et al. (2001) also reported a similar, although slightly higher, mean of 21.7 mg L^{-1}. This similarity in mean reported DIC values reflects the underlying carbonate bedrock common to many islands in the High Arctic.

Dissolved organic carbon (DOC) concentrations ranged from 1.2 mg L^{-1} to 7.4 mg L^{-1}, with a mean of 2.2 mg L^{-1} (Table 1), which is at the lowest end of the DOC spectrum for Canadian natural inland waters (McNeely et al., 1979). This mean is comparable to values reported for ultraoligotrophic sites near Wynniatt Bay, Victoria Island (Michelutti et al., 2002b) (mean $= 1.46$ mg L^{-1}), as well as near Alert, Ellesmere Island (Antoniades et al., 2000) (mean $= 2.0$ mg L^{-1}). This reflects the consistent lack of vegetation in the catchment areas of the sampled lakes and ponds in this study, with the exception of site DR, where

we recorded the maximum DOC concentration of 7.4 mg L^{-1}. Relative to all of the other sampled lakes and ponds in the Haughton Crater region, pond DR clearly differentiated itself based on its lush catchment area, low relief, and dark colouring. Although all the other sites were extremely clear, the water in pond DR had a strong "tea" color. High occurrences of goose scats and musk-ox tracks at this site indicated that pond DR was heavily visited by local wildlife. This activity may have been a source of nutrient enrichment to the pond, encouraging vegetational growth and photosynthetic activity in the aquatic system and resulting in the higher DOC concentrations.

DOC levels have been identified as one of the key controlling factors in determining the level of underwater penetration of solar ultraviolet radiation (UVR) into aquatic systems (reviewed by Vincent and Pienitz, 1996). DOC strongly absorbs the more biologically damaging, shorter UV wavelengths (Scully and Lean, 1994), thus acting as a naturally occurring sunscreen in lakes and ponds. In the clear, ultraoligotrophic lakes and ponds in the Haughton Crater area, low DOC levels would allow for high penetration levels of UVR.

Nutrients (Nitrogen and Phosphorus)

TKN is a measure of ammonia and organic nitrogen, both of which are key to the assessment of available nitrogen for biological activities (McNeely et al., 1979). TKN ranged from 55.0 μg L^{-1} to 716.0 μg L^{-1}, with a mean concentration of 127.0 μg L^{-1} (Table 1). The TKN mean is comparable to that recorded by Michelutti et al. (2002b) (mean $= 150$ μg L^{-1}) and Lim et al. (2001) (mean $= 112$ μg L^{-1}) on Victoria and Bathurst Islands, respectively. NO_3NO_2 was below detection levels in all sites, while TN (TKN + PON) ranged from 63.0 μg L^{-1} to 777.0 μg L^{-1} (mean $= 148.4$ μg L^{-1}). TN concentrations were below the mean in the lakes (mean$_{lakes} = 105.0$ μg L^{-1}), whereas the mean TN for ponds, driven by site DR having the maximum recording TN level at 777.0 μg L^{-1}, was higher (mean$_{ponds} = 195.0$ μg L^{-1}) (Table 1). With the removal of DR, the mean TN for ponds decreases to 141.82 μg L^{-1}, which is still greater than that for the lakes alone. As previously noted (see "Carbon Measurements" section), this shallow pond was highly vegetated compared to the other Haughton Crater sites and most likely received nitrogenous inputs from fecal matter deposited within its catchment. Furthermore, due to its shallowness, wind agitation and wildlife activity may also have played
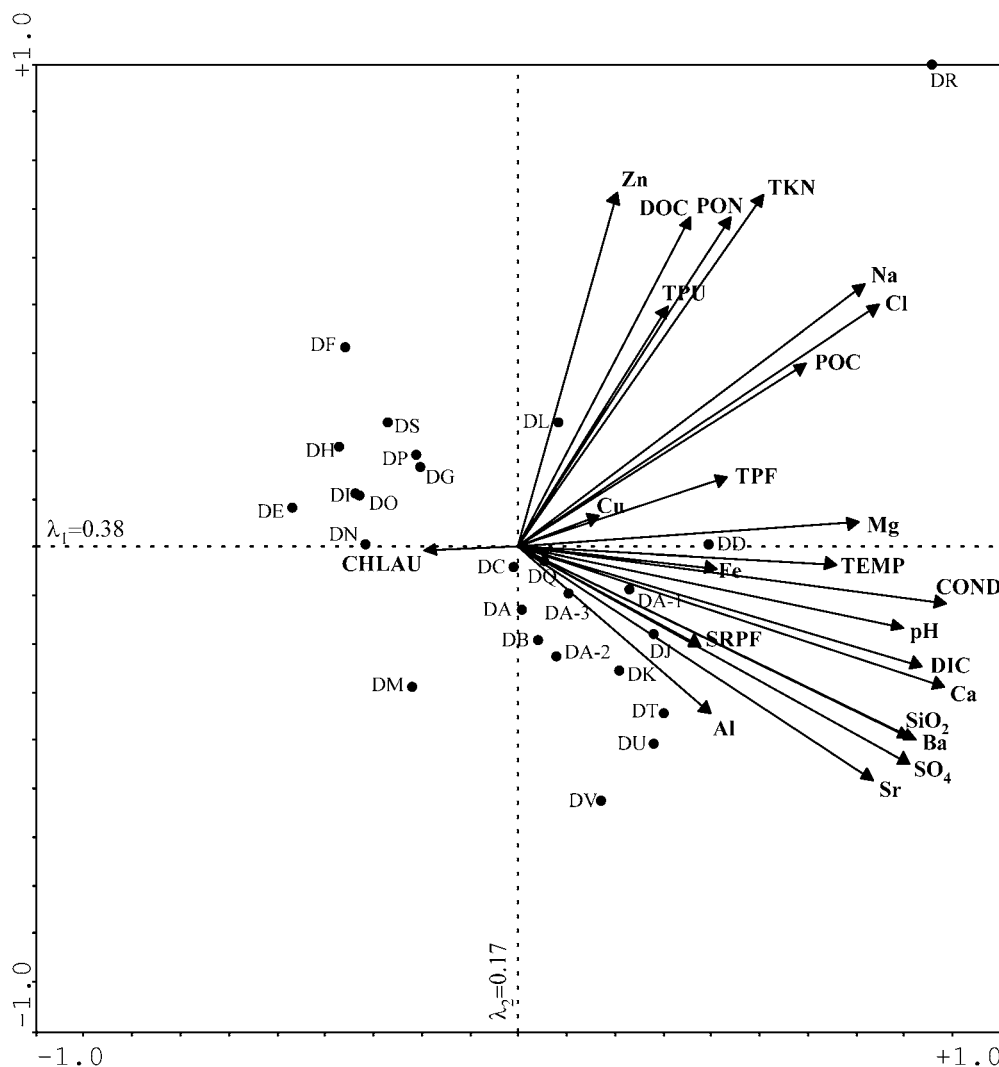
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FIGURE 3. PCA of 24 environmental variables and 25 Haughton Crater sites and subsites.

a dominant role in reintroducing nitrogen found in the pond sediment back into the water column.

Some temporal and spatial variability was observed at site DA. TN increased by 18 μg L^{-1} over an 11-d period at sample point DA/DA-3. Specifically, the initial TN value at DA was 93.0 μg L^{-1}, while that for DA-3 had risen to 111.0 μg L^{-1}. Subsite DA-1 (127.0 μ L^{-1}) also increased in TN relative to DA, while subsite DA-2 was lower at 90.0 μg L^{-1}. The difference in TN concentrations around the lake may be a result of variance in local runoff inputs.

The mean TPU concentration of 3.7 μg L^{-1} (range = below detection limit [<0.2 μg L^{-1}] to 8.7 μg L^{-1}) indicates that most of the lakes and ponds in the Haughton Crater region can be classified as ultraoligotrophic (Vollenweider, 1968). Although not as low as the mean TPU value reported for Victoria Island by Michelutti et al. (2002b), the Haughton Crater mean is approximately three times less than that reported by Hamilton et al. (2001) for 173 sampled lakes and ponds across the Canadian High Arctic. Pond DR had the maximum recorded concentration of TPU at 8.7 μg L^{-1}, which, coupled with its elevated TN concentration, confirms that it is the most nutrient-enriched site of the data set. Excluding pond DB, the sites with the lowest TPU levels were lakes (DE, DG, and DH).

Chemical and physical characteristics play an important driving role in determining the biota that live within an aquatic environment. In order to identify the primary limiting nutrient for phytoplankton in the Haughton Crater area lakes and ponds, a series of nitrogen-to-

phosphorus ratios were calculated. Specifically, TN-to-TPU ratios (TN:TPU) were examined.

The TN:TPU ranged from 12:1 (DF) to 91:1 (DH), with a mean of 43:1 (Table 1). This is comparable to the TN:TPU ranges reported by other arctic limnological surveys (e.g., Pienitz et al., 1997; Gregory-Eaves et al., 2000; Lim et al., 2001). Based on guidelines by Sakamoto (1966) listing lakes with TN:TP greater than 17 as being P-limited, the mean ratio for the Haughton Crater systems indicates P-limitation. Only one site, DF (12:1), had TN:TP significantly outside this P-limitation guideline.

BIOTIC COMPONENTS

Chlorophyll *a* (CHLA-U) concentrations ranged from below the detection limit (<0.1 μg L^{-1}) in lake DI to 1.60 μg L^{-1} in pond DN, with an overall mean of 0.8 μg L^{-1} (Table 1). This small range is similar to that reported by Michelutti et al. (2002b) for the ultraoligotrophic water bodies on Victoria Island.

CHLA-U was not significantly ($P \leq 0.05$) correlated with TKN or TPU (Table 2); therefore although ratio analyses would indicate that the majority of the sites are P-limited, other variables may also be affecting the phytoplankton productivity in the Haughton Crater lakes and ponds.

POC-to-CHLA-U (POC:CHLA-U) ratios were calculated (Table 1) in order to estimate whether the POC in the sites was mostly derived from algal or terrestrial/detrital sources. The range for the Haughton Crater

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sites was 139:1 to 5300:1, with a mean of 888:1. Eppley et al. (1977) suggested that lakes with POC:CHLA-U ratios greater than 100 would derive most of their POC from terrestrial/detrital sources. Therefore, our study sites are on average receiving the majority of their POC from allochthonous inputs, like lakes and ponds from other regions in the high arctic (Hamilton et al., 2001). The POC:CHLA-U for site DT (196:1) is significantly lower than both the mean and the ratio for neighboring site DU (2990:1). Furthermore, lake DT had a CHLA-U concentration of 1.5 $\mu g\, L^{-1}$, which is higher than both the mean and the [CHLA-U] value reported for the nearby site DU (0.1 $\mu g\, L^{-1}$). DT is likely not receiving as much terrestrial/detrital inputs from its watershed as lake DU, so algal and other autochthonous inputs from within the lake are most likely the dominant contributors to POC concentrations in this particular lake. Lake DU, in comparison, most likely receives heavy seasonal pulses of allochthonous inputs from the inflow channel connecting it with DT, as reflected by its high POC:CHLA-U. Therefore, algal productivity in DU may be lower than in DT.

PRINCIPAL COMPONENTS ANALYSIS (PCA)

PCA was used to detect dominant trends and relationships between sites and environmental variables (Fig. 3). Environmental variables are represented by arrows, while sites are marked by points on the biplot. Arrow lengths, as well as their angles relative to axis 1 and 2, illustrate the relative weight of a particular environmental variable in determining the construction of the ordination axes (ter Braak and Prentice, 1988). Furthermore, the angles between the arrows are representative of the degree of correlation between environmental variables. The chemical composition of any given site can be inferred from the ordination based on the projection of site scores in relation to the environmental arrows (Jongman et al., 1987). That is, those sites clustered together will share similar characteristics, while those at opposite spectra to each other will be vastly different.

Axis 1 of the PCA accounted for 38.4% of the cumulative percentage variance in the data set, while axis 2 comprised the remaining variance totaling 55.3% in cumulative value. Eigenvalues for axes 1 and 2 were $\lambda_1 = 0.38$ and $\lambda_2 = 0.17$, respectively. Differences in conductivity (COND) (especially with respect to Ca^{2+}, Ba^{2+} and HCO_3^- [DIC] levels) along axis 1 and nutrient and carbon inputs (TKN, PON, DOC), and to a lesser degree metal content (Zn, Al), along axis 2 were the dominant limnological gradients identified by the PCA (Fig. 3) that drive the distribution of the 25 sample points. Species scores (Table 3) revealed that the variables with the strongest effect on the construction of axis 1 were, in order of decreasing strength, COND, Ca, DIC, Ba, and SO_4. Axis 2 was most strongly affected by Zn, TKN, PON, and DOC (Table 3). Generally, the deeper sites from the Haughton Crater area tended to cluster and ordinate separately from the shallower water bodies based on these key environmental gradients. Specifically, 6 of the 10 lakes ordinate in the left half of the PCA, while 9 of the 12 ponds are projected onto the right half of the ordination (Fig. 3). This separation may represent overall differences in ionic and nutrient concentrations between the dilute lakes and the relatively more concentrated shallow ponds.

Conductivity (COND), more specifically Ba, SO_4, Ca, and DIC, had the strongest influence on the construction of axis 1 as illustrated by the arrow lengths and close relationship to this axis (Fig. 3). These four ionic constituents also show a high positive correlation with pH, SiO_2, and Sr. These relationships are also supported by the results of the Pearson correlation matrix (Table 2), which shows significant ($P \leq 0.05$) positive correlations between all of these values. Sites DJ, DK, DT, DU, and DV all have COND levels above the mean (Table 1), and most notably, they have elevated [SO_4] which accounts for their clustering and association with these particular variables on the PCA ordination (Fig. 3). However, it is most likely slight variations in TKN, PON, and DOC concentrations

	Variable	Axis 1	Axis 2
1	Ca	**.8803**	−.2893
2	Mg	.7037	.0513
3	Na	.7173	.5452
4	SO₄	**.8115**	−.4468
5	Cl	.7488	.4987
6	Al	.3975	−.3447
7	Ba	**.8242**	−.4008
8	Fe	.4083	−.0440
9	Cu	.1679	.0646
10	Sr	.7357	**−.4804**
11	Zn	.2021	**.7313**
12	SiO₂	.8065	−.3929
13	DOC	.3577	**.6793**
14	DIC	**.8353**	−.2471
15	POC	.5974	.3815
16	SRPF	.3777	−.2032
17	TPU	.3086	.4958
18	TPF	.4333	.1416
19	TKN	.5050	**.7307**
20	PON	.4384	**.6835**
21	CHLAU	**−.1947**	−.0063
22	TEMP	.6551	−.0351
23	pH	.7992	−.1654
24	COND	**.8872**	−.1160

that are driving the differences amongst these sites. For example, sites DJ and DK both have TKN, PON, and DOC values near or above the means, while sites DT, DU, and DV, which are projected lower on the PCA than DJ and DK, have TKN, PON, and DOC values near or below the means (Table 1).

As expected, pond DR ordinates in the upper right quadrat, in close association with the nutrient gradient extremes driving axis 2 (Fig. 3). This site posted the maximum recorded DOC, TKN, PON, TPU, and TPF concentrations in the data set (Table 1). Pond DR differentiated itself against the other sample sites based on the lushness of its catchment area and its low relief. Its high DOC concentration is most likely the result of humic-loaded terrestrial runoff into this pond. Together the POC:CHLA-U (1288:1) for DR and the correlation ($P \leq 0.05$) between POC and DOC also indicate that terrestrial/detrital sources from the catchment are most likely responsible for the majority of the inputs into this pond. Therefore, axis 2 most likely also reflects minor variations in the level of allochthonous inputs amongst the sites. Michelutti et al. (2002a) reported a similar gradient in their PCA ordination of 38 lakes and ponds on Axel Heiberg Island, which lies to the northwest.

The sites that ordinate in the upper left quadrat of the PCA ordination (DE, DF, DG, DH, DI, DO, DP, and DS), in the opposite direction to the ionic gradient extremes, are clustered together based on their similarly low Ca, Ba, SO_4, HCO_3 (DIC), and COND values (Table 1). All of these ionic variables were below their mean concentrations in each of these sites (Table 1). This cluster of sites had similarly unvegetated, rocky catchments and steep surrounding relief. Interestingly, 6 of the 8 sites clustered in the upper left of the ordination are deeper lakes, and in addition to pond DP are all located to the northeast of base camp at varying distances (Fig. 1). All of these lakes had temperatures below the mean (mean = 7.0°C). Also, with the exception of the two smallest lakes, DF and DI, which may have both just become ice free, all of these lakes were still >40% ice covered at the time of sample collection. No other sites in

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the data set had ice on their surfaces during the sampling period. Meltwater derived from thawing ice cover may have caused these sites to be become diluted in ionic constituents relative to the other lakes and ponds in the Haughton Crater area.

Ponds DM, DN, and DO, all from a similar geographic region in the crater area (Fig. 1), ordinate on the two left quadrats of the PCA ordination away from the COND and nutrient gradient extremes (Fig. 3). Although it is expected that ponds will typically be warmer, higher in COND, and more nutrient rich than lakes (e.g., Lim et al., 2001), these shallow ponds were unusually cold (TEMP values $<$ mean of 7.0°C), oligotrophic (TPU values $<$ mean of 3.7 µg L^{-1}) and dilute (COND values $<$ mean of 97.0 µS cm^{-1}) compared to the other sites (Table 1). As discussed earlier in this section, axis 2 probably also reflects small variations in terrestrial/detrital inputs. Therefore, these three ponds most likely receive less nitrogen, phosphorus, and DOC inputs from local runoff than the other lakes and ponds in the area. These ponds also ordinate in close association with the weak CHLA-U gradient that extends along the negative portion of axis 1 (Fig. 3). CHLA-U concentrations for DM (1.0 µg L^{-1}), DN (1.6 µg L^{-1}), and DO (0.9 µg L^{-1}) are all above the mean (0.8 µg L^{-1}), with DN posting the maximum recorded CHLA-U value in the data set (Table 1). POC:CHLA-U for these sites are all below the mean (888:1), indicating that (1) these sites receive less terrestrial input versus other sites, and (2) a higher proportion of the POC concentrations in DM, DN, and DO are attributable to algal biomass than in the other Haughton Crater lakes and ponds.

The weak metal gradient associated with axis 2 (Fig. 3) is most likely the dominant characteristic differentiating site DD from the rest of the data set. As discussed in the "Metals" section, pond DD had the maximum Al, Cu, and Fe concentrations in the data set (Table 1), which accounts for the projection of this site at the extreme of the metal gradient (Fig. 3). DD also had COND slightly above the mean and the maximum recorded [Ca] and [Mg] values, resulting in its being ordinated in the right portion of the ordination, in a positive association with axis 1 (Fig. 3).

Interestingly, site DA and subsites DA-1, DA-2, and DA-3 ordinated in close proximity to each other, indicating that although COND and nutrient concentrations may have increased through the ice-free season, on the whole the limnological properties of this lake remained constant.

Conclusions

Overall, the physical properties of the lakes and ponds in the Haughton Crater area were similar to those reported by previous limnological surveys from the High Arctic. However, the presence of impact-generated carbonate melt rocks in the Haughton Crater area has affected the conductivity levels, specifically the Mg^{2+}, SO_4^{2-}, Ba^{2+}, Sr^{2+}, and SiO_2 concentrations, in sites that are in close association with this substrate. Selenite ($CaSO_4 \cdot 2H_2O$) formations, commonly associated with the lower levels of the carbonate melt sheets, are likely the source of elevated SO_4^{2-} concentrations in four sites (DJ, DK, DT, and DU) that were in direct contact with them.

In general, the lakes and ponds in the Haughton Crater area were extremely clear, with their mean DOC (mean = 2.2 mg L^{-1}) being one of the lowest reported averages in the High Arctic. The lakes and ponds were classified as ultraoligotrophic aquatic systems, and TN:TPU analysis revealed that most of the Haughton Crater area lakes and ponds may be P-limited. During the initial thaw period, meltwater from surface ice can serve to dilute ionic and nutrient concentrations in lake waters, while later in the season warmer temperatures and greater evaporation rates may result in an overall increase in lake concentration levels. Lake DA, for example, was resampled later in the summer field season and showed

increases in conductivity levels and nutrient concentrations similar to the seasonal trends recorded from sites on Cape Herschel by Douglas and Smol (1994).

The first two axes of the PCA ordination account for 55.3% of the limnological variation among the study sites. Axis 1 ($\lambda_1 = 0.38$) was driven primarily by COND, while axis 2 ($\lambda_2 = 0.17$) represented a nutrient and carbon concentration gradient. Key limnological patterns among the sites, such as chemical and nutrient similarities between deeper, semi-ice-covered lakes, were further elucidated by the ordination.

This limnological study will form the foundation of a long-term aquatic environmental monitoring program to be established by the authors in the Haughton Crater area in association with colleagues at the NASA/SETI Haughton Mars Project.

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