METALS

All sample sites were analysed for 60 metal parameters. Of the 60 parameters only 27 (aluminum, antimony, arsenic, barium, cadmium, cerium, chromium, copper, cobalt, gallium, iron, lanthanum, lead, lithium, manganese, molybdenum, nickel, rubidium, scandium, strontium, tin, titanium, uranium, vanadium, yttrium, zinc, zirconium) were detectable. Although most metals are insoluble in water, low concentrations could be expected in areas of high mineralization. Distribution patterns of concentration typically reflect the geology or degree of mineralization as well as areas of impact.

Metal parameters not detected are not portrayed on the following pages.

Please refer to the discussion of accuracy of Exotic Metals in the Data Handling - Laboratory Data Section.

Iron

Symbol: Fe

Background: Iron is the fourth most abundant element in the earth's crust, and probably, the most important metal in the universe. Iron is very reactive chemically, easily oxidized or reduced, weathered or leached which is probably why it is represented as a constituent of all of the mineral classes in natural environments. Iron acts as a catalyst in the carbon cycle. It is also necessary for the formation of chlorophyll in plants. The growth cycles of freshwater algae and related aquatic microorganisms can greatly influence the concentration of iron in surface waters. According to the Canadian Water Quality Guidelines, the concentration of iron for most Canadian surface waters is usually less than 500 $\mu g \cdot L^{-1}$.

Common Minerals:

Magnetite	Fe_3O_4	Goethite	$Fe_2O_3 \cdot H_2O$
Hematite	Fe_2O_3	Siderite	$FeCO_3$
Wustite	FeO	Pyrite	FeS_2
Ilmenite	$FeO \cdot TiO_2$		

Major Uses: Alloy steels, construction, motor vehicles, railroads, shipbuilding, aircraft, and machinery to name a few.

Hazards: Although there are some hazards associated with mining of iron ores with respect to tailings ponds, the major hazards result from the manufacturing of iron and steel in the form of air and water pollution.

Guidelines: As outlined in the Canadian Water Quality Guidelines (1990).

Drinking Water	Freshwater Aquatic Life
<300 $\mu g \cdot L^{-1}$	300 $\mu g \cdot L^{-1}$

Discussion:

Although iron concentrations are characteristic of most surface freshwaters, the concentration of 406 $\mu g \cdot L^{-1}$ from sample CA86011BW1 exceeds the guidelines for Drinking Water and Freshwater Aquatic Life. This site also contains the highest concentrations of aluminum and vanadium metals. The distribution pattern of concentration does not distinguish the Slave Province from the Bear Province. The relatively higher concentrations observed appear to be site specific. Iron concentrations were lower in lakes retested in 1994.

Iron concentration in lake water
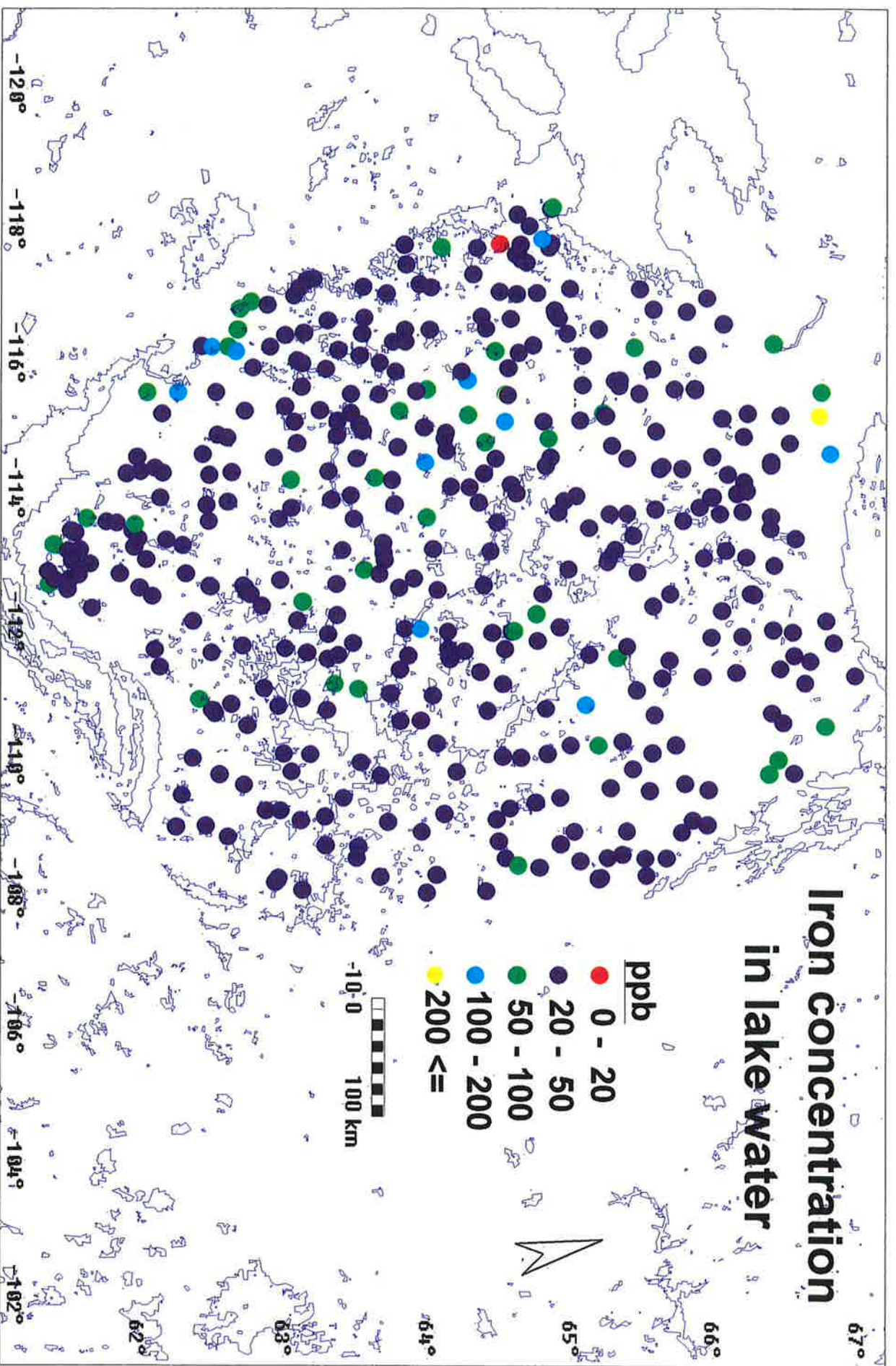
Lithium

Symbol: Li

Background: Lithium is very reactive chemically with a tendency to enter silicate minerals rather than sulphates. In silicates, lithium replaces iron and magnesium rather than sodium and potassium. It is usually found in small amounts in nearly all igneous rocks and in mineral springs. During weathering and sedimentation, lithium is readily adsorbed by clay minerals. Most natural surface fresh waters contain lithium in concentrations below 200 $\mu g \cdot L^{-1}$.

Common Minerals:

|	
Spodumene	$LiAlSi_2O_6$
Lepidolite	$K_2Li_3Al_4Si_7O_{21}(OH,F)_3$
Amblygonite	$LiAlFPO_4$
Petalite	$LiAlSi_4O_{10}$

Major Uses: Multi-purpose greases, ceramics, metallurgy, welding, laundry bleaches, synthetic rubber, air conditioning, batteries, and the production of hydrogen.

Hazards: Although most of the hazards associated with lithium result from the mining and refining processes, it is corrosive and requires special handling.

Guidelines: As of 1994 there were no Canadian water quality guidelines.

Discussion:

Lithium concentrations are characteristic of most surface freshwaters being less than 200 $\mu g \cdot L^{-1}$. The distribution pattern of lithium is similar in nature to sodium and potassium, as expected, since these elements are classified as alkaline metals. The maximum measured concentration for lithium was 9.8 $\mu g \cdot L^{-1}$ at site CA85I2AW1 which also contains the highest measured concentration for scandium. Lithium concentrations are relatively unchanged in lakes retested in 1994.

Lithium concentration in lake water

ppb

- 0.0 – 0.1
- 0.1 – 1.0
- 1.0 – 10.0
- 10.0 <=

0–10
100 km
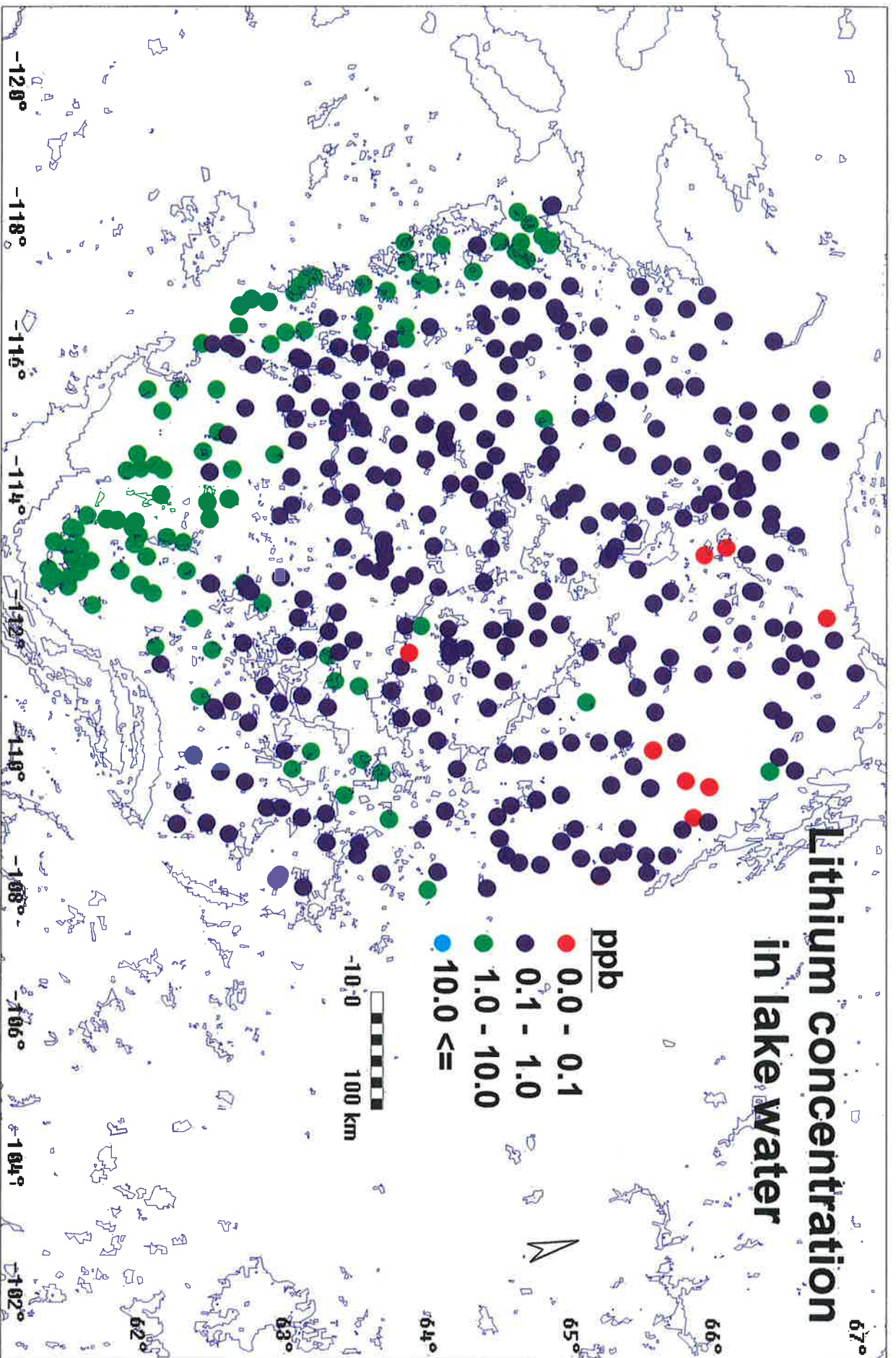
Aluminum

Symbol: Al

Background: Aluminum is the most abundant metallic element in the earth's crust with a strong affinity for oxygen. Under normal conditions of chemical weathering, the degree of acidity or alkalinity of the weathering solution determines whether hydrated aluminum oxides or hydrated aluminum silicates are formed. The feldspars and certain silicates, are decomposed into clays and soluble material. The clays are transported by streams and rivers. In soils, aluminum concentration increases through leaching. Aluminum also accumulates in plant tissue as water is lost through transpiration. These plants become enriched in extractable aluminum and when these plants die, the aluminum is returned to the soil. According to the Canadian Water Quality Guidelines, the average concentration of aluminum in most natural surface waters is said to be <1000 $\mu g \cdot L^{-1}$.

Common Minerals:

Corundum	Al_2O
Cryolite	Na_3AlF_6
Spinel	$MgAl_2O_4$
Bauxite (gibbsite)	$Al_2O_3 \cdot 3H_2O$
Anorthite	$CaAl_2Si_2O_8$
Albite	$NaAlSi_3O_8$
Micas	

Major Uses: Aeroplanes, automobiles, industrial machinery, ships, chemicals, electrical equipment, cans and containers, kitchen utensils, and construction to name a few.

Hazards: Most of the hazards associated with aluminum result from the processing of aluminum and aluminum ores either in the form as air pollution or in the form of tailings.

Guidelines: As outlined in the Canadian Water Quality Guidelines (1990).

Drinking Water	**Freshwater Aquatic Life**
(under review)	0.005-0.100 mg·L^{-1}

Discussion:

Aluminum concentrations exceed the Canadian Water Quality Guidelines of 5-100 $\mu g \cdot L^{-1}$ for freshwater aquatic life in four lakes. The highest concentration was 323.7 $\mu g \cdot L^{-1}$ from site CA86011BW1. Iron and vanadium also measured relatively higher concentrations at the same site. The high aluminum concentration probably results from a combination of geology, high turbidity and shallow lake depth. In all other lakes, high concentrations are probably attributed to geology particularly in the Bear Province. Aluminum values increased slightly in the area impacted by previous mining activity as well as currently operating lodges and outfitters. Aluminum concentrations were higher in 19 of 32 lakes retested in 1994.

Aluminum concentration
in lake water

ppb

- 🟡 0.0 - 0.5
- 🔵 0.5 - 5.0
- 🟢 5.0 - 50.0
- 🟣 50.0 - 100.0
- 🔴 100.0 +

km 100   100 km
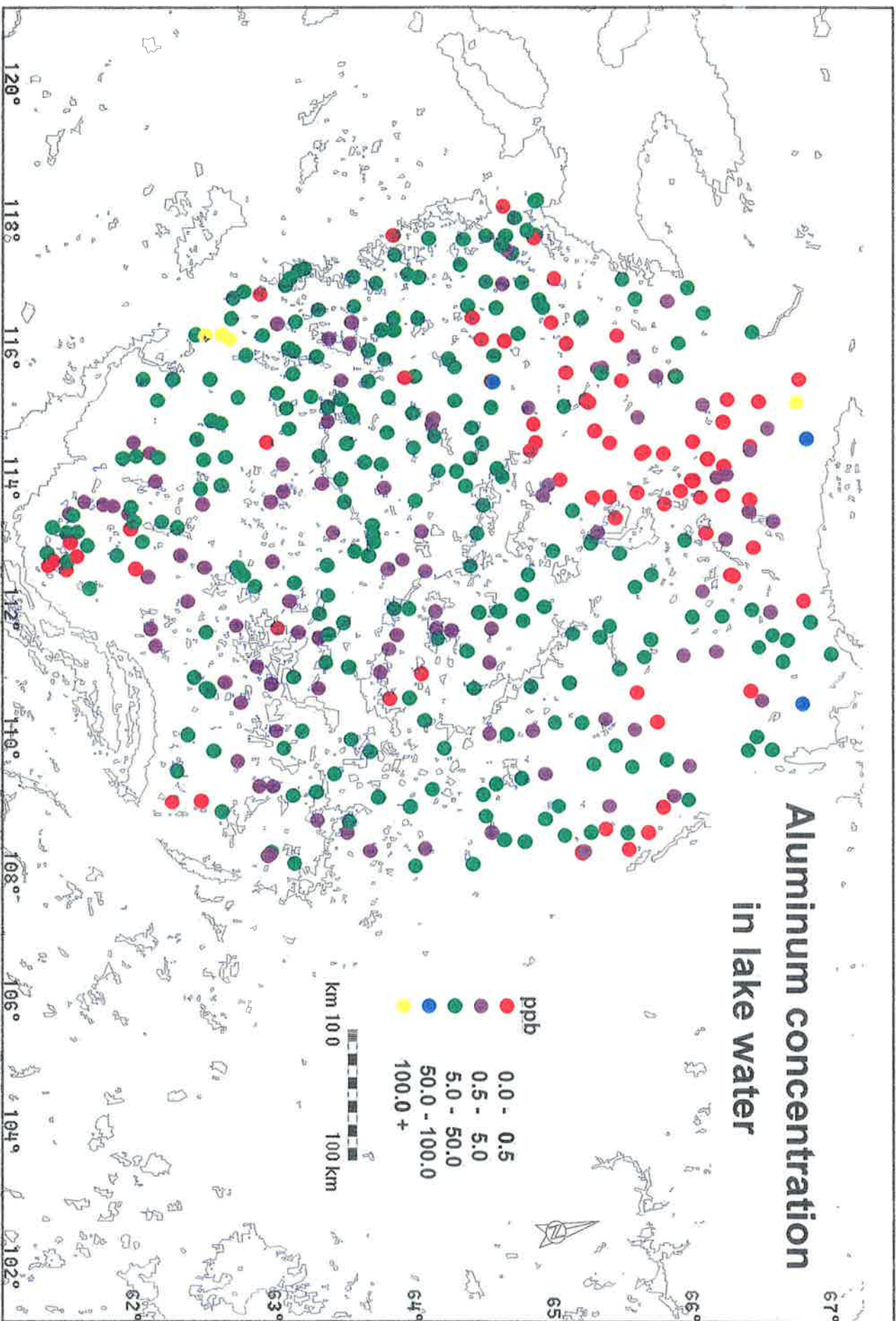
Vanadium

Symbol: V

Background: Vanadium is a relatively abundant element and widely distributed throughout a large variety of rocks. It tends not to concentrate and form ore deposits. In hydrothermal ores, vanadium is not usually enriched due to low solubility. It enters the environment through various means, such as natural seepage from carbonaceous deposits, atmospheric deposition, weathering of vanadium-enriched ores, clays, and through leaching of coal mining waste dumps and coal ash. According to the Canadian Water Quality Guidelines, the concentration of vanadium in most fresh waters range between 0.3 - 200 $\mu g \cdot L^{-1}$.

Common Minerals:

Carnotite	$K_2(UO_2)_2V_2O_8 \cdot 3H_2O$
Roscoelite	$K(V^{+3},Al,Mg)_2(AlSi_3)O_{10}(OH)_2$
Vanadinite	$Pb_5(VO_4)_3Cl$
Patronite	VS_4

**Major Uses:**   Production of speciality steels and titanium-base alloys, chemicals, ceramics, dyes, inks, and paint.

Hazards: Although most of the hazards associated with vanadium result from the recovery processes, vanadium and its compounds are toxic and should be handled with care. Radiation can occur from processing uranium ores, as well as stack emissions from drying kilns and roasting cycles.

Guidelines: As of 1994 there were no Canadian water quality guidelines.

Discussion:

Vanadium concentrations in the Slave and Bear Provinces are well within the 0.3-200 $\mu g \cdot L^{-1}$ range characteristic of most surface fresh waters. A larger distribution of relatively higher concentrations are observed in the Bear Province. The maximum measured concentration for vanadium was 1.32 $\mu g \cdot L^{-1}$ obtained from site CA86011BW1. This site also contains the highest measured concentrations of aluminum and iron metals. Concentrations were lower in 25 of 32 lakes retested in 1994.

Vanadium concentration in lake water

ppb
- 0.0 - 0.1
- 0.1 - 1.0
- 1.0 <=

0 100 km
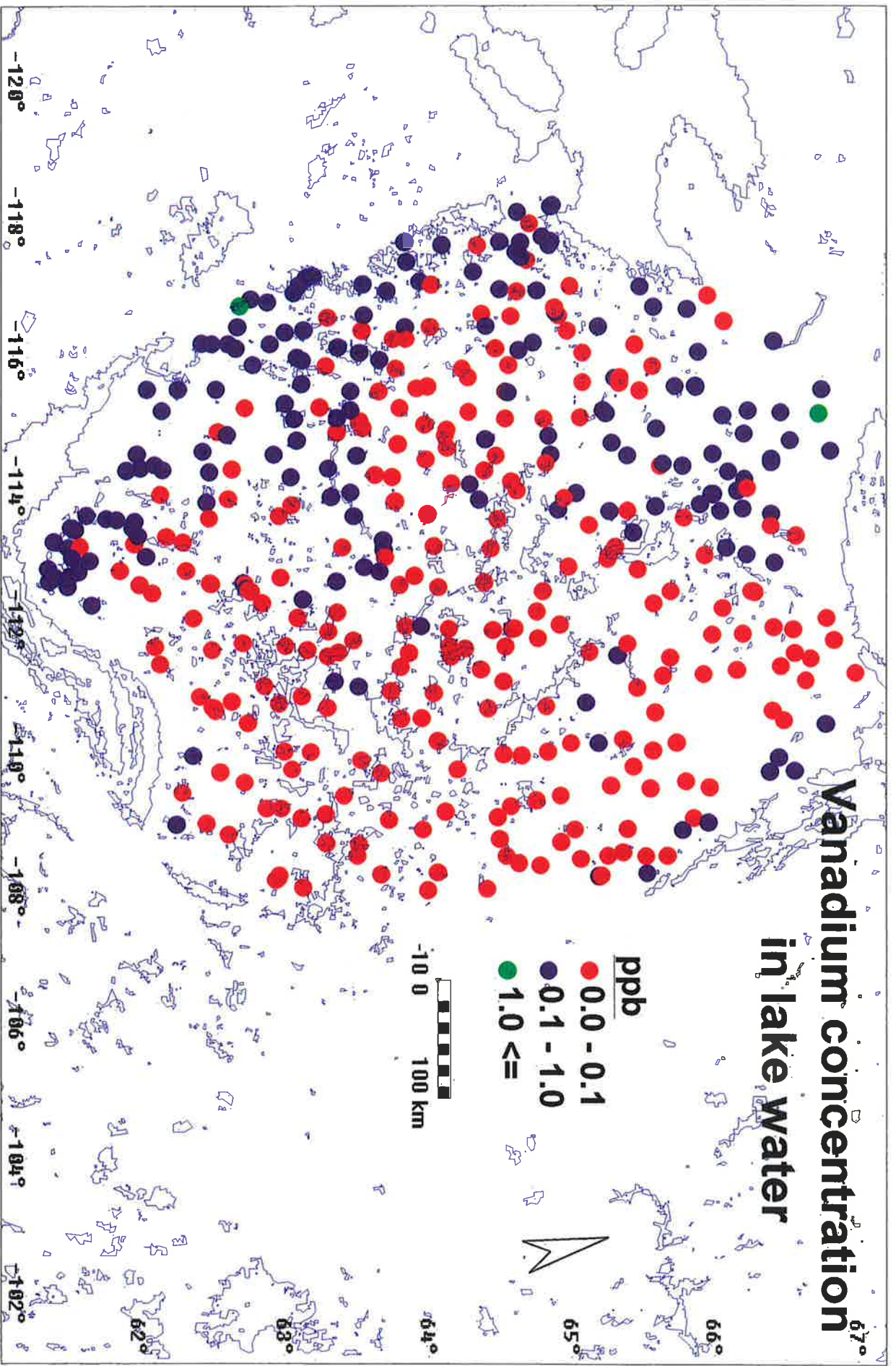
Chromium

Symbol: Cr

Background: Chromium does not exist naturally in elemental form but rather in combination with a large number of other minerals of which only chromite is of commercial importance. Deposits of chromite result from segregation from ultrabasic magma and are associated with rocks such as peridotites, dunites, serpentine, and talc-schists. Chromite is often associated with other minerals, such as platinum, gold, and nickel. It is generally resistant to chemical weathering. Only very small amounts of chromium go into solution resulting in low chromium content in precipitates and evaporates. According to the Canadian Water Quality Guidelines, the concentration of chromium for most Canadian fresh waters ranges between 0.2 - 44.0 $\mu g \cdot L^{-1}$.

Common Minerals:

Chromite	$Fe^{+3}Cr_2O_4$
Eskolite	Cr_2O_3
Daubreelite	$FeS \cdot Cr_2S_3$
Stichtite	$3[Mg_6Cr_2CO_3(OH)_{16} \cdot 4H_2O]$

Major Uses: Metallurgical, refractory, chemicals, paints dyes, explosives, ceramics and paper.

Hazards: Chromium and most of its compounds are not considered toxic, however they are employed in wood preservatives to help fix toxic compounds, such as copper sulphate and sodium arsenate in the treated products. The acute toxicity of chromium appears to decrease as hardness and pH increase.

Guidelines: As outlined in the Canadian Water Quality Guidelines (1990).

| **Drinking Water** | **Freshwater Aquatic Life** |
| 50.0 $\mu g \cdot L^{-1}$ | 2.0 - 20.0 $\mu g \cdot L^{-1}$ |

Discussion:

Chromium concentrations are within the 0.2-44.0 $\mu g \cdot L^{-1}$ range characteristic of most surface freshwaters. Higher concentrations are observed in the Bear Province than in the Slave Province. These higher concentrations appear to be site specific. Sample site CA86J7CW1-3V measured the maximum concentration of 3.41 $\mu g \cdot L^{-1}$. Chromium concentrations were lower in 21 of 32 lakes retested in 1994.

Chromium concentration in lake water

ppb
- 0.0 - 0.2
- 0.2 - 1.0
- 1.0 - 2.0
- 2.0 <=

100 km
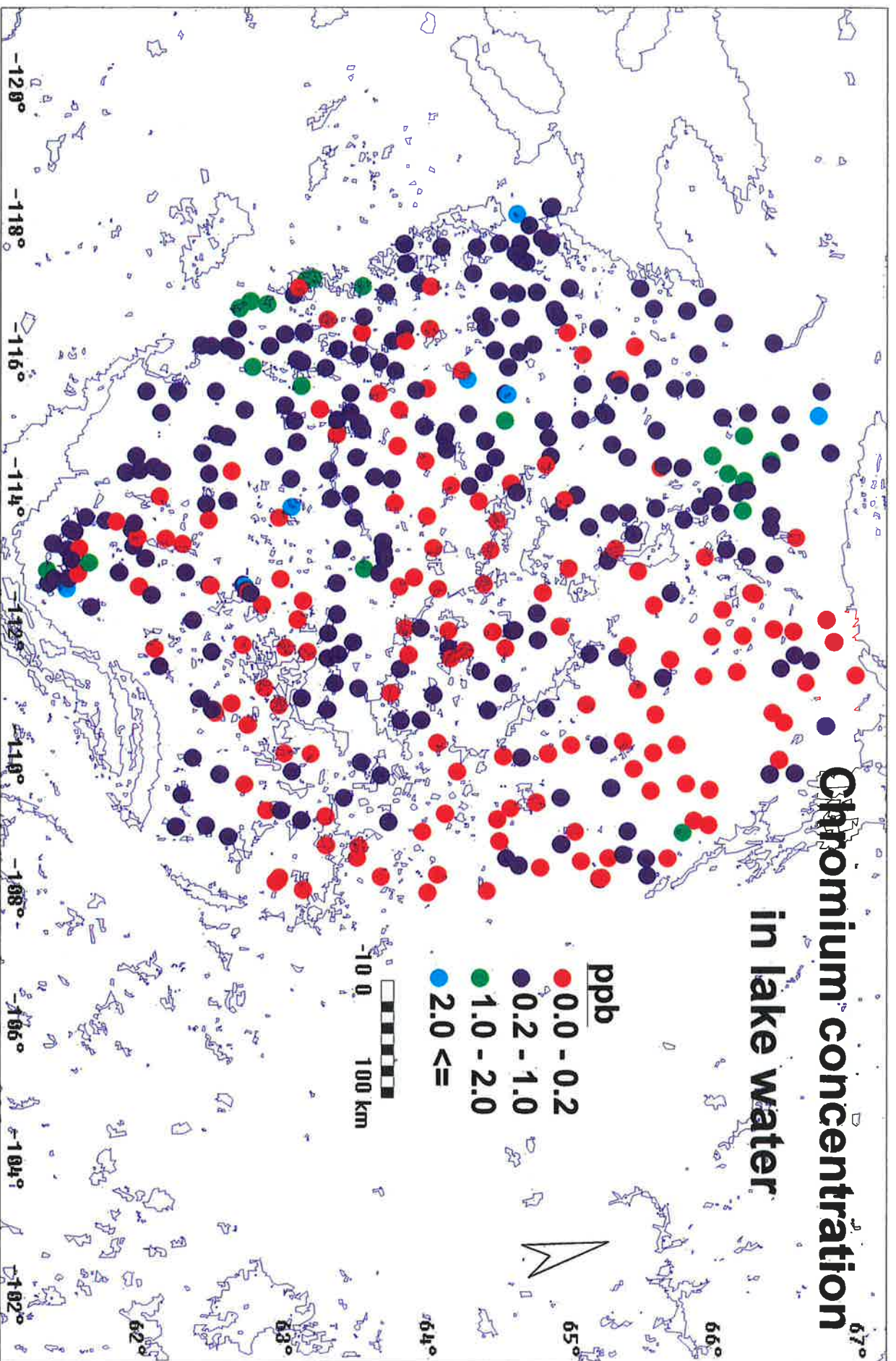
Manganese

Symbol: Mn

Background: Manganese occurs in nature in combination with other elements in the form of ore minerals. In rock minerals, manganese is brought into solution through weathering processes such as, acid leaching, oxidation reduction reactions and extraction with chelating agents. Once in solution, manganese may be subjected to redeposition through formation of carbonates, oxides, silicates or sulphates. Manganese is likely to oxidize in aerated alkaline waters, leading to discolouration of the water. However, manganese is beneficial in soil fertility and in nutrition for plants and animals. According to the Canadian Water Quality Guidelines, the concentration of manganese for most Canadian surface fresh waters seldom exceeds 1000 $\mu g \cdot L^{-1}$.

Common Minerals:

Pyrolusite	MnO_2
Manganite	$Mn_2O_3 \cdot H_2O$
Cryptomelane	KMn_8O_{16}
Hausmannite	$MnO \cdot Mn_2O_3$

Major Uses: Primarily for the production of ferroalloys, as well as for chemicals, dry-cell batteries, and for decolorizing glass.

Hazards: Most of the hazards associated with manganese result from the mining and processing of manganese ores. Although, not considered toxic, manganese imparts objectionable and tenacious stains to laundry and plumbing fixtures.

Guidelines: As outlined in the Canadian Water Quality Guidelines (1990).

Drinking Water

$\leq 50.0 \ \mu g \cdot L^{-1}$

Discussion:

Manganese concentrations are characteristic of most surface freshwater of being less than 1000 $\mu g \cdot L^{-1}$. However, the Canadian Drinking Water Quality Guideline of 50 $\mu g \cdot L^{-1}$ is exceeded in four lakes. Three of the four lakes are in the Slave Province clustered in an area noted to contain previous mining activity as well as currently operating lodges and outfitters (Acres International Limited.1993). The observed distribution pattern of manganese concentration indicates relatively higher concentrations in the Slave Province. Sample site CA85I7CW1 measured the highest concentration of 82.6 $\mu g \cdot L^{-1}$. This sample site also contains the highest measured concentrations of arsenic and rubidium metals. In lakes retested in 1994, manganese concentrations were lower especially in lakes that measured relatively high in 1993.

Manganese concentration in lake water

ppb
- 0.0 - 0.1
- 0.1 - 1.0
- 1.0 - 10.0
- 10.0 - 50.0
- 50.0 <=

0   100 km
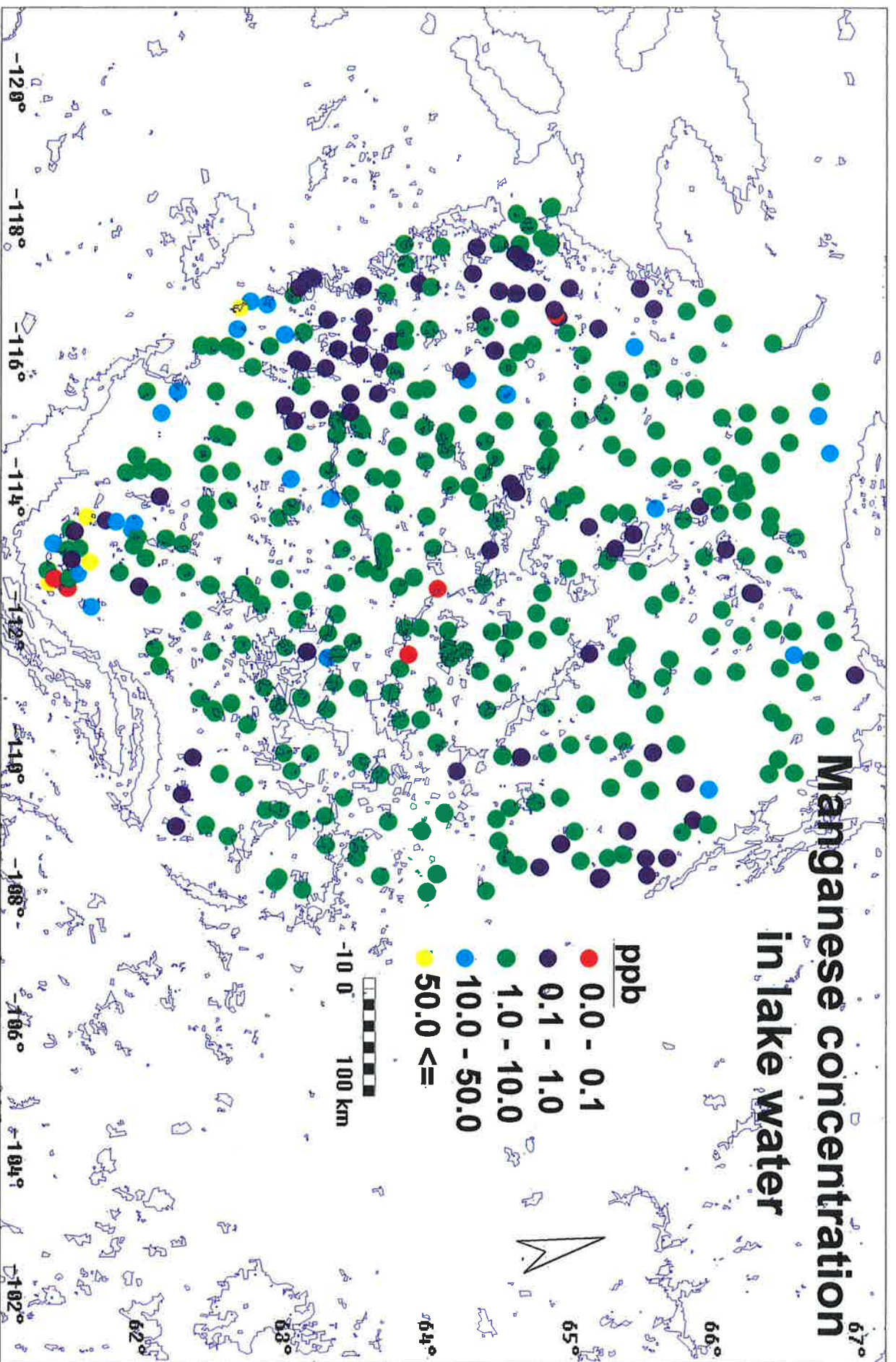
Cobalt

Symbol: Co

Background: Cobalt is mostly concentrated in ultrabasic and associated rocks of magmatic origin. In disseminated deposits and in veins and fissure fillings, cobalt occurs as sulphates and/or arsenides which in common with other sulphates and arsenides, frequently are oxidized near the surface by the action of weathering and surface water. The geology of cobalt closely parallels that of nickel and copper. The amount of cobalt in aerobic surface waters is generally very small. Concentrations increase during fall circulation and winter, primarily in organic fractions. It has a tendency to concentrate more in sediment than in water and also in areas of heavy metal contamination. According to the Canadian Water Quality Guidelines, the concentration of cobalt for most Canadian surface fresh waters is typically < 1.0 $\mu g \cdot L^{-1}$ and for freshwater sediments < 20.0 $mg \cdot L^{-1}$.

Common Minerals:

| Carrollite	$CuCo_2S_4$
Smaltite	$CoAs_2$
Skutterudite	$CoAs_3$
Cobaltite	$CoAsS$
Linnaeite	Co_3S_4

Major Uses: Metal alloys, permanent magnets, cemented carbides, pigments and catalysts.

Hazards: Most of the hazards associated with cobalt result from the processing of pyrite, iron, copper and nickel ores, where cobalt is recovered as a byproduct.

Guidelines: As of 1994 there are no Canadian water quality guidelines.

Discussion:

Cobalt concentrations are characteristic of most surface fresh waters of being less than 1 $\mu g \cdot L^{-1}$ with the exception of site CA76M7BW1 which measured the highest concentration of 1.14 $\mu g \cdot L^{-1}$ It is uncertain if this high cobalt concentration is considered significant to the study area. Site CA76M7BW1 also has the highest measured concentrations of copper and zinc. The distribution pattern of cobalt concentrations do not distinguish the Slave from the Bear Province. The higher concentrations observed are considered site specific. Cobalt concentrations were higher in 10 of 32 lakes retested in 1994.

Cobalt concentration
in lake water

ppb
- 0.0 - 0.1
- 0.1 - 1.0
- 1.0 <=

0   100 km
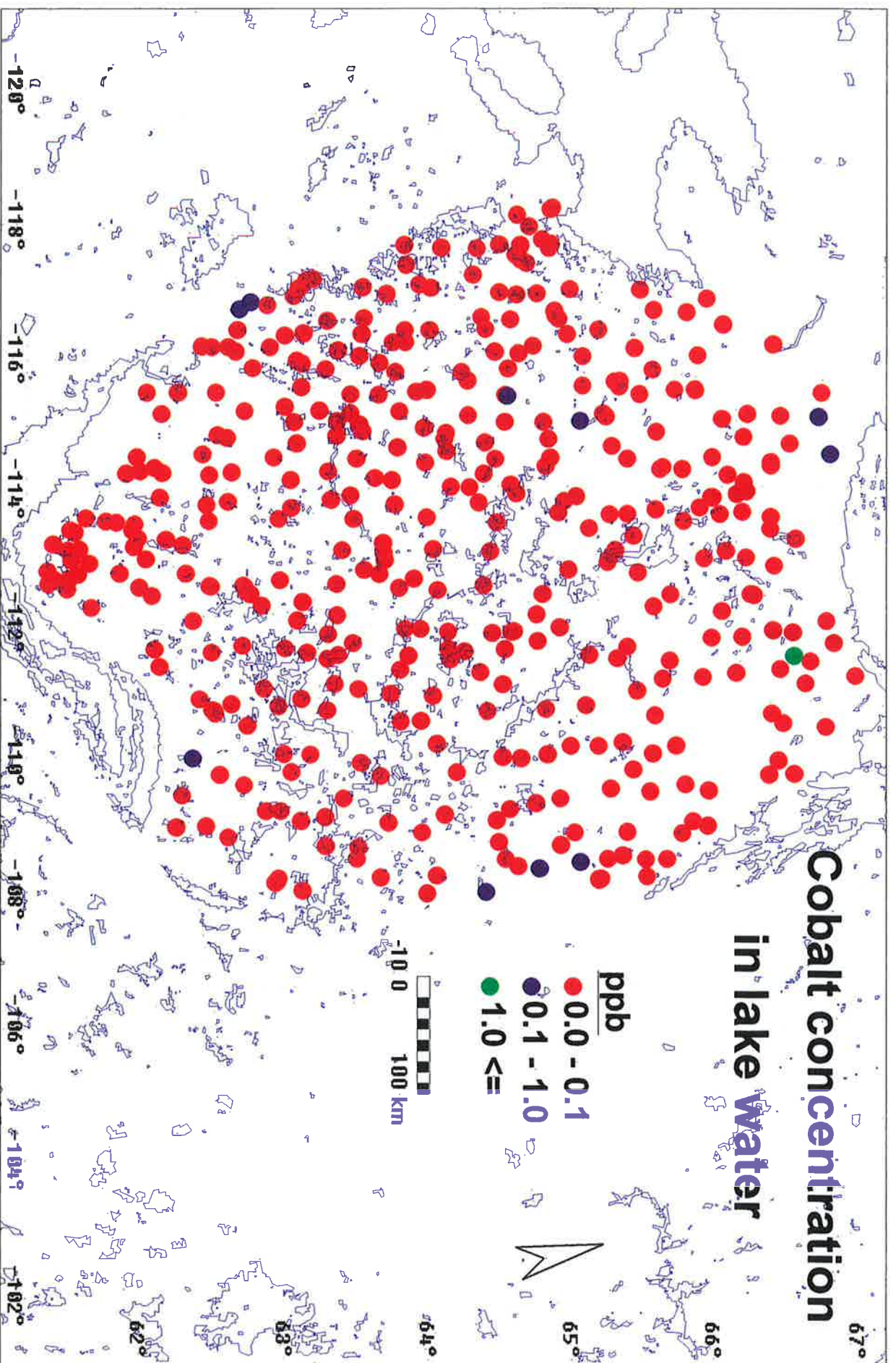
Nickel

Symbol: Ni

Background: Geochemically, nickel is siderophile and will join metallic iron wherever such a phase is present. The high affinity of nickel for sulphur accounts for its frequent occurrence in magnetic or metamorphic segregates of sulphide bodies. Nickel tends to concentrate in mafic and ultramafic rocks, mainly in the olivine, pyroxene, and hypersthene of igneous origin. Nickel enters the environment through weathering of rocks and minerals and through human activity. The weathering of ultrabasic rocks, give rise to iron-, nickel-, and silica rich solutions. Human activities such as the burning of fossil fuels and the manufacturing of foods, baked goods and soft drinks are also considered major contributors of nickel to the environment. According to the Canadian Water Quality Guidelines, the concentration of nickel for most Canadian surface fresh waters can range from 1.0 - 280 $\mu g \cdot L^{-1}$ depending on geographic location. Concentrations tend to be higher in acidic environments and in waters low in hardness.

Common Minerals:

Breithauptite	NiSb
Gersdorffite	(Ni, Fe, Co)AsS
Millerite	NiS
Niccolite	NiAs
Pentlandite	$(Fe, Ni)_9S_8$

Major Uses: Principally in alloys (stainless steel), batteries, dyes, pigments, as a catalyst for hydrogenation of fats and oils, desulphurization of petroleum products, and in insecticides

Hazards: Nickel is a carcinogen, hazardous to human life in the form of dust, and toxic to aquatic life in the aquatic environment. In the aquatic environment, toxicity increases with decreasing hardness.

Guidelines: As outlined in the Canadian Water Quality Guidelines (1990).

Freshwater Aquatic Life

25.0 - 150.0 $\mu g \cdot L^{-1}$

Discussion:

Nickel concentrations are within the 1-280 $\mu g \cdot L^{-1}$ range characteristic of most Canadian surface freshwater as well as below the 25.0 - 150.0 $\mu g \cdot L^{-1}$ guideline for the protection of Freshwater Aquatic Life. The observed distribution pattern of nickel concentrations shows no distinct differences between the Slave and Bear provinces. However, concentrations are relatively higher in the Slave Province. The maximum measured concentration for nickel was 3.93 $\mu g \cdot L^{-1}$ obtained from site CA76G6CW1-2V. Nickel concentrations were lower in 18 of 32 lakes retested in 1994.

Nickel concentration
in lake water

ppb
- 🔴 0.0 - 0.1
- 🟣 0.1 - 1.0
- 🟢 1.0 - 3.0
- 🔵 3.0 <=

-10 0   100 km
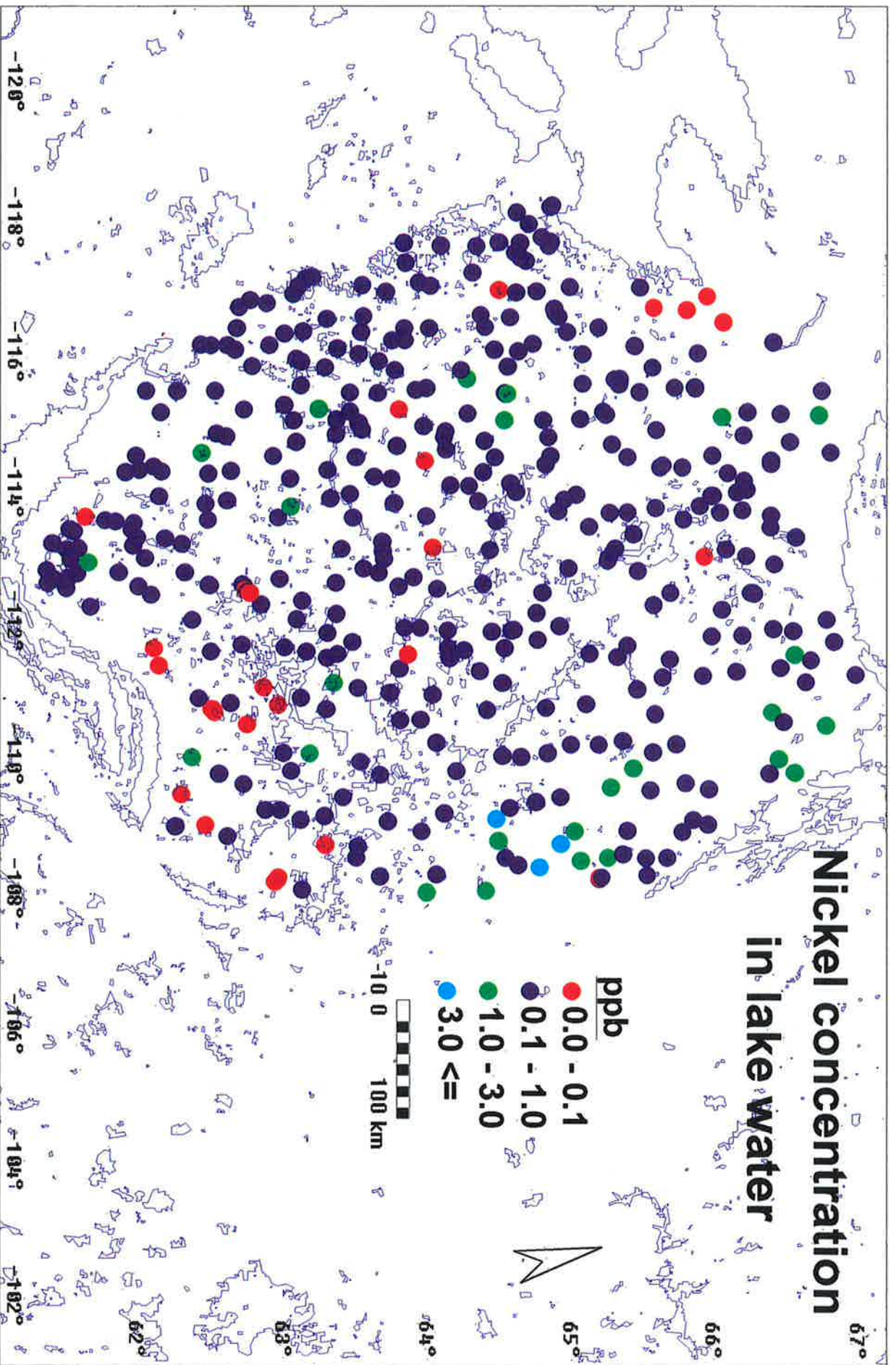
Copper

Symbol:	Cu

Background: Copper occurs in both the elemental form and combined with other elements in a host of different minerals. It is known to concentrate in organic rich sediments. During weathering and sedimentation its behaviour may be compared with that of zinc. In most natural fresh waters, soluble copper is present as complexes of cupric carbonate. At low concentrations copper is an essential element for plants, however at higher levels it becomes toxic to various forms of life. According to the Canadian Water Quality Guidelines, the concentration of copper in most surface fresh waters is below 20 $\mu g \cdot L^{-1}$ and for freshwater sediments the mean concentration ranges between 12-57 $\mu g \cdot g^{-1}$. Copper concentrations increase in acidic environments and waters low in hardness.

Common Minerals:

Chalcopyrite	$CuFeS_2$
Covellite	CuS
Chalcocite	Cu_2S
Cuprite	Cu_2O
Malachite	$Cu_2(CO_3)(OH)_2$
Azurite	$Cu_3(CO_3)_2(OH)_2$

Major Uses: Electrical equipment, alloy, construction, transportation, communication, appliances, utensils, jewellery, and plumbing.

Hazards: Most of the hazards associated with copper result from open pit mining and processing of copper ores. The release of copper to the aquatic environment has toxic effects.

Guidelines: As outlined in the Canadian Water Quality Guidelines (1990).

Drinking Water	**Freshwater Aquatic Life**
$\leq 1000.0 \ \mu g \cdot L^{-1}$	2.0 $\mu g \cdot L^{-1}$ (hardness 0 - 120 mg $\cdot L^{-1}$)
	4.0 $\mu g \cdot L^{-1}$ (hardness 120 - 180 mg $\cdot L^{-1}$)
	6.0 $\mu g \cdot L^{-1}$ (hardness > 180 mg $\cdot L^{-1}$)

Discussion:

Copper concentrations are characteristic of most surface fresh waters being less than 20 $\mu g \cdot L^{-1}$ with the exception of site CA76M7BW1, which measured high at 107.6 $\mu g \cdot L^{-1}$. Site CA76M7BW1 also contains the highest measured concentration of cobalt and zinc. Although all copper concentrations are within the Canadian Water Quality Guideline for Drinking Water of being less than 1.0 mg $\cdot L^{-1}$, guidelines for the protection of freshwater aquatic life are exceeded in six lakes. The higher concentrations are observed in the northeastern portion of the Slave Province particularly in the High Lake area which is a known copper, lead, zinc deposit. Copper concentrations were higher in 23 of 32 lakes retested in 1994.

Copper concentration
in lake water

ppb

- 🔴 0.0 - 0.1
- 🟣 0.1 - 1.0
- 🟢 1.0 - 2.0
- 🔵 2.0 - 4.0
- 🟡 4.0 <=

0   100 km
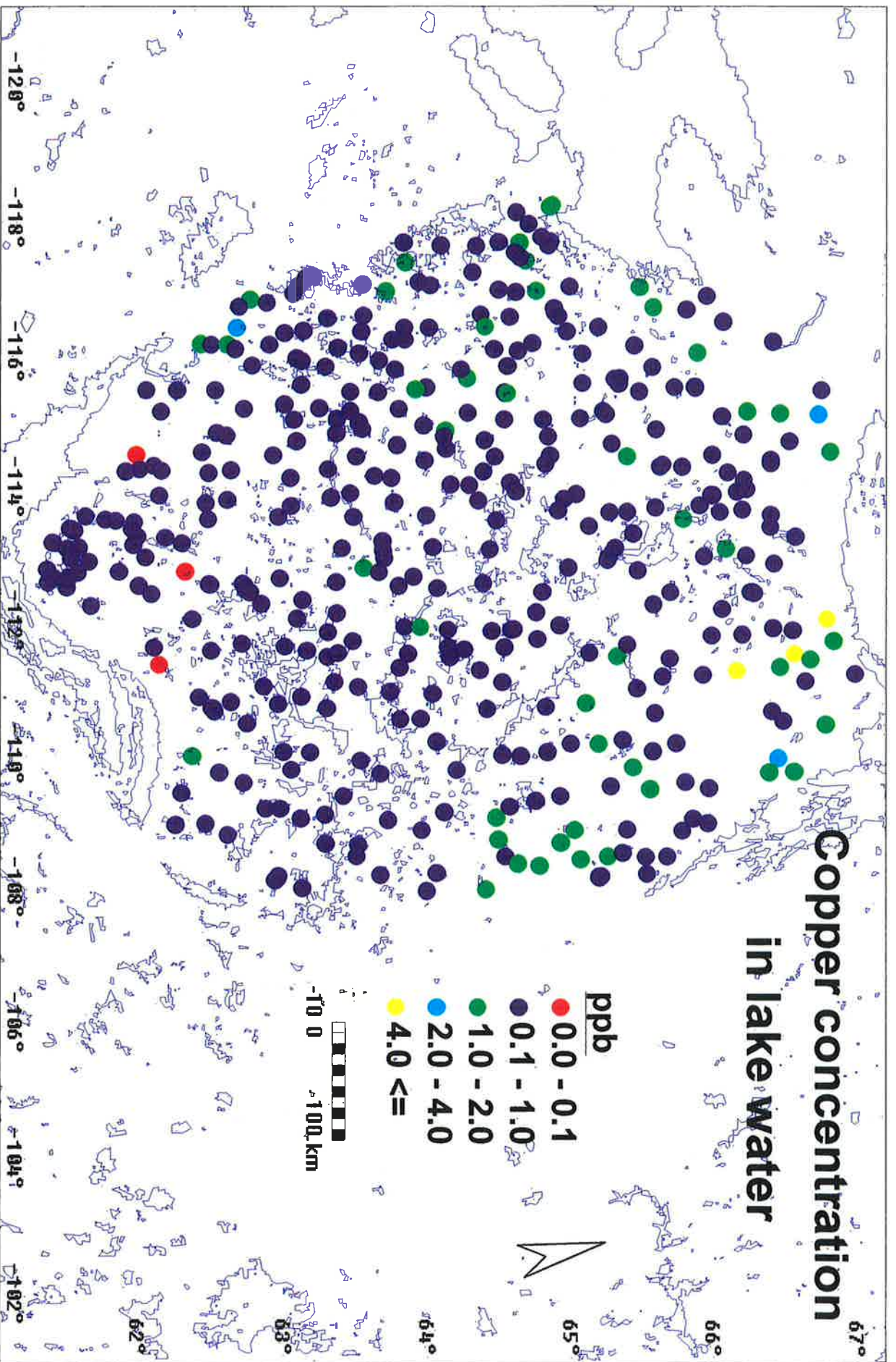
Zinc

Symbol: Zn

Background:

Zinc is found in numerous minerals but the principal ore mineral is sphalerite (zinc sulphide). Sphalerite is commonly associated with lead and iron sulphates and to a lesser degree with copper sulphates, gold and silver minerals. Zinc is weathered from sulphide ore bodies as a very soluble sulphate. The dipositive ion may be removed by reaction with carbonates or by precipitation in reduzate sediments as sulphide. According to theoretical calculations, the greatest dissolved zinc concentrations in fresh waters are possible at low pH, low alkalinity, and high ionic strength. The Canadian Water Quality Guidelines state that the concentration of zinc in surface fresh waters varies with geographic location. In western Canada the concentration ranges between 1-290 $\mu g \cdot L^{-1}$. In freshwater sediments the average concentration is approximately 120 $mg \cdot kg^{-1}$.

Common Minerals:

Sphalerite	ZnS
Zincite	ZnO
Willemite	Zn_2SiO_4
Franklinite	$(Fe,Zn,Mn)O \cdot (Fe,Mn)_2O_3$
Smithsonite	$ZnCO_3$
Hemimorphite	$H_2Zn_2SiO_5$

Major Uses:

Galvanizing, brass and bronze products, pigments, chemicals, batteries and electrical equipment.

Hazards:

Most of the hazards associated with zinc are in the form of air and water pollution resulting from the mining and processing of zinc ores. Sulphur and other chemicals are released to the environment through the processing of sulphide ores.

Guidelines:

As outlined in the Canadian Water Quality Guidelines (1990).

Drinking Water	**Freshwater Aquatic Life**
≤ 5000 $\mu g \cdot L^{-1}$	30.0 $\mu g \cdot L^{-1}$

Discussion:

Zinc concentrations are within the 1-1170 $\mu g \cdot L^{-1}$ range characteristic for most surface freshwater of central Canada. However, site CA76M7BW1 measuring 324 $\mu g \cdot L^{-1}$, exceeds the freshwater aquatic life guideline of 30 $\mu g \cdot L^{-1}$. This site (High Lake) is a known zinc deposit. The relatively higher zinc concentration confirms the finding. The observed zinc concentrations are non typical of theoretical calculations of being greater in waters containing low pH, low alkalinity and high ionic strength. The distribution of zinc concentrations show no distinct differences between the Slave and Bear Provinces. The relatively higher concentrations observed appear to be site specific. Zinc concentrations were higher in 19 of 32 lakes retested in 1994.

Zinc concentration
in lake water

ppb

- 0.0 - 0.5
- 0.5 - 5.0
- 5.0 - 10.0
- 10.0 <=

100 km
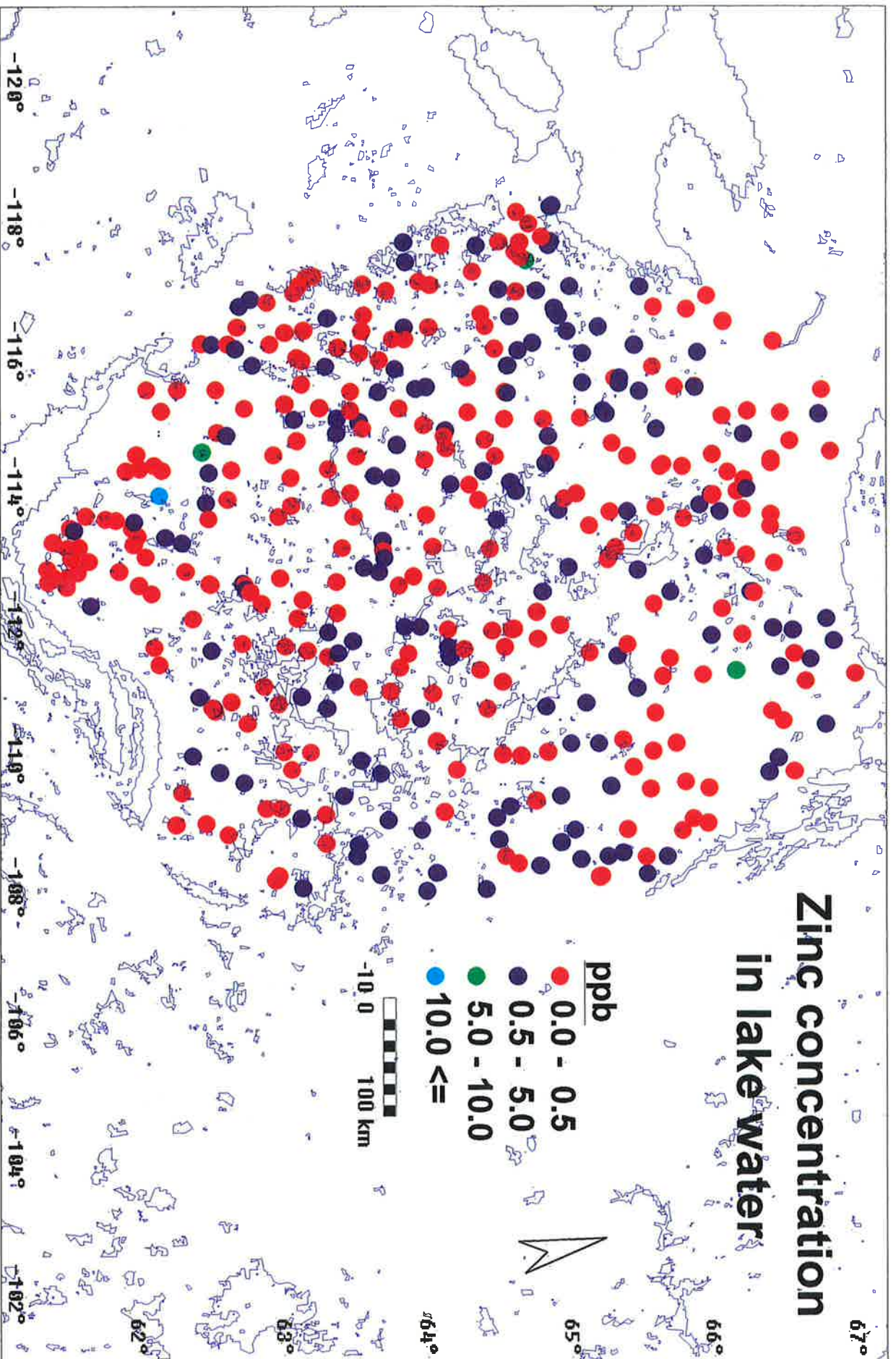
Rubidium

Symbol: Rb

Background: Rubidium is usually found associated with cesium or other alkali metals and occurs in greatest abundance in granites, granite pegmatites, and greisen. Although widely disseminated in low concentrations, rubidium does not occur as the predominant metal in any mineral. Micas are the most important rubidium carriers in common rocks. Elemental rubidium, unlike its compounds, is very reactive with water and air. Rubidium decomposes water with the evolution of hydrogen. Common salts are soluble ionic compounds. Rubidium is usually discussed in terms of its abundance with respect to potassium.

Common Minerals: Lepidolite $K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$
           Amazonite $KAlSi_3O_8$
           Pollucite $(Cs,Na)_2Al_2Si_4O_{12} \cdot H_2O$
           Muscovite $KAl_2(Si_3Al)O_{10}(OH,F)_2$
           Biotite $K(Mg,Fe^{+2})_3(Al,Fe^{+3})Si_3O_{10}(OH,F)_2$

Major Uses: Photocells, as a fuel for ion propulsion engine, and manufacturing of special glasses.

Hazards: Rubidium metal can cause skin burns. Some of its more common salts are highly toxic. However, since the amount of rubidium available to the environment is so minute it presents no deleterious effects.

Guidelines: As of 1994 there were no Canadian water quality guidelines.

Discussion:

The distribution pattern of rubidium concentration appears to follow the tree line. Relatively higher concentrations are observed below the tree line. The distribution pattern would more likely be expected to follow that of other alkali metals such as lithium, sodium and/or potassium. The maximum measured concentration for rubidium was 8.00 $\mu g \cdot L^{-1}$ at site CA85I7CW1. This site also contains the highest measured concentrations of arsenic and manganese metals. Lakes retested in the southern portion of the Slave Province identified to contain previous mining activity and currently operating lodges and outfitters (Acres International Limited, 1993.) tested higher in 1994. All other lakes measurements were relatively unchanged in 1994.

Rubidium concentration in lake water

ppb

- 🔴 0.0 - 0.1
- 🟣 0.1 - 1.0
- 🟢 1.0 - 5.0
- 🔵 5.0 <=

0 100 km
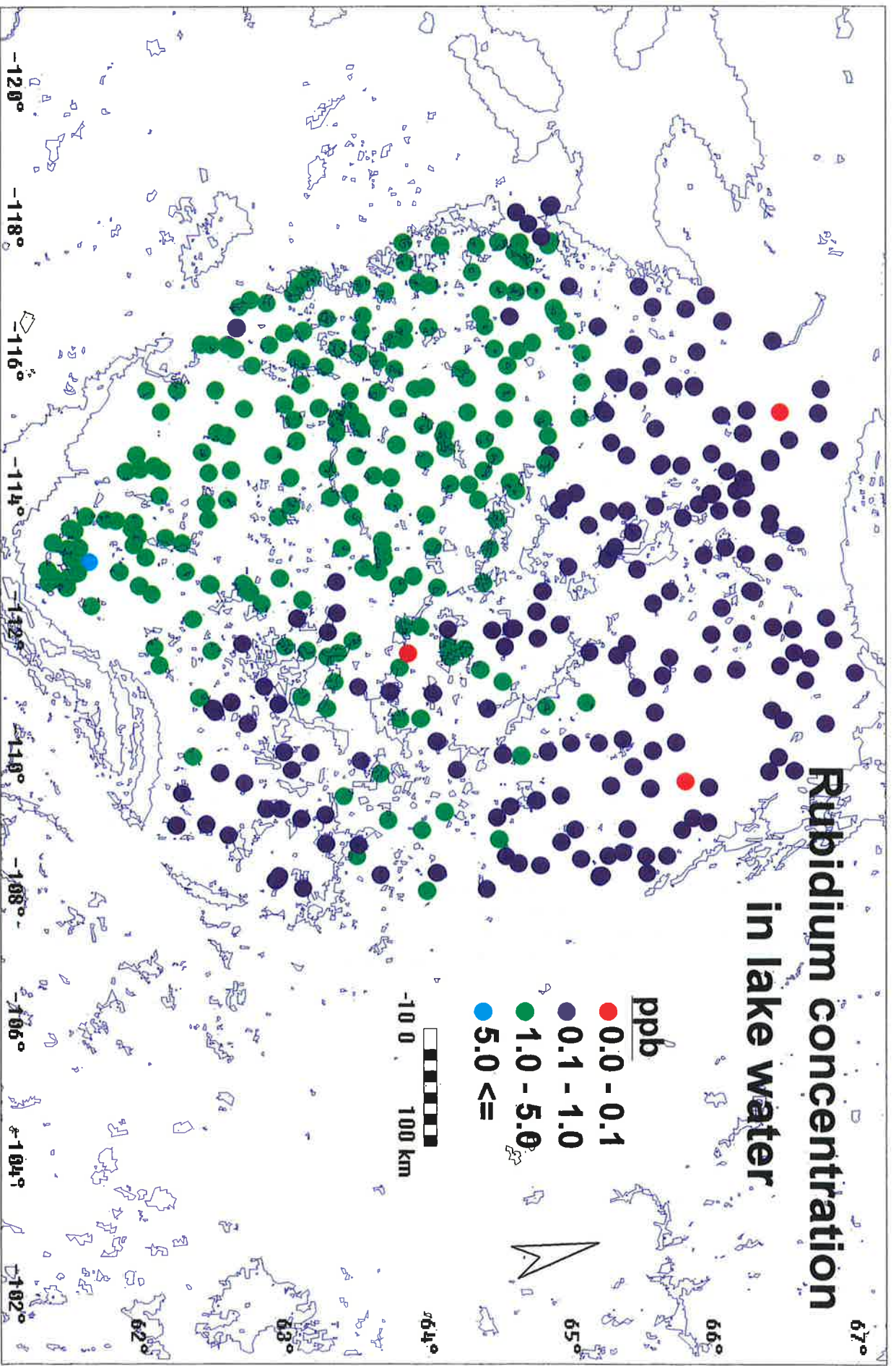
Strontium

Symbol: Sr

Background: Strontium is the least abundant of the alkaline earth metals. Its distribution in minerals, rocks, sediments, and water is affected to a certain extent by the presence of calcium. Most commercial or potentially commercial deposits of strontium minerals occur as beds, veins, veinlets, nodules, or irregular masses in or near sediments or sedimentary rocks. Although the concentration of strontium in fresh waters is very low, levels as high as 39,000 $\mu g \cdot L^{-1}$ have been detected in well waters in the Midwestern United States.

Common Minerals:
Celestite $SrSO_4$
Strontianite $SrCO_3$

Major uses: Pyrotechnics, zinc refining, greases, ceramics (glazes and frits), paints, welding rod coating and television glass.

Hazards: Strontium, in its naturally occurring form is not considered hazardous, however, radioactive strontium is. Strontium accumulates in bones. Radioactive strontium results from nuclear testing and possesses a serious threat to all forms of life.

Guidelines: As of 1994 there were no Canadian water quality guidelines.

Discussion:

Strontium concentrations are characteristic of most fresh waters. The distribution pattern of strontium concentration, as expected, is similar to that of calcium. Observed concentrations are notably higher in the Bear Province than in the Slave Province. Sample site CA85N14AW1-4H measured the maximum concentration of 177.3 $\mu g \cdot L^{-1}$. Strontium concentrations were relatively unchanged in lakes retested in 1994.

Strontium concentration in lake water

ppb

- 🔴 0.0 - 0.1
- 🟣 0.1 - 1.0
- 🟢 1.0 - 10.0
- 🔵 10.0 - 100.0
- 🟡 100.0 <=

100 0   100 km
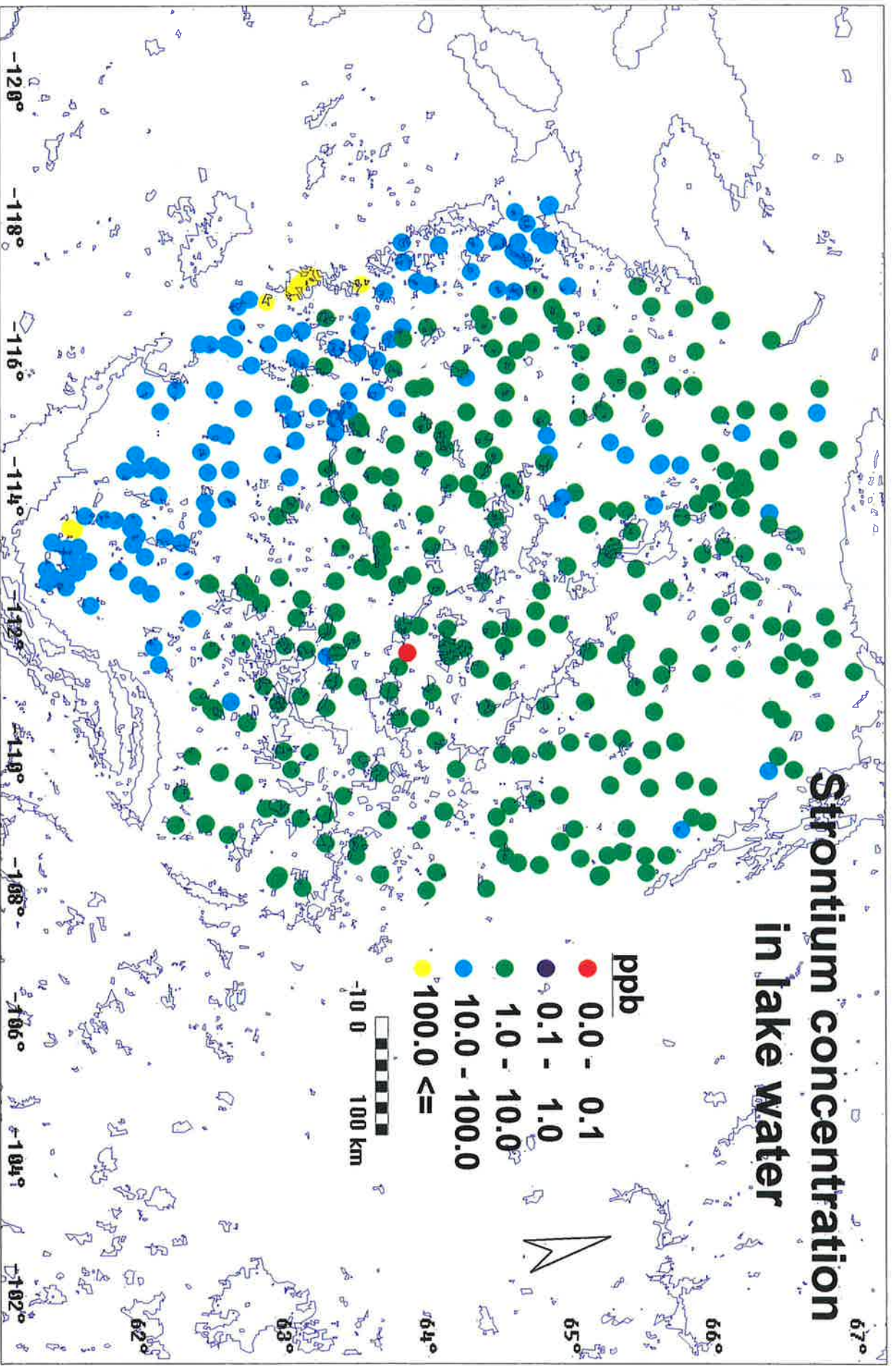
Cadmium

Symbol:	Cd

Background: Cadmium is usually found in conjunction with sulphates, particularly sphalerite (zinc sulphide) making it an indicator for zinc. Cadmium is also found in lead ores (galena). In nature, cadmium results from the oxidation of sulphide deposits forming cadmium sulphate which is soluble in acidic waters. It is normally recovered as a byproduct through processes such as roasting and smelting of zinc ores. According to the Canadian Water Quality Guidelines, the concentration of cadmium for most surface fresh waters ranges between 0.1-10.0 $\mu g \cdot L^{-1}$. Concentrations higher than 10.0 $\mu g \cdot L^{-1}$ are attributed to anthropogenic sources.

Common Minerals:

Greenochite	CdS
Xanthocroite	$CdS(H_2O)_x$
Cadmoselite	CdSe
Monteporrite	CdO
Otavite	$CdCO_3$

Major Uses: Electroplating of iron and steel, batteries, and as a pigment in paints.

Hazards: Cadmium fumes or vapours that are derived from processing of zinc ores is highly toxic.

Guidelines: As outlined in the Canadian Water Quality Guidelines (1990), the total cadmium concentration is dependent on water hardness and should not exceed the following:

Drinking Water	**Freshwater Aquatic Life**	
	hardness (mg·L^{-1} as CaCO$_3$)	($\mu g \cdot L^{-1}$)
5.0 $\mu g \cdot L^{-1}$	0-60 (soft)	0.2
	60-120 (medium)	0.8
	120-180 (hard)	1.3
	>180 (very hard)	1.8

Discussion:

Cadmium concentrations are within the 0.1 and 10.0 $\mu g \cdot L^{-1}$ range characteristic of most surface freshwaters. The maximum concentration of 0.88 $\mu g \cdot L^{-1}$ from sample CA76M7BW1 exceeds the guidelines for the protection of Freshwater Aquatic Life. This sample site (High Lake) is a well known copper, lead - zinc deposit. Although cadmium was detected in four lakes it is only portrayed in three lakes on the adjoining map. Only the last layer or value at each particular site is portrayed, because the data is sorted according to sample number; the higher value of the vertical variability sample is being masked by the presence of the other. Lakes that detect cadmium appear to be site specific. Cadmium values measured less than detection limit in lakes retested in 1994.

Cadmium concentration in lake water

ppb
- 0.0 - 0.1
- 0.1 - 1.0
- 1.0 +

Km 10.0   100 km
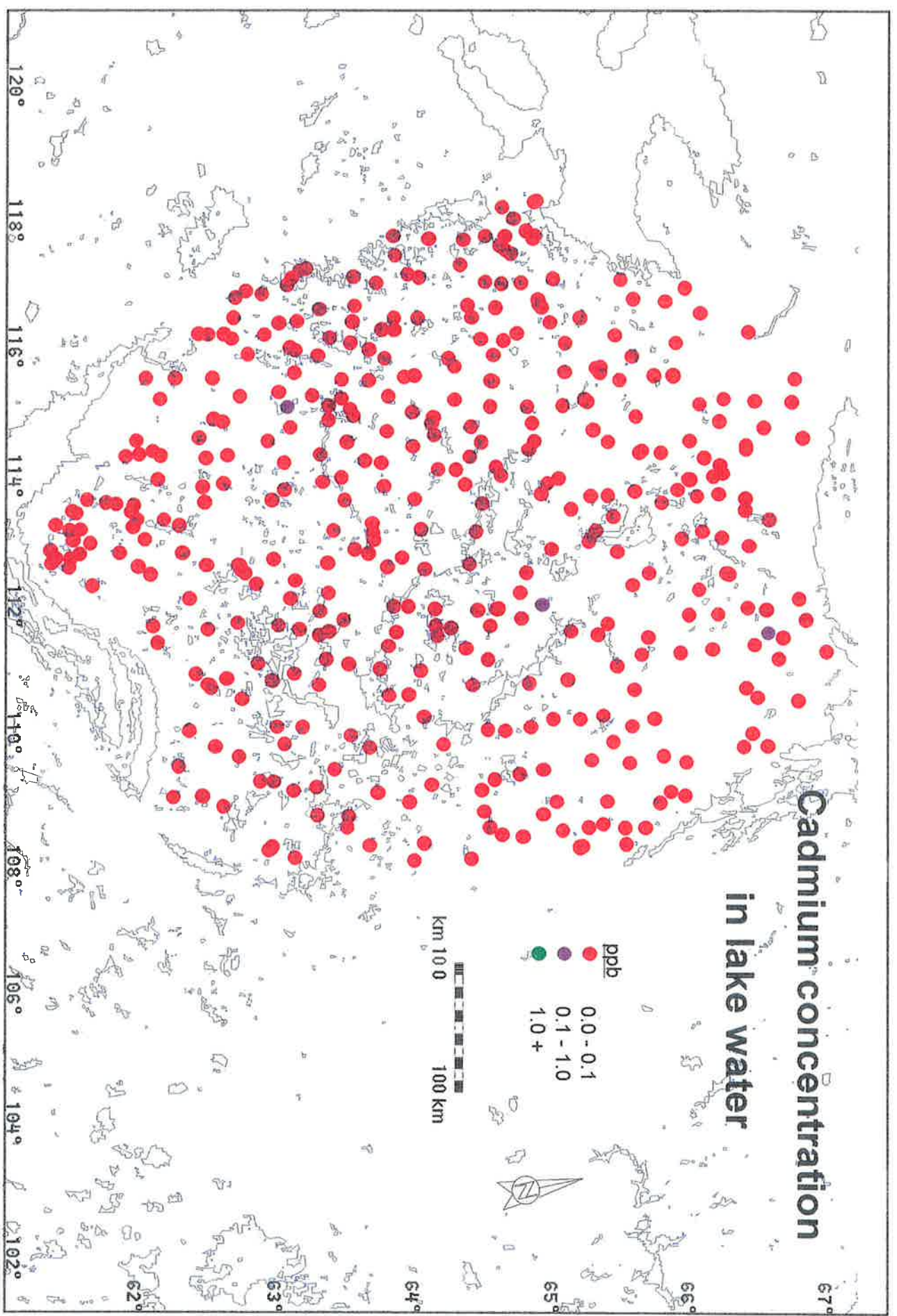
Barium

Symbol: Ba

Background: Barium occurs mostly in barite, the principal commercial mineral source. Most commercial barium sources are replacement deposits in limestone, dolomite, sandstones and shales, or residual deposits in which barite is enclosed in clay caused by differential weathering. Barium is sometimes found in metallic ores such as lead, zinc, and silver. Although, barite occurs in many parts of the world in large quantities, its abundance in fresh water is relatively low. According to the Canadian Water Quality Guidelines, the concentration of barium for most surface fresh water rarely exceeds 1.0 mg·L^{-1} whereas in sediments the concentration ranges between 90-2300 mg·kg^{-1}.

Common Minerals: Barite $BaSO_4$
                           Witherite $BaCO_3$

Major Uses: Weighting agent for drilling muds (oil and gas industry), glass, paints and rubber.

Hazards: According to the Standard Methods for the Examination of Water and Wastewater, barium doses of 550-600 mg are considered fatal to human beings. Other hazards associated with barium are land disturbances, and the production of H_2S (hydrogen sulphide gas) produced from the production of barium chloride.

Guidelines: As outlined in the Canadian Water Quality Guidelines (1990).

                           ### Drinking Water

                           1.0 mg·L^{-1}

Discussion

Barium concentrations although characteristic of most surface freshwater of being less than 1.0 mg·L^{-1}, are higher in the northern portion of the Bear Province particularly in Coppermine River area. The maximum concentration of 82.72 μg·L^{-1} was measured from sample site CA86P2DW1. The higher concentrations observed in the Slave Province are believed to result from previous mining activity. Barium concentrations were lower in 23 of 32 lakes retested in 1994.

Barium concentration
in lake water

ppb

- 🔴 0.0 - 0.1
- 🟣 0.1 - 1.0
- 🟢 1.0 - 25.0
- 🔵 25.0 - 50.0
- 🟡 50.0 <=

-10 0   100 km
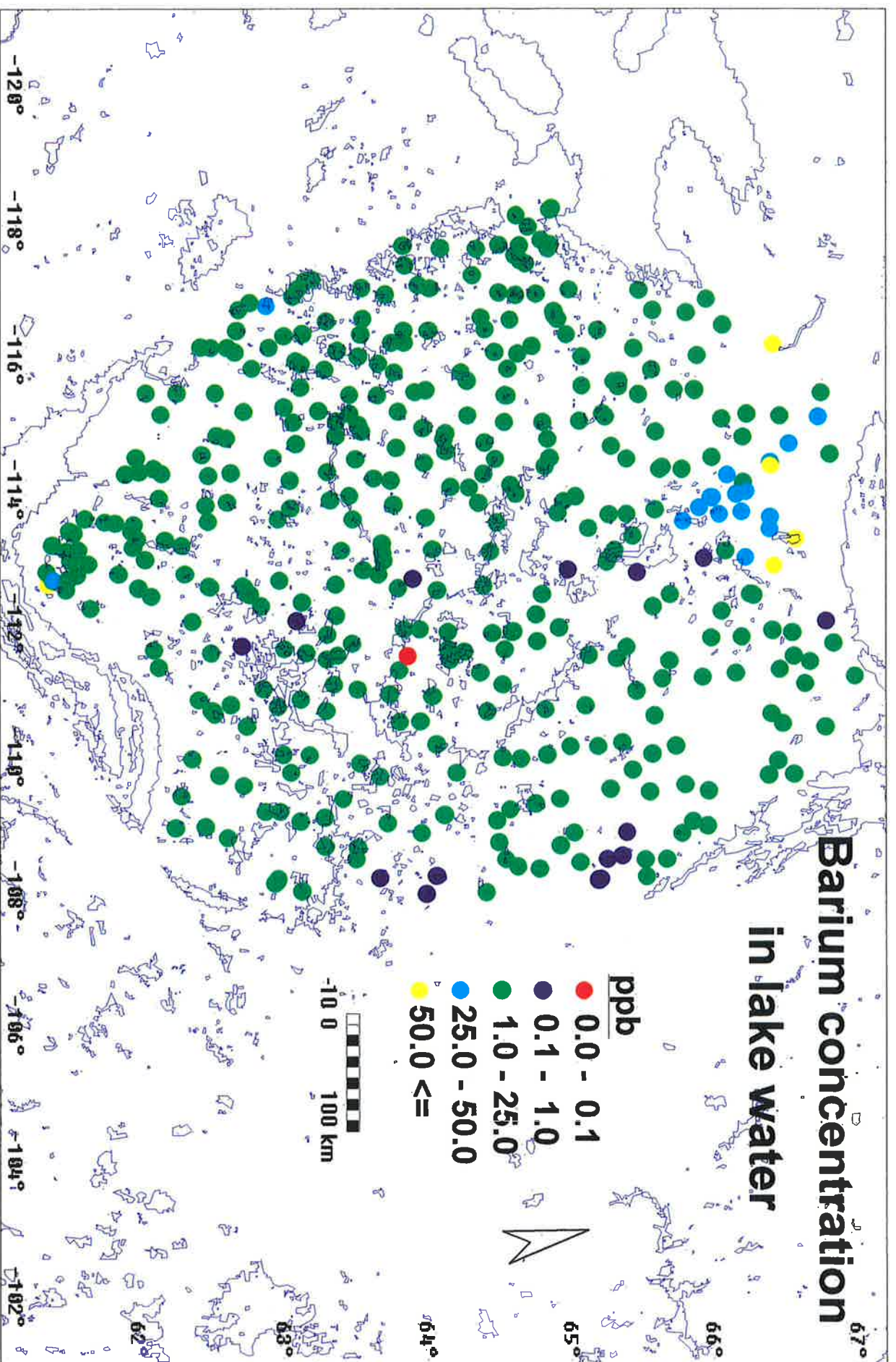
Lead

Symbol: Pb

Background: Lead is one of the oldest metals used by man, occurring naturally as decay products of uranium and thorium. Lead is recovered from ores varying widely in lead content as well as being recovered as a byproduct of the processing of other metals. Although most of the lead entering the environment naturally is through the weathering of sulphide ores, namely Galena (PbS), the major source is through anthropogenic input. Because many of its salts as well as the metallic form are insoluble in water, lead entering the aquatic environment will more likely attach itself to suspended sediments rather than be dissolved in the water column. According to the Canadian Water Quality Guidelines, the concentration of lead in most surface fresh waters is dependent on water hardness and acidity but generally it is less than 5 $\mu g \cdot L^{-1}$.

Common Minerals:

Galena	PbS
Cerussite	$PbCO_3$
Anglesite	$PbSO_4$

Major Uses: Construction, piping, solder, batteries, bearings, and paints just to name a few. Lead was once used as a gasoline additive.

Hazards: Lead poisoning may occur by ingestion or exposure to vapours. Lead vapours are released into the atmosphere primarily through emissions from lead smelters.

Guidelines: As outlined in the Canadian Water Quality Guidelines (1990).

Drinking Water	**Freshwater Aquatic Life**	
	hardness (mg·L^{-1} as CaCO$_3$)	($\mu g \cdot L^{-1}$)
10.0 $\mu g \cdot L^{-1}$	0-60 (soft)	1.0
	60-120 (medium)	2.0
	120-180 (hard)	4.0
	>180 (very hard)	7.0

Discussion:

With the exception of site CA86I11BW1, the concentration of lead is characteristic of most surface freshwater of being less than 5 $\mu g \cdot L^{-1}$. The concentration of 10.8 $\mu g \cdot L^{-1}$ at site CA86I11BW1 exceeds the Canadian Drinking Water Quality Guidelines of 10.0 $\mu g \cdot L^{-1}$. This site also contains the highest measured concentrations of tin and antimony metals. Also, due to low water hardness, lead concentrations exceed the guidelines for the protection of Freshwater Aquatic Life in five lakes. The distribution of lead concentration appears to be site specific and there is no distinct difference in distribution between the Slave and Bear Provinces. Lead concentrations were higher in 27 of 32 lakes retested in 1994.

Lead concentration
in lake water

ppb

- 🔴 0.0 - 0.2
- 🟣 0.2 - 1.0
- 🟢 1.0 - 7.0
- 🔵 7.0 <=

100 0   100 km
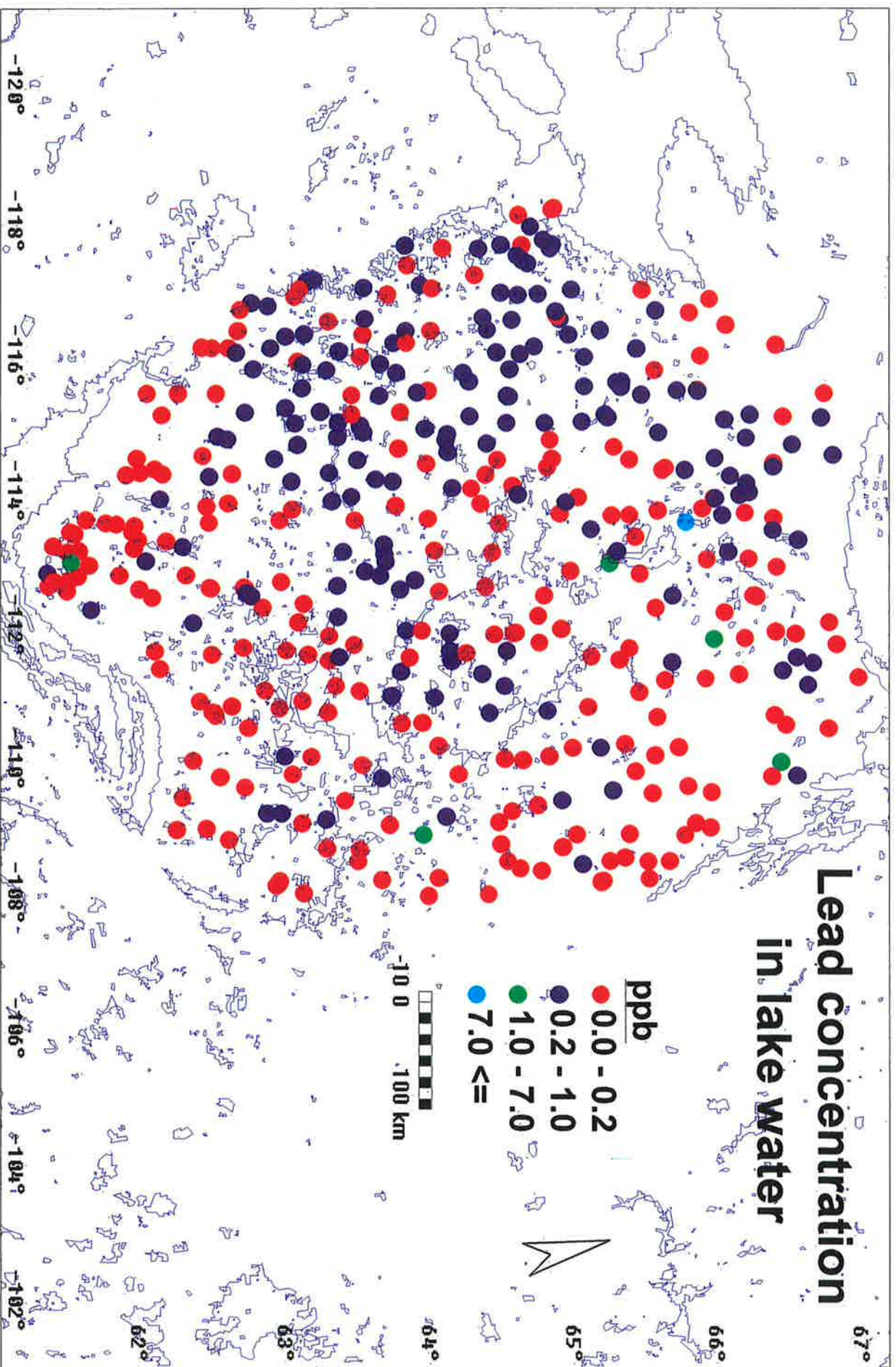
Uranium

Symbol: U

Background: Uranium is always found in chemical combinations with other elements with which it forms more than 100 known minerals. These minerals occur separately or in veins in different types of rocks, particularly sedimentary. The massive form, known as pitchblende, occurs in hydrothermal sulphide veins. Uranium minerals are chemically weathered in humid climates to soluble U(VI) complexes and removed by river water. The rate at which uranium enters a given water source is dependent on parameters such as dissolved oxygen, total dissolved carbonate, temperature, pH, and organic content. Uranium is also widespread in the atmosphere. According to the Canadian Water Quality Guidelines, the concentration of uranium in Canadian Shield Lakes ranges between 0.001-170.0 $\mu g \cdot L^{-1}$.

Common Minerals:

Uranite	UO_2
Carnotite	$K_2O \cdot 2UO_3 \cdot V_2O_5 \cdot nH_2O$
Autunite	$Ca \cdot 2UO_2 \cdot 2PO_4 \cdot 10\text{-}12H_2O$
Tobernite	$Cu(UO_2)_2(PO_4)_2 \cdot 8\text{-}12H_2O$

Major Uses: Nuclear energy, medicine, chemicals, metals and explosives.

Hazards: Radiation is capable of damaging living tissue. Radiation is associated with all process of uranium ore from exploration to disposal of waste.

Guidelines: As outlined in the Canadian Water Quality Guidelines (1990).

Drinking Water

100 $\mu g \cdot L^{-1}$

Discussion:

Uranium concentrations in the Slave and Bear Provinces are well within the 0.001-170 $\mu g \cdot L^{-1}$ range characteristic of most inland surface freshwaters of the Canadian Shield. A larger distribution of relatively higher concentrations are observed in the Bear Province. These high values are characteristic of the Bear Province geology. The maximum measured concentration for uranium was 1.62 $\mu g \cdot L^{-1}$ obtained from site CA85N1DW1-3T. Uranium concentrations were higher in 11 of 32 lakes retested in 1994.

Uranium concentration in lake water

ppb
- 0.0 - 0.1
- 0.1 - 1.0
- 1.0 <=
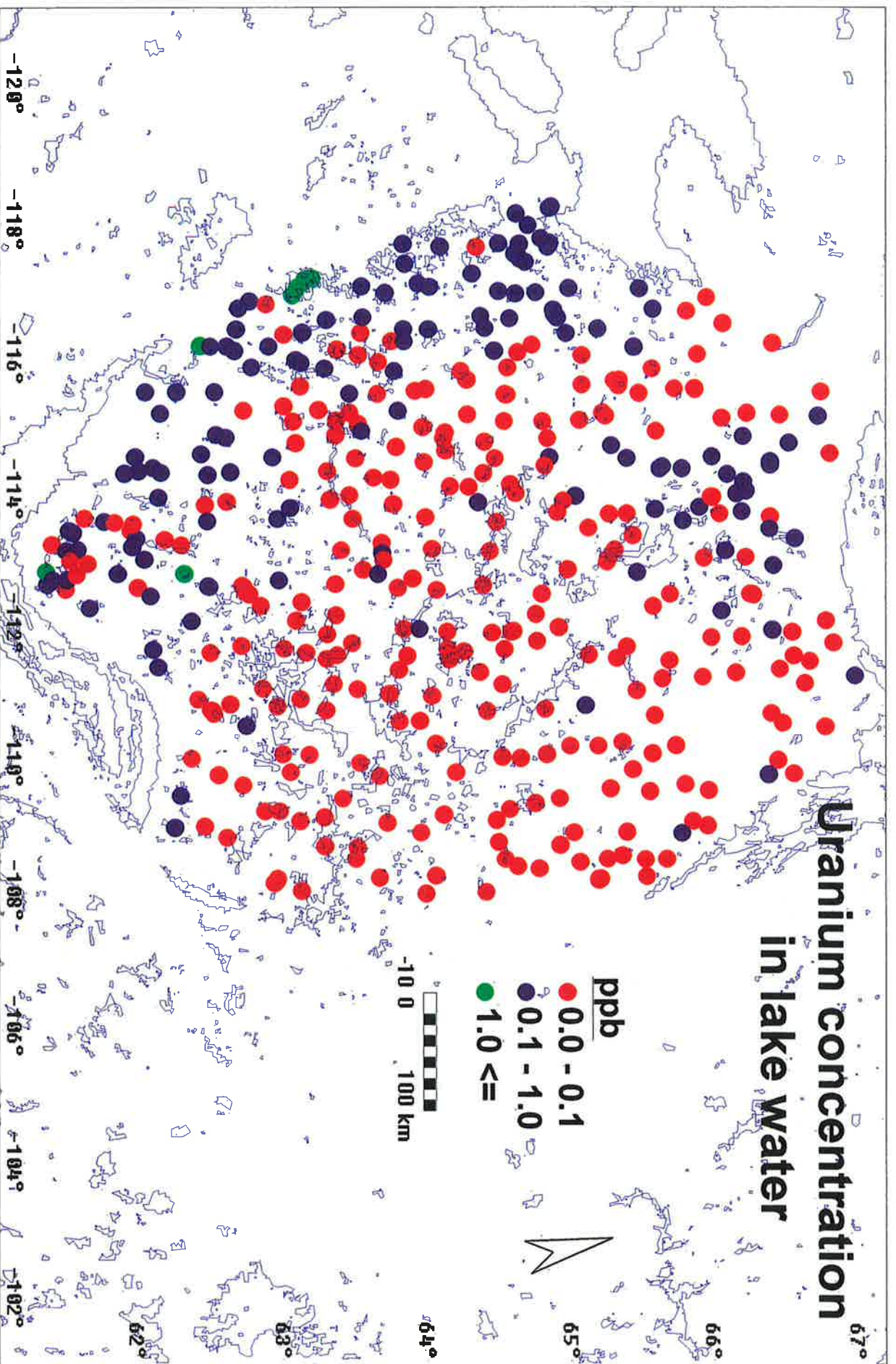
Scandium

Symbol: Sc

Background: Scandium tends to concentrate in wolframite and phosphate rock. The largest commercial resources of scandium are byproducts of uranium and tungsten. Scandium is found as an impurity in other minerals, principally oxides, tungstates, carbonates, phosphates and silicates. Overall, the amount of scandium is rare and very expensive with very little economical use. Scandium and its elemental groups are highly insoluble in water.

Common Minerals:

Thortveitite	$(Sc,Y)_2Si_2O_7$
Sterrettite	$ScPO_4 \cdot 2H_2O$
Kolbeckite	$ScPO_4 \cdot 2H_2O$
Wolframite	$(Fe^{+2},Mn^{+2})WO_4$
Cassiterite	SnO
micas	

Major Uses: Chemicals, research, and (due to its light weight and high melting point) as a metal for space missiles.

Hazards: Since little is known about scandium, the hazards associated with this element are those mostly associated with uranium since it is a by-product.

Guidelines: As of 1994 there were no Canadian water quality guidelines.

Discussion:

Scandium, although highly insoluble, was detected in nine lakes. The maximum concentration measured 0.19 $\mu g \cdot L^{-1}$ at site CA85I2AW1 which also contains the highest measured concentration of lithium. The distribution of scandium concentration appears to be site specific. Scandium concentrations measured lower or the same in all 32 lakes retested in 1994.

Scandium concentration in lake water

ppb

- 🔴 0.00 - 0.10
- 🟣 0.10 - 0.15
- 🟢 0.15 <=

-10 0   100 km
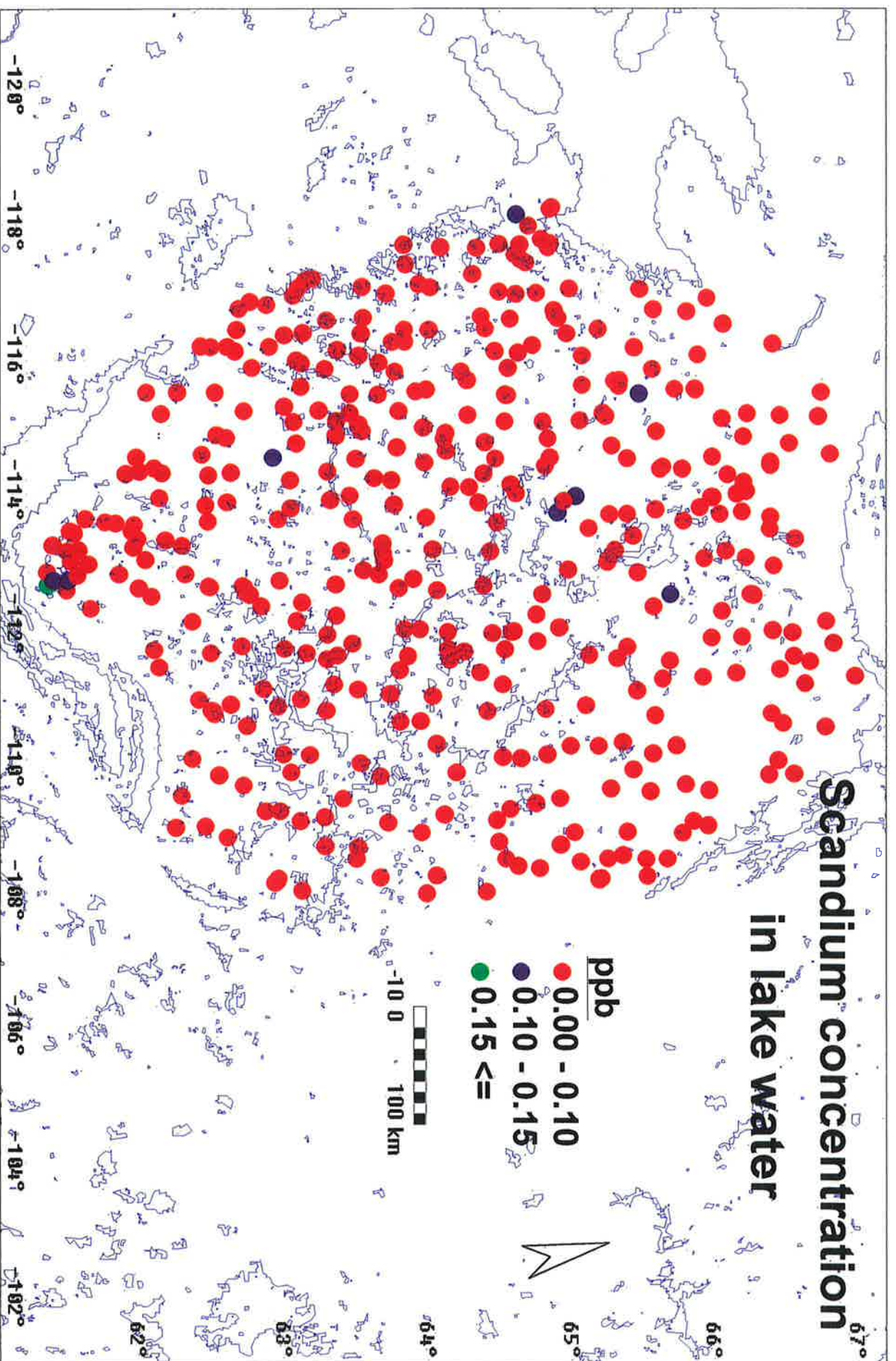
Titanium

Symbol: Ti

Background: Titanium is the most common trace element in igneous rocks. In the earth's crust titanium combines with oxygen to form stable oxides. Many of the titanium bearing minerals are resistant to weathering. However, they are sometimes found associated with other heavy, resistant minerals. The titanium contained in the structure of femic minerals is dissolved in water during weathering but then is promptly hydrolysed and carried into the hydrolzates. Most of the titanium entering the aquatic environment results from mining, municipal, and organic chemical plant effluents as well as through the smelting of ores. According to the Canadian Water Quality Guidelines, the average concentration of titanium for most surface fresh waters is 5 $\mu g \cdot L^{-1}$.

Common Minerals:

Ilmenite	$FeTiO_3$
Rutile	TiO_2
Titanomagnetite	$Fe(Fe,Ti)_2O_4$
Perovskite	$CaTiO_3$

Major Uses: Pigments, welding-rod coatings, alloys, ceramics, and glass fibre.

Hazards: Most of the hazards associated with titanium result from the mining and processing of titanium rich ores. Titanium salts cause serious corrosion problems.

Guidelines: As of 1994 there were no Canadian water quality guidelines.

Discussion:

In 15 of 374 lakes, titanium concentrations were higher than 5 $\mu g \cdot L^{-1}$ characteristic of most surface freshwater. The higher concentrations are observed in the Bear Province. The highest concentration of 9.96 $\mu g \cdot L^{-1}$ was measured at site CA85I6BW1. In all lakes retested in 1994 titanium concentrations measured less than detection limit.

Titanium concentration in lake water
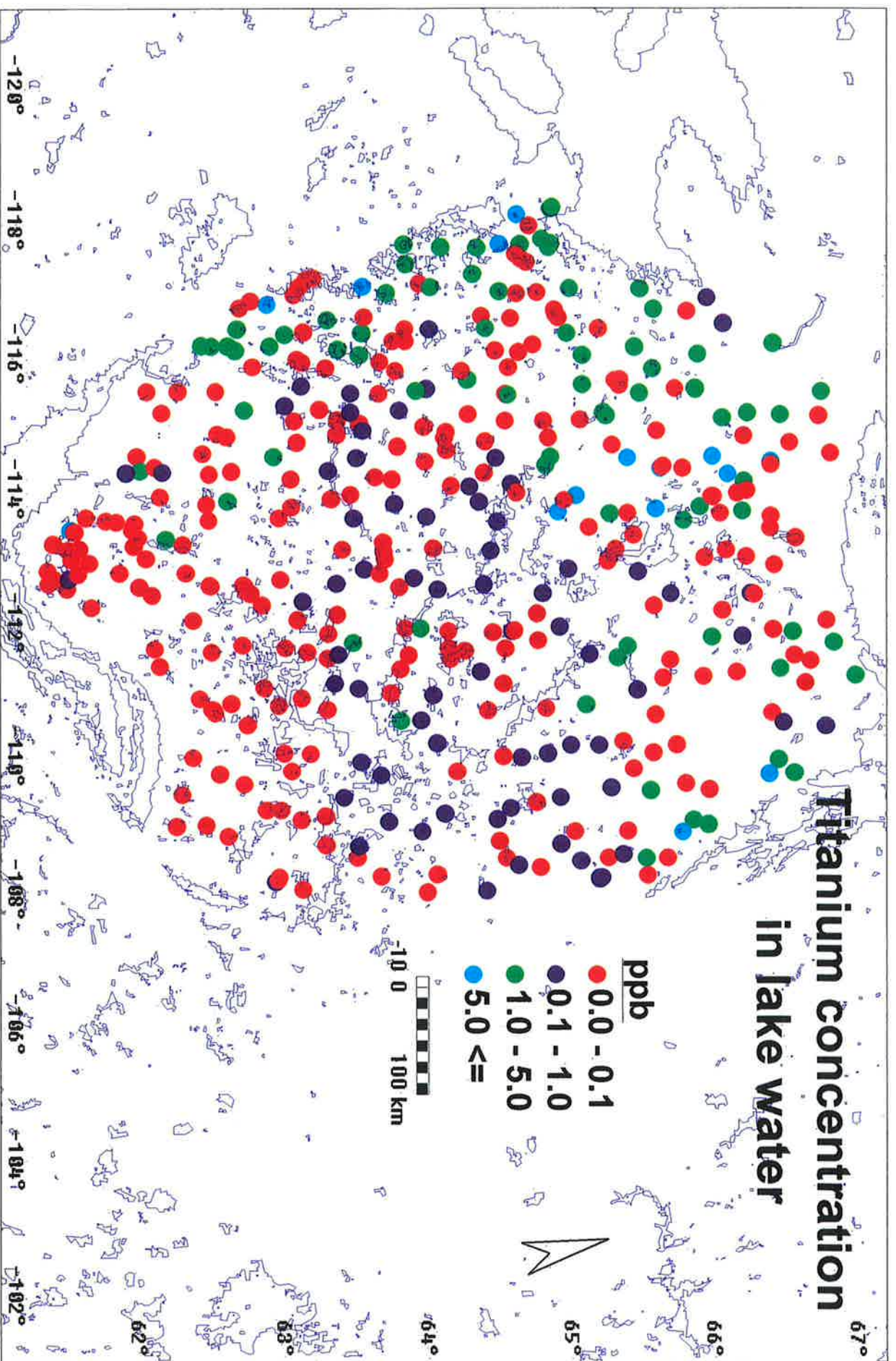
Gallium

Symbol: Ga

Background: Gallium is a widely dispersed element present in most minerals in the 5-200 $mg \cdot L^{-1}$ range. It is derived almost entirely as a byproduct from the processing of aluminum and zinc ores namely bauxite and sphalerite. The geochemistry of gallium closely parallels that of aluminum. Of the common rock forming minerals, micas contain the most gallium. Although germanite and germanium are known to contain gallium, gallite is the only mineral known to contain gallium as an essential constituent. Although little is known about the behaviour of gallium in the aquatic environment, it is however an important micronutrient of certain aquatic plants.

Common Minerals: Gallite $CuGaS_2$
                          Albite $NaAlSi_3O_8$
                          Bauxite $Al_2O_3 \cdot 2H_2O$
                          Blende ZnS

Major Use: Semiconductors, heat-exchange medium, and in dental amalgams.

Hazards: Most of the known hazards associated with gallium are those associated with the mining and milling of aluminum and zinc ores. Although the toxicity of gallium is of low order it should be handled with care.

Guidelines: As of 1994 there were no Canadian water quality guidelines.

Discussion:

Although little is known about gallium in the aquatic environment, higher concentrations are observed in the Bear Province. The relatively higher concentration observed appear to be site specific. The maximum measured concentration for gallium was 9.7 $\mu g \cdot L^{-1}$ obtained from site CA86J7CW1-3V. Maximum concentrations of yttrium, molybdenum, lanthanum and cerium were also detected at this site. In lakes retested in 1994, gallium concentrations were unchanged.

Gallium concentration in lake water

ppb
- 0.0 - 0.1
- 0.1 - 1.0
- 1.0 <=

0.0
100 km
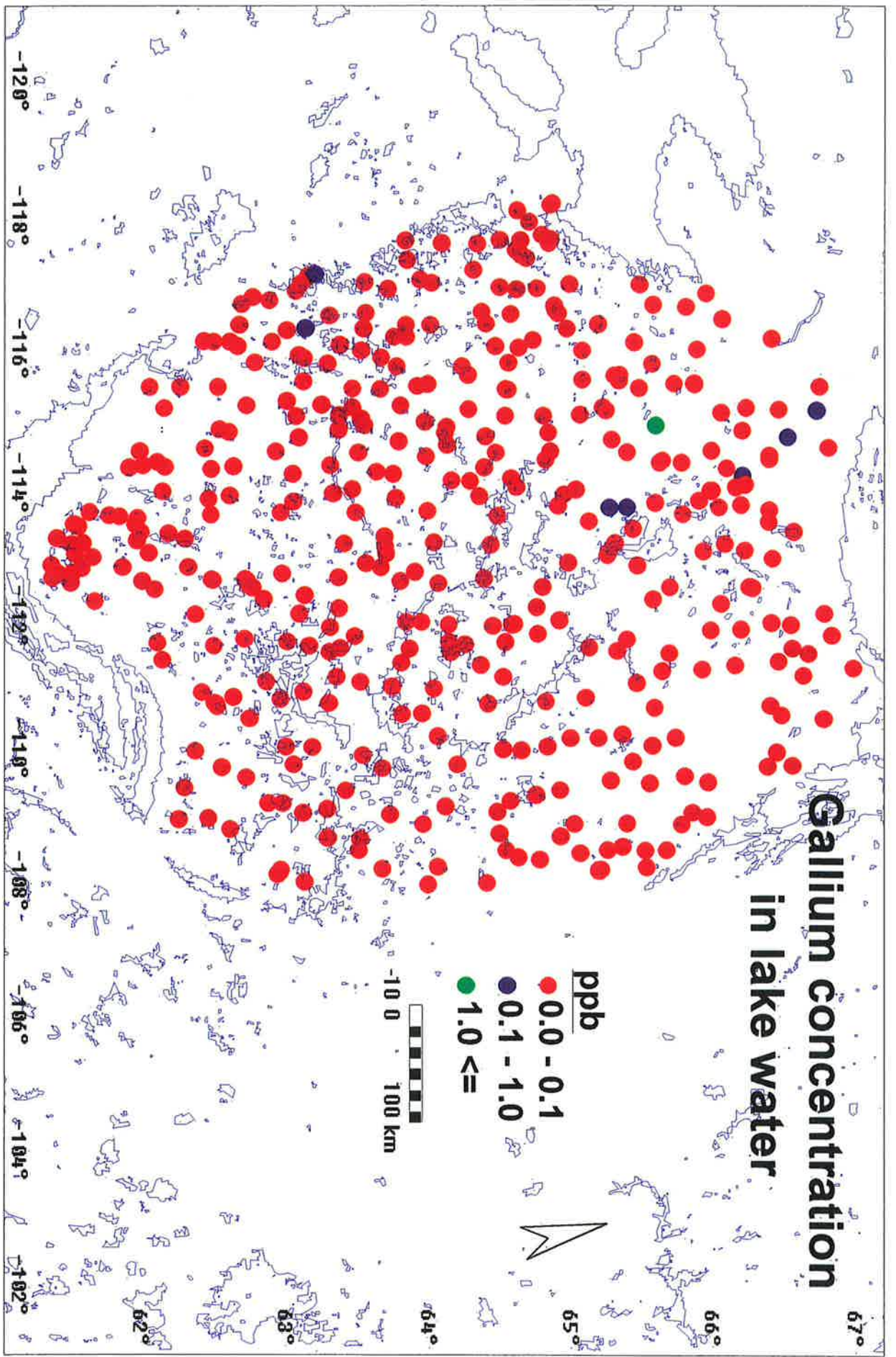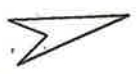
Yttrium

Symbol:	Y

Background:
Yttrium occurs in highest concentration in rare earth minerals that concentrate heavy rare earths. Most of the domestic supply of yttrium is from concentrates produced as a byproduct of uranium ore processing. Yttrium forms complexes which are transported in alkali, halogen, and carbon dioxide rich hydrothermal fluids. Yttrium adsorbs on clay particles as well as organic material. The major source of yttrium is monazite. Monazite is recovered as a byproduct from the processing of beach sands and river gravels for titanium minerals.

Common Minerals:
Xenotime   (yttrium phosphate with cerium)
Monazite   (yttrium phosphate)
Gadolinite   (complex beryllium-iron-yttrium silicate)

Major Uses:
Phosphors for colour television, garnets for microwave control, permanent magnets, structural materials, for atomic energy, metallurgical process, glass and refractories.

Hazards:
Because yttrium is recovered as a byproduct, the hazards associated with it are those attributed to the mining and milling of various rare earth ores.

Guidelines:
As of 1994 there were no Canadian water quality guidelines.

Discussion:

Yttrium, although highly insoluble, was detected in five lakes. It is uncertain whether these low reading are significant. The five sites are located in the northern part of the study area in both the Bear an Slave Provinces. The maximum measured concentration for yttrium was 0.20 $\mu g \cdot L^{-1}$ from site CA86J7CW1-3V which also contains the highest concentrations of gallium, molybdenum, lanthanum, and cerium metals. Yttrium concentrations measured lower or the same in all 32 lakes retested in 1994.

Yttrium concentration
in lake water

ppb
● 0.0 - 0.1
● 0.1 <=

-10 0   100 km
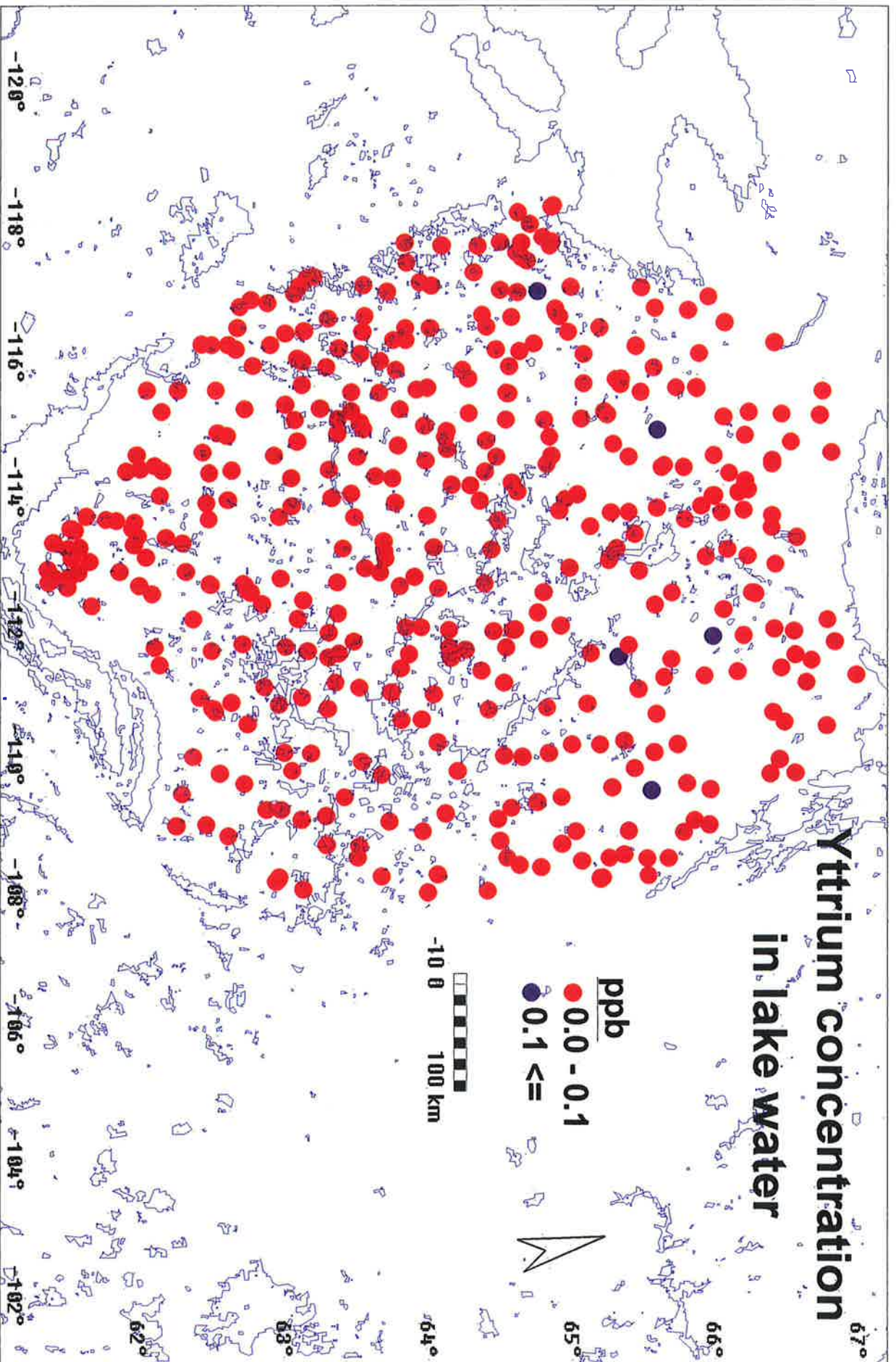
Zirconium

Symbol:	Zr
Background:	Zirconium is found principally in zircon, a zirconium silicate. Although rarely found in rock in economically mineable concentrations, weathering and erosion, particularly of granitic rocks, have led to deposition of minable concentrations of heavy mineral sands along rivers and ocean beaches and in dunes. More commonly, zirconium is recovered as a byproduct in the mining of titanium minerals from placer type deposits. Zirconium and hafnium always occur together in minerals which are associated in sand deposits with minerals containing titanium and rare earth elements.

Common Minerals:

Zircon	$ZrSiO_4$
Baddeleyite	ZrO_2
Eudialite	$(Na, Ca, Fe)_6Zr[OH, Cl/(Si_3O_9)_2]$

Major Use: Refractories (non-metal), construction in nuclear reactors (metal), and in petrochemical, urea, and sulphuric and hydrochloric acid processing plants.

Hazards: Zirconium metal powder combines readily with oxygen and nitrogen and is quite combustible. Dry chemicals are used to extinguish any fires. The mud and slime materials associated with recovery of heavy minerals from most sand deposits constitute a disposal problem.

Guidelines: As of 1994 there were no Canadian water quality guidelines.

Discussion:

Zirconium was detected in six lakes within the study area. The distribution of zirconium concentrations shows no distinct differences between the Slave and Bear Provinces. The relatively higher concentrations observed appear to be site specific. The maximum measured concentration for zirconium was 4.76 $\mu g \cdot L^{-1}$ obtained from site CA76E12DW1-2V. In all lakes retested in 1994, zirconium concentrations measured less than detection limit.

Zirconium concentration in lake water

ppb
● 0.0 - 0.1
● 0.1 - 1.0
● 1.0 <=

0   100 km
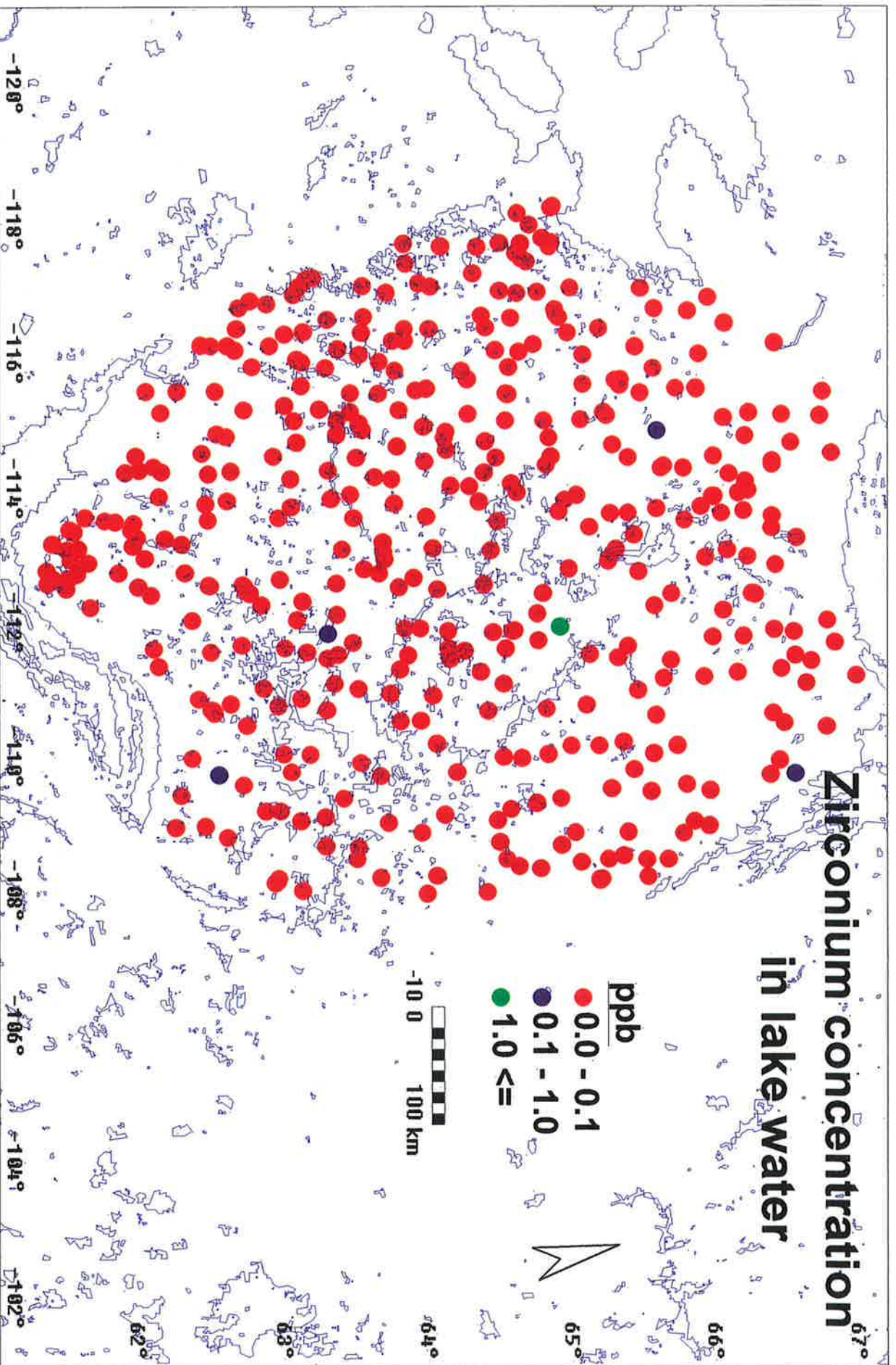
Molybdenum

Symbol: Mo

Background: Molybdenum is mined both as a primary ore mineral and as a by-product of copper mining. Molybdenum has a high affinity for sulphur which in turn produces molybdenite, the most common molybdenum bearing mineral. Molybdenum is said to be essential to nitrogen-fixing plants. It is also said to be cyclic, in that it results from the hydrological and lithological cycles. Molybdenum can enter the aquatic environment in several different ways such as through the mining and milling of molybdenum, uranium, and copper ores, burning of fossil fuels, weathering, and through the use of fertilizers. Some forms of molybdenum are soluble. However, according to the Canadian Water Quality Guidelines, the concentration of molybdenum for most surface fresh waters is less than 1000 $\mu g \cdot L^{-1}$, more typically between 0.03 and 10 $\mu g \cdot L^{-1}$. In fresh water sediments, the concentration of molybdenum could be as high as 20 $\mu g \cdot g^{-1}$. Concentrations of molybdenum in both water and sediment will tend to be higher in areas of mineralization.

Common Minerals:

Molybdenite	MoS_2
Molybdite	MoO_3
Wulfenite	$PbMoO_4$
Powellite	$CaMoO_4$

Major Uses: As a hardening alloy, cutting and wear-resistant material, electronic semiconductor devices, lubricants, paints and pigments.

Hazards: Most of the hazards associated with molybdenum result from the mining process. Sulphur oxide is released into the atmosphere as a result of the roasting process of molybdenite to molybdic oxide.

Guidelines: As of 1994 there were no Canadian water quality guidelines.

Discussion:

Molybdenum concentrations are within the 0.03-10 $\mu g \cdot L^{-1}$ range characteristic of most surface freshwater. The observed distribution pattern of molybdenum indicates higher concentrations in the Bear province. The relatively higher molybdenum concentration observed in the Slave province occurs in an area identified as being impacted by previous mining activity as well as currently operating lodges and outfitters (Acres International Limited, 1993). More specifically, Thor Lake. The maximum measured concentration for molybdenum was 5.78 $\mu g \cdot L^{-1}$ obtained from site CA86J7CW1-3V which also contains high concentrations of gallium, yttrium, lanthanum and cerium metals. Molybdenum concentrations were higher in 23 of 32 lakes retested in 1994.

Molybdenum concentration in lake water
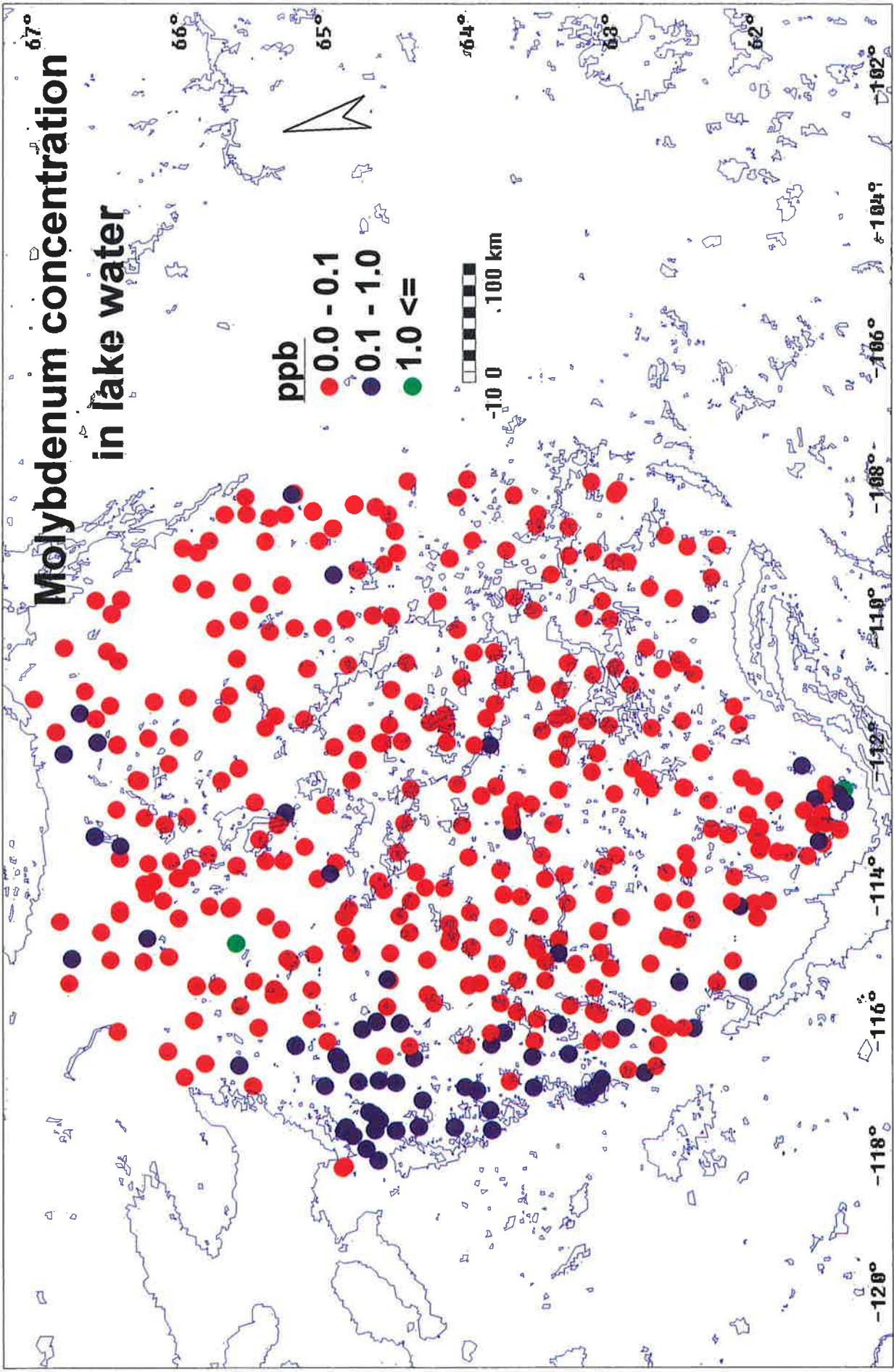
Tin

Symbol: Sn

Background: Tin is a relatively rare element. The principal ore of tin is cassiterite. The main sources are placer and alluvial deposits, derived from weathering and erosion of vein and disseminated replacement tin deposits. Tin deposits are associated with granite, granodiorite, quartz monzonite, and related porphyries and pegmatites. Tin does not readily associate with other elements. Although tin is considered nontoxic and nonreactive, it is known to be methylated in the aquatic environment. Tin is soluble in fresh waters at very low concentrations. According to the Standard Methods for the Examination of Water and Wastewater, the concentration of tin in most surface fresh waters is less than 100 $\mu g \cdot L^{-1}$. Concentrations will tend to be higher in areas of mineralization and process waste waters.

Common Minerals:

Cassiterite	SnO_2
Stannite	Cu_2SnFeS_4
Teallite	$PbSnS_2$
Montesite	$PbSn_4S_5$
Stokesite	$CaSnSi_3O_9 \cdot 2H_2O$

Major Uses: As a metal, solders, alloys of bronze and brass, and chemical compounds.

Hazards: The hazards associated with tin are in the mining and smelting processes. The smelting of tin ores produce SO_2 gases.

Guidelines: As of 1994 there were no Canadian water quality guidelines.

Discussion:

Tin concentrations, although detected in only three of 374 lakes, were less than 100 $\mu g \cdot L^{-1}$ characteristic of most surface freshwaters. The maximum concentration measured 1.06 $\mu g \cdot L^{-1}$ at site CA86I11BW1 which also contains the highest measured concentrations of antimony and lead metals. The three detected sites in the Bear Province appear to be site specific. In lakes retested in 1994, the concentration of tin measured less than detection limit.

Tin concentration
in lake water

ppb
● 0.0 - 0.1
● 0.1 - 1.0
● 1.0 <=

10 0   100 km
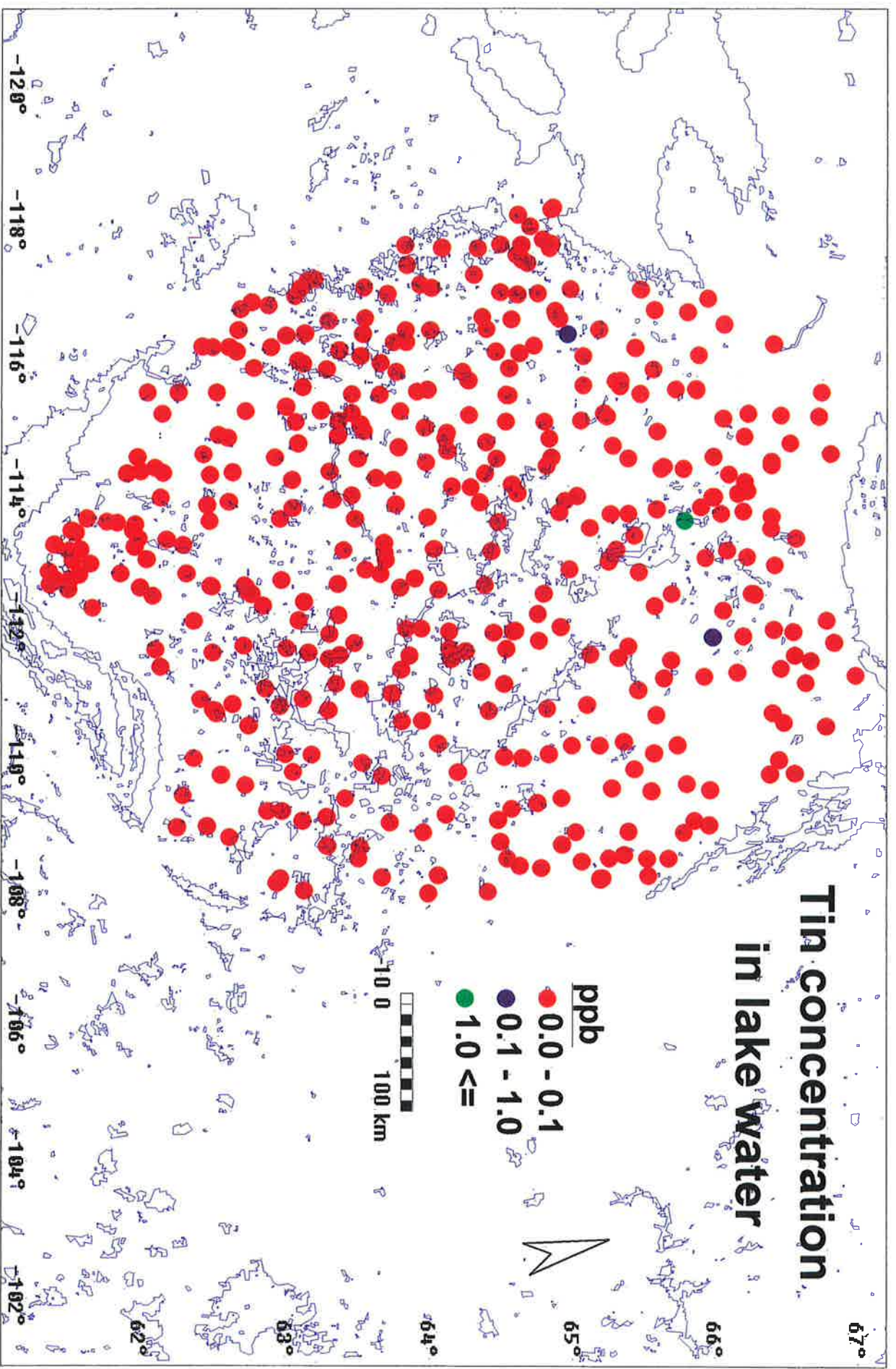
Antimony

Symbol: Sb

Background: Antimony is a relatively rare element which combines readily with sulphates. Most antimony deposits are formed by precipitation from low temperature hydrothermal solutions at shallow depths. Although produced primarily from ores associated with igneous activity, it is also produced as a smelter byproduct of base metal ores. Antimony finds its way into the aquatic environment through the weathering of rocks and soil, mining effluents, municipal and industrial discharges, and atmospheric emissions. Little is known about the behaviour of antimony during weathering and erosion. According to the Canadian Water Quality Guidelines, the concentration of antimony in most surface fresh waters range from <1.0 - 9100 $\mu g \cdot L^{-1}$ in the Atlantic to <10.0 - 200 $\mu g \cdot L^{-1}$ in the Pacific.

Common Minerals:

Stibnite	Sb_2S_3
Kermesite	Sb_2S_2O
Senarmontite	Sb_2O_3
Jamesonite	$2PbS \cdot Sb_2S_3$
Boulangerite	$5PbS \cdot 2Sb_2S_3$

Major Uses: As a metal - alloying constituent of lead and other metals, storage batteries, printing metal, solder and ammunition.

As a non-metal - fire retardant, industrial chemicals, rubber and plastic products and ceramic and glass products.

Hazards: The hazards associated with antimony are mostly related to mining and processing of lead and lead-silver ores.

Guidelines: As of 1994 there were no Canadian water quality guidelines.

Discussion

Antimony concentrations are within the 1-200 $\mu g \cdot L^{-1}$ characteristic of most natural freshwaters. The distribution pattern of antimony concentration is unlike any other metal in the study area. The lakes in the southeast portion (Slave Province) measure less than detection limit. The resulting pattern is probably a function of geology. The maximum measured concentration was 12.54 $\mu g \cdot L^{-1}$ at site CA86IBW1. This site also contains the highest measured concentrations of lead and tin. Antimony concentrations were higher in 26 of 32 lakes retested in 1994.

Antimony concentration in lake water

ppb
● 0.0 - 0.1
● 0.1 - 1.0
● 1.0 <=
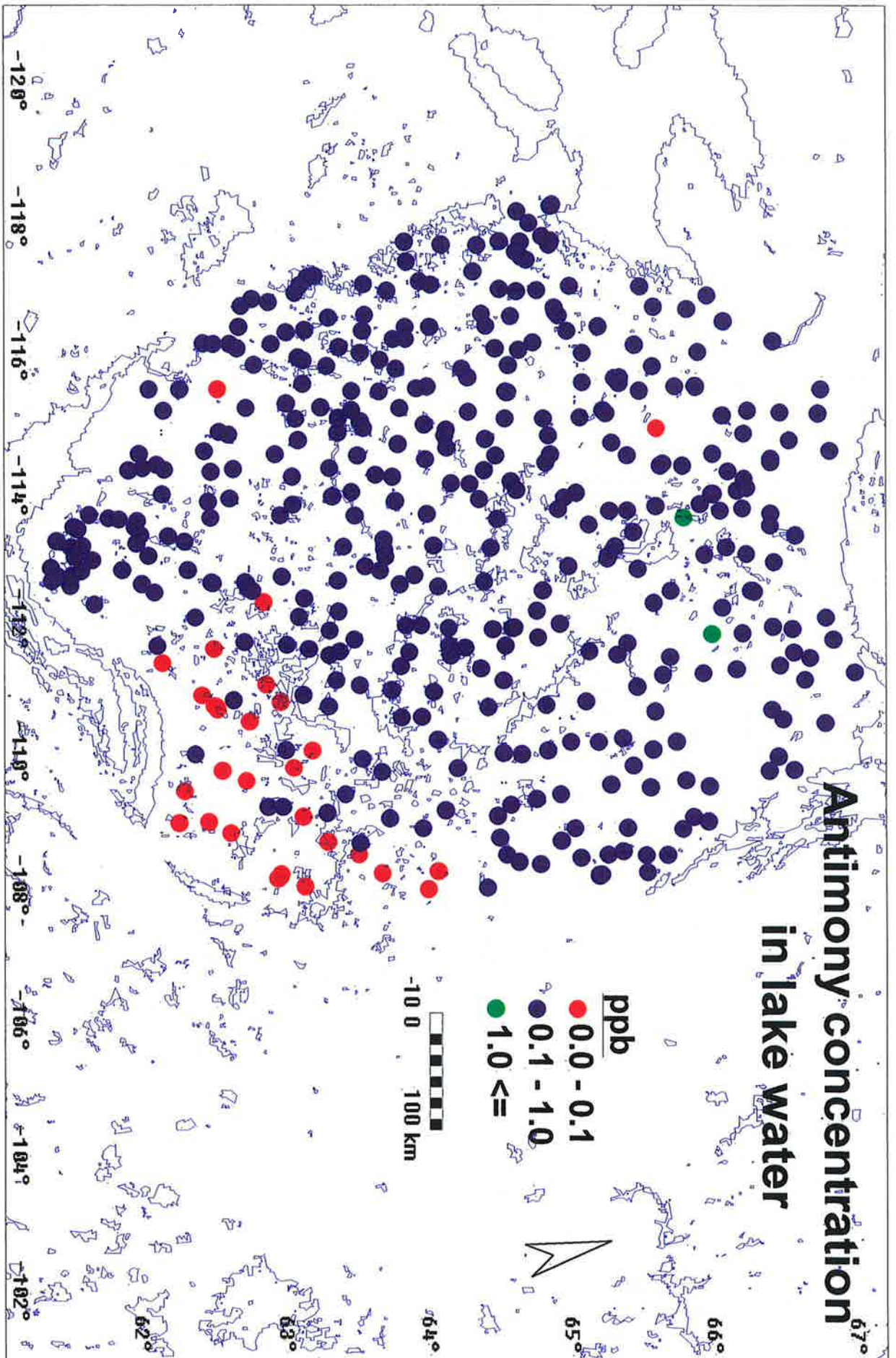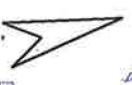
Lanthanum

Symbol: La

Background: Lanthanum is a very reactive rare earth of the lanthanide series. It occurs in highest concentrations in rare earth minerals that favour light rare earths generally nitrates, sulphates, carbonates, niobates, and tungstates with high cation coordination number, often containing structural halogens and alkali metals. The major source of lanthanum has been from monazite in beach sands. Monazite is very resistive to weathering. Information on the presence and behaviour of lanthanum in the aquatic environment is not known at this time. However, it is expected that, if it is present at all in the aquatic environment, it would exist in trace quantities ($\mu g \cdot L^{-1}$) in water with higher concentrations expected in sediment.

Common Minerals:

Monazite	(light rare earths, Th) PO_4
Bastnaesite	(light rare earths, Th) FCO_3

Major Uses: Electronics, optical filters, misch metal (mixed rare earth alloy) and as an oxide polishing powder.

Hazards: Most of the hazards associated with lanthanum are a result of titanium mining or uranium and molybdenum production.

Guidelines: As of 1994, there were no Canadian water quality guidelines. However, guidelines exist for associating or contributing elements of uranium and molybdenum.

Discussion

Although little is known about the behaviour of lanthanum in the aquatic environment, relatively higher concentrations are observed in the Bear Province. It is uncertain whether the 11 lakes which measure higher than detection limit is of any significance. The maximum measured concentration for lanthanum was 1.25 $\mu g \cdot L^{-1}$ at site CA86J7CW1-3V. This site also contains the highest measured concentrations of gallium, yttrium, molybdenum and cerium metals. In lakes retested in 1994, Lanthanum concentrations were unchanged.

Lanthanum concentration in lake water

ppb
- 0.0 - 0.1
- 0.1 - 1.0
- 1.0 <=

0 100 km
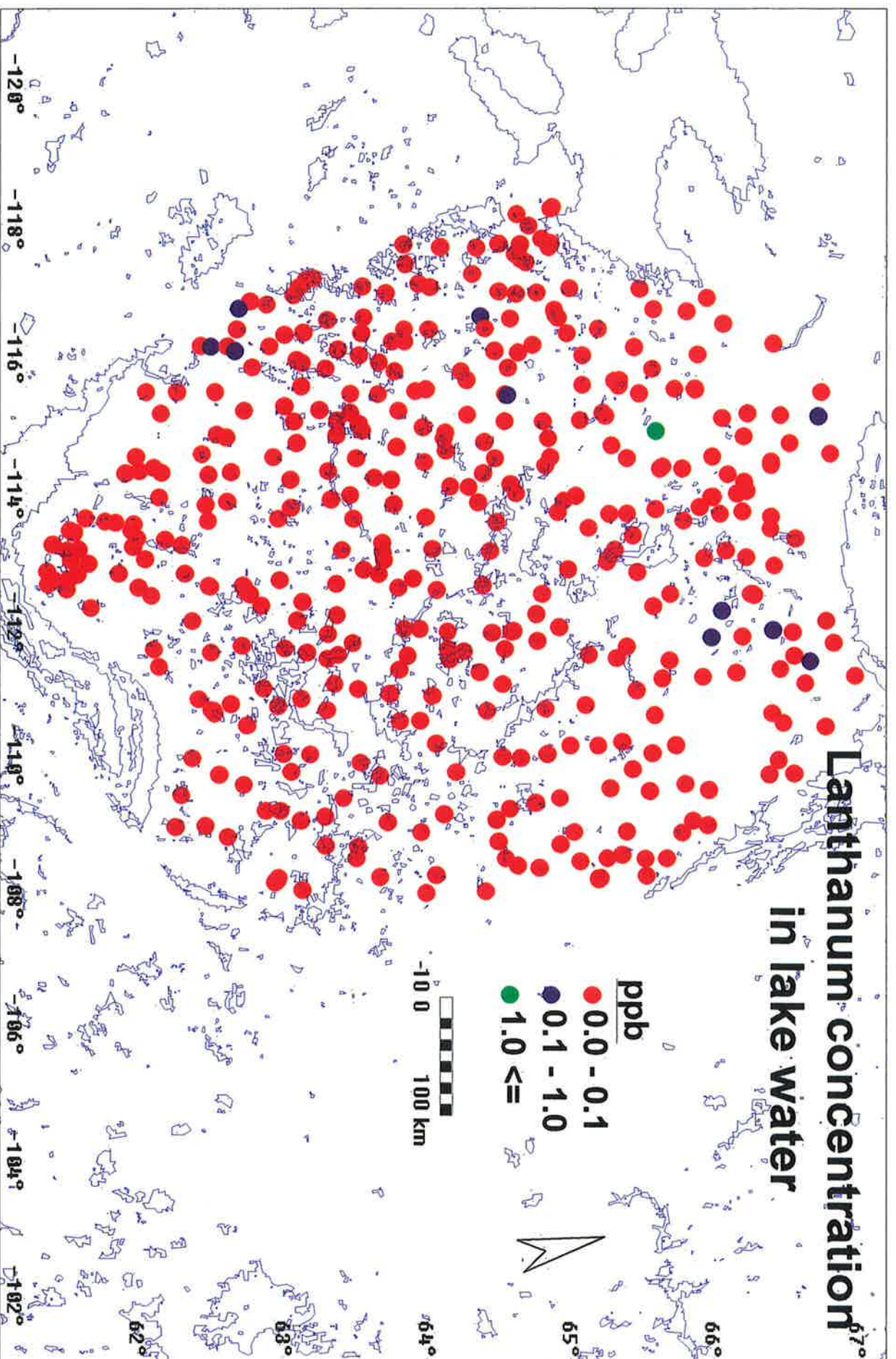
Cerium

Symbol: Ce

Background: Cerium is a very reactive rare earth of the lanthanide series. It occurs in highest concentrations in rare earth minerals that favour light rare earths generally nitrates, sulphates, carbonates, niobates, and tungstates with high cation coordination number, often containing structural halogens and alkali metals. The major source of cerium comes from monazite which is found in beach sands. Monazite is very resistive to weathering. Information on the presence and behaviour of cerium in the aquatic environment is not known at this time. However, it is expected that if it is present at all in the aquatic environment that it would exist in trace quantities ($\mu g \cdot L^{-1}$) in water with higher concentrations expected in sediment.

Common Minerals: Monazite   (light rare earths, Th) PO_4

                            Bastnaesite   (light rare earths, Th) FCO_3

Major Uses: Electronics, optical filters, misch metal (mixed rare earth alloy) and as an oxide polishing powder.

Hazards: Most of the hazards associated with cerium are a result of titanium mining or uranium and molybdenum production.

**Guidelines:**   As of 1994, there were no Canadian water quality guidelines. However, guidelines exist for associating or contributing elements of uranium and molybdenum.

Discussion:

Although little is known about cerium in the aquatic environment it was detected in seven lakes. It is uncertain if the detected cerium concentrations be considered significant to the study area. The distribution pattern of cerium concentrations does not distinguish the Slave from the Bear Province. The higher concentrations observed appear to be site specific. The maximum measured concentration for cerium was 2.74 $\mu g \cdot L^{-1}$ from site CA86J7CW1-3V. This site also contains the highest measured concentrations of gallium, yttrium, molybdenum and lanthanum metals. Cerium concentration, were lower or the same in 30 of 32 lakes retested in 1994.

Cerium concentration
in lake water

ppb
- 0.0 – 0.1
- 0.1 – 1.0
- 1.0 <=

100 0   100 km
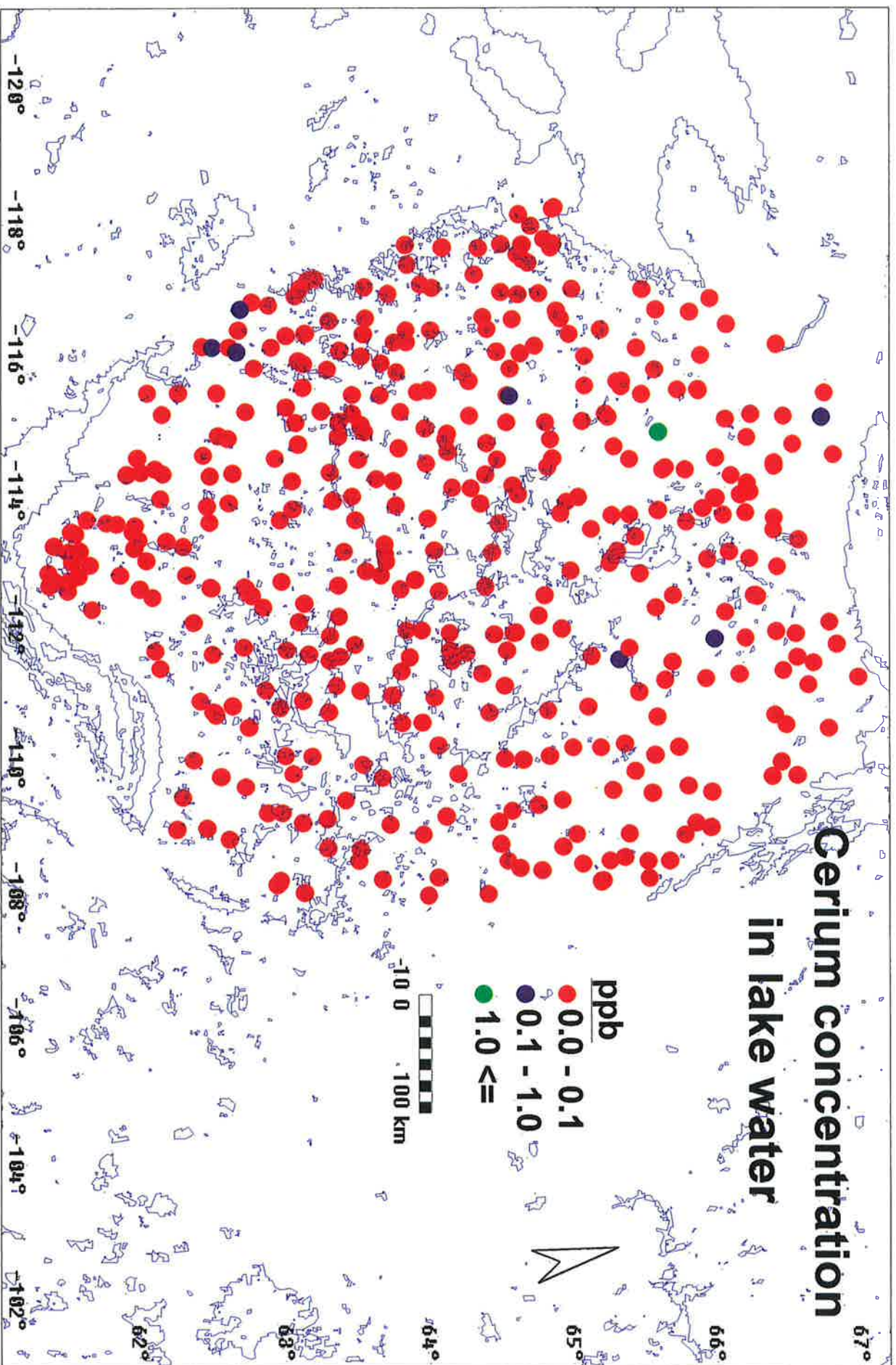
QUALITY ASSURANCE/ QUALITY CONTROL (QA/QC)

Field and travel blanks

The purpose of the field and travel blanks was to determine if contamination is occurring as a result of the sampling environment or sample handling techniques. Physical and major ions measured less than detection. Small variances are exhibited in nutrient parameters. According to the laboratory, the relatively high concentration of antimony (0.20 μg·L^{-1}) is characteristic of the type one water produced in the laboratory.

Triplicate

The triplicate samples illustrate uniformity and precision in sampling and laboratory techniques. Poor sampling handling of sample CA76D12DW1-3T resulted in high readings. It is possible that the sample was mislabeled or contaminated. One possibility is that the higher turbidity value might have been a factor.

Vertical

There is no significant vertical variability in physical and major ion parameters. The differences noted in nutrient parameters may be attributed to the biological process occurring beneath the surface or due to lake turnover. With the exception of titanium, there is no significant vertical variability in metals. It is uncertain why titanium values fluctuate vertically in the water column.

Horizontal

There is no significant horizontal variability in physical and major ion parameters or nutrients within the lakes sampled. The low alkalinity value of sample CA86F5CW1-1H is a laboratory reporting error because there is no significant difference in the parameters that contribute to alkalinity. The significant differences of metal concentration is very likely attributed to the geology in contact with water at that particular location within the lake.

CONCLUSION

The overview of water quality within the Slave Structural Province area is a "snapshot" of the current existing conditions of water quality. The use of GIS technology provides a visual representation of these current conditions. The geographic display simplifies identification of anomalous areas that occur naturally or as a result of impacts. Notable differences are detectable even in extreme low concentration such as $\mu g \cdot L^{-1}$ (ppb). However, caution should be used in viewing the visual representations because of the nature of GIS. Only the last layer presented is displayed, and therefore may not represent the data accurately. Areas of interest should always be checked against the real data.

In general, water chemistry between the Bear and Slave Provinces, although characteristic of most natural surface waters, is measurably different. With the exception of pH and turbidity, physical and major ions were notably higher in the Bear Province. Nutrient parameters showed no significant differences. However, in lakes retested, reactive silica concentrations decreased when potassium concentrations increased. Total coliforms exceeded water quality guidelines in half of the lakes tested. Of the 26 metal parameters detectable, copper, manganese, and strontium measured higher in the Slave Province. Yttrium, cobalt, cerium, scandium, arsenic, zinc, zirconium, nickel, gallium, iron and lead are all site specific. The distribution of rubidium concentrations appears to be limited by the tree line. All other metals measured higher in the Bear Province. Although concentrations are characteristic of most surface freshwater, specific sites exist where the concentration exceeds the limits outlined in the Canadian Water Quality Guidelines.

The notable differences in horizontal variability might suggest that the geology of a particular location within a lake is being reflected in the water. Vertical variability in several sites might suggest either lake turnover or lake stratification.

APPENDIX A

SAMPLING EQUIPMENT

FIELD

Hanna - portable Piccolo pH metre
Oakton - portable conductivity meter (0 - 1999μS)
Van Dorn - 3 litre horizontal water sampler
Ekman - light weight dredge
Whirlpac - sterile sample bags
EPA - pre-cleaned high density polyethylene bottles
Thermometer - alcohol (-40° - + 40°)
Spatula - stainless steel
Basin - Polyethylene
Type I water
Nitric Acid - 5%
Depth finder (Hummingbird)
Sample preservatives
Coleman coolers
Note book
Pen - waterproof ink
Watch
GPS (global positioning system)
Maps - NTS scale 1:250,000
beaker - 500 mL
CESSNA 185 FLOAT PLANE

SAMPLE BOTTLES AND PRESERVATIVES

METALS	- 500 mL (PLASTIC)	5 mL 1:1 NITRIC ACID
MERCURY	- 150 mL (GLASS)	2 mL 1:1 SULPHURIC ACID 1 mL 5 % POTASSIUM DICHROMATE
BACTERIOLOGICAL	- 250 mL (HDPE) AUTOCLAVE	
PHYSICALS	- 1000 mL (HDPE)	
NUTRIENTS	- 500 mL (HDPE)	
CYANIDE	- 500 mL (HDPE)	5 mL 10% SODIUM HYDROXIDE

APPENDIX B

SAMPLE NUMBERING

Figure 5 illustrates the logic behind this numbering system. For example, in sample number CA85I11DW1-2T, the first two letters "CA" identify the project as Central Arctic. The following number, letter, number combination CA<u>85I11</u>DW1-2T, identifies the 1:50,000 NTS map sheet. The next letter "D", CA85I11<u>D</u>W1-2T, represents the map sheet quadrant in which the sample location can be found. The quadrants were constructed by dividing the 1:50,000 scale map sheet into four quarters or quadrants. Each quadrant is labelled in a clockwise direction beginning with A in the lower right hand quadrant (same method used by the Department of Energy Mines and Resources Canada for the National Topographic System). The next letter "W" (CA85I11D<u>W</u>1-2T) represents the sample media as being water. The next number represents the numeric sequence in which the site was established in that particular quadrant e.g. CA85I11DW<u>1</u>-2T indicates this as being the first site established in the A quadrant of map sheet 85-I-11.

85I
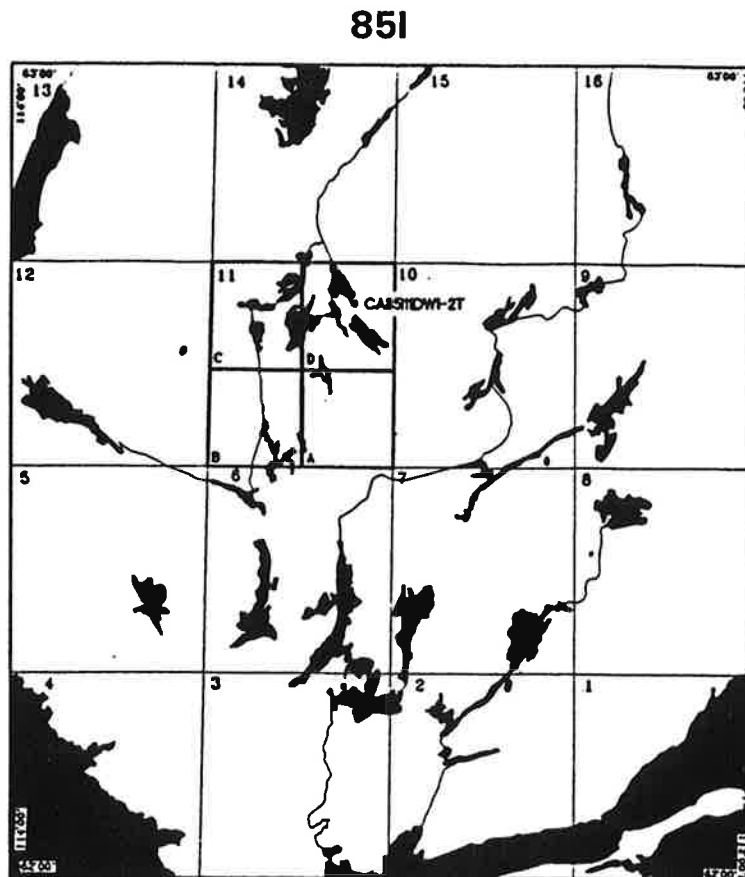
CA85I11DW1

FIGURE 5. SAMPLE NUMBERING

147

APPENDIX C

QUALITY ASSURANCE / QUALITY CONTROL SAMPLE DESCRIPTION

FIELD BLANK (F)
A field blank consists of filling a set of sample bottles with ultra pure distilled water and adding the appropriate preservative in the field at one of the sample sites each day. The purpose of the field blank is to determine if samples are being contaminated from the sampler as well as inconsistencies in sampling techniques.

TRAVEL BLANK (TR)
A travel blank consists of filling a set of sample bottles in the laboratory or on the lake shore with ultra pure distilled water and adding the appropriate preservative prior to going in the field. These sample bottles remain on the sample trip for the remainder of the day. The purpose of the travel blank is to determine if the samples are being contaminated through transporting and handling of sealed samples.

DUPLICATE SAMPLE (D)
A duplicate sample consists of splitting a sample in half thereby getting two identical samples from the same Van Dorne grab sample. All sample sets are treated with the appropriate preservative. The purpose of a duplicate sample is to determine inconsistencies in the laboratory analysis as well as in precision and accuracy.

TRIPLICATE SAMPLE (T)
A triplicate sample consists of collecting three samples from the exact same sampling site. In order to collect a triplicate sample the Van Dorne water sampler is lowered down to sample depth three times, once for each sample set. All sample sets are treated with the appropriate preservative. The purpose of the triplicate sample is to determine precision and accuracy of the sampler as well as the laboratory.

HORIZONTAL VARIABILITY SAMPLE (H)
A horizontal variability sample consists of taking three to five sample sets at the same depth but at different locations horizontally along a transect going from one end of a lake to the other end. All sample sets are treated with the appropriate preservative. The purpose of the horizontal variability sample is to determine homogeneity (ie. variance in lake water chemistry in going from one end of the lake to the other).

VERTICAL VARIABILITY SAMPLE (V)
A vertical variability sample consists of taking three sample sets vertically through the water column. Sample sets are collected using a horizontal Van Dorne water sampler near surface, at mid depth and near the lake bottom. All sample sets are treated with the appropriate preservative. The purpose of the vertical variability sample is to determine if there is any variance in the water chemistry vertically within the water column, as well as test for homogeneity.

APPENDIX D

INSTRUMENTATION / METHOD OF ANALYSIS

Physicals & Major Ions

pH	Radiometer VIT 90 specific pH electrode
specific conductivity	Radiometer VIT 90 specific pH electrode
turbidity	HACH Ratio XR
colour	HELLIGE Aqua Tester
filterable residue (suspended solids)	Glass Fibre Filtration (porosity C), 0.45μm
non filterable residue (total dissolved solids)	Glass Fibre Filtration (porosity C), 0.45μm
calcium	FAA (Flame Atomic Absorbtion)
magnesium	FAA (Flame Atomic Absorbtion)
total hardness as ($CaCO_3$)	calculation
total alkalinity as ($CaCO_3$)	Radiometer VIT 90 specific pH electrode
sodium	FAA (Flame Atomic Absorbtion)
potassium	FAA (Flame Atomic Absorbtion)
chloride	Automated Technicon / colorimetric
sulphate	Automated Technicon / colorimetric

Nutrients

Ammonia as (nitrogen)	Auto Analyzer / colorimetric
nitrate and nitrite	Auto Analyzer / colorimetric
total phosphorous	Auto Analyzer / colorimetric
reactive silica.	Auto Analyzer / colorimetric

Cyanide

Total cyanide	digestion / distillation / colorimetry

Bacteriological

Total coliform	Filtration HA & media (M - EMDO AGAR) incubation @ 35°C
Faecal coliform	Filtration HA & media (M - FC AGAR) incubation @ 44.5°C

Mercury

Total mercury	Stannous Chloride reduction / cold vapour Atomic Absorption detection

Metals

Arsenic	PE 2380 flame less A.A. Spectrophotometer / Hydride Generation
Iron	PE 5000 FAA (flame) Spectrophotometer
All other metals	PE /Sciex Elan 5000 ICP-MS

QaQc

Laboratory quality assurance/quality control is available upon request from the DIAND Water Resources Laboratory.

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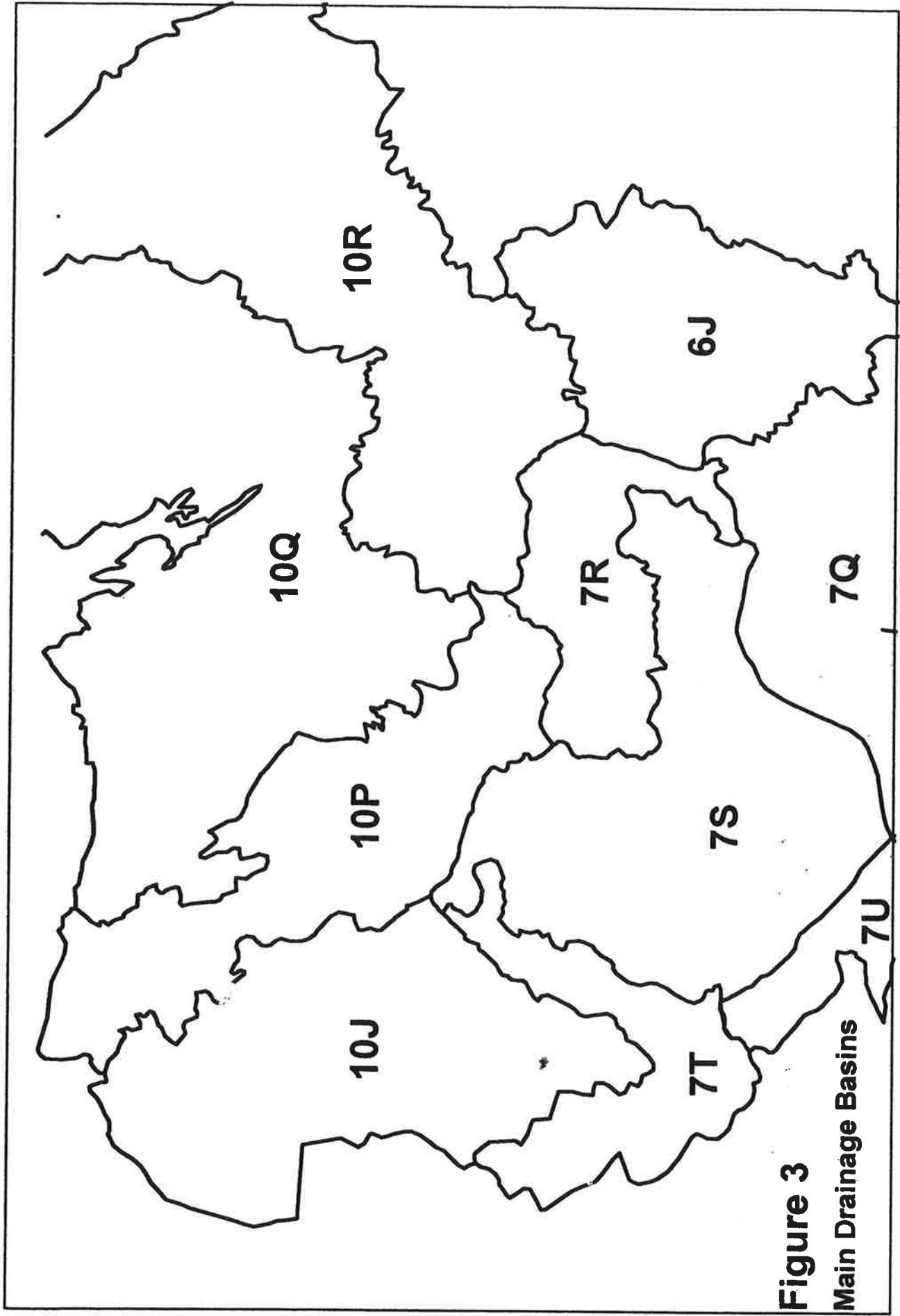Weast, Robert C. (Ed.), 1974, CRC Handbook of Chemistry and Physics, 55th Edition. Cleveland, Ohio: CRC Press.

Figure 3
Main Drainage Basins

Figure 4
1:250000 NTS
MAPSHEETS

Limnological characteristics of 56 lakes in the Central Canadian Arctic Treeline Region

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ABSTRACT

Measured environmental variables from 56 lakes across the Central Canadian Treeline Region exhibited clear limnological differences among subpolar ecozones, reflecting strong latitudinal changes in biome characteristics (e.g. vegetation, permafrost, climate). Principal Components Analysis (PCA) clearly separated forested sites from tundra sites based on distinct differences in limnological characteristics. Increases in major ions and related variables (e.g. dissolved inorganic carbon, DIC) were higher in boreal forest sites in comparison to arctic tundra sites. The higher values recorded in the boreal forest lakes may be indirectly related to differences in climatic factors in these zones, such as the degree of permafrost development, higher precipitation and runoff, duration of ice-cover on the lakes, and thicker and better soil development. Similar to trends observed in DIC, substantially higher values for dissolved organic carbon (DOC) were measured in boreal forest lakes than in arctic tundra lakes. This was likely due to higher amounts of catchment-derived DOC entering the lakes from coniferous leaf litter sources. Relative to arctic tundra lakes, boreal forest lakes had higher nutrient concentrations, particularly total nitrogen (TN), likely due to warmer conditions, a longer growing season, and higher precipitation, which would enhance nutrient cycling and primary productivity. Results suggest that modern aquatic environments at opposite sides of the central Canadian arctic treeline (i.e. boreal forest and arctic tundra) exhibit distinct differences in water chemistry and physical conditions. These limnological trends may provide important information on possible future changes with additional warming.

Key words: arctic treeline, climatic change, dissolved inorganic carbon, dissolved organic carbon, major ions, nutrients

1. INTRODUCTION

Circumpolar treeline regions are typically characterized by sharp changes in climate and vegetation. These steep gradients are often reflected by changes in the physical and chemical properties of aquatic systems as one crosses from forested to tundra environments (e.g. Pienitz *et al*. 1997a, b). Changes in climate are predicted to be most pronounced at these higher latitude regions, as suggested by General Circulation Models (GCMs) (Foley *et al*. 1994; Bonan *et al*. 1995) as well as by paleoecological data (Overpeck *et al*. 1997; Mann *et al*. 1999). These aquatic ecosystems will likely be affected both directly (e.g. water temperature increases, changes in precipitation/evaporation ratios) and indirectly (e.g. increased duration of ice-free season, change in the length and stability of lakewater stratification, permafrost thawing, and changes in the distribution of catchment vegetation) by climatic warming (Slaughter *et al*. 1995; Rouse *et al*. 1997; Schindler 1997; Serreze *et al*. 2000).

Limnological studies in the Central Canadian Arctic Treeline Region are still relatively rare (Healey & Woodall 1973; Welch & Legault 1986; Pienitz *et al*. 1997a; Rühland & Smol 1998) and point to a need to extend these studies within this relatively unknown but

important ecotonal region. Due to the vastness of the treeline region of Canada's Northwest and Nunavut Territories, it is not surprising that distinct differences in physical settings exist (e.g. local geology, hydrology, etc.). As a consequence, lakewater chemistry can be quite variable both within and among the different vegetational/climatic ecozones. These dissimilarities were highlighted in a previous study (Rühland & Smol 1998) where the 70 study lakes spanned two distinct geological provinces (Bear and Slave provinces) resulting in differences in both chemistry and aquatic biota (diatoms). In this present study, our lakes represent a transect northeast from this previous study, and as a result is entirely contained within the Slave Geological Province, thereby minimizing the influence of geology, and maximizing any climatic changes along the vegetational gradient.

Comparisons of limnological studies carried out across the circumpolar treeline region has highlighted many similarities as well as differences in the trends and relationships in lakewater chemistry from region to region. For example, major cations (e.g. calcium, sodium, magnesium, potassium) and related variables (alkalinity, DIC, pH) were found to increase along latitudinal transects from arctic tundra to boreal forest catchments in most regions with the exception of Fennoscandia (Weckström *et al*. 1997a, b; Blom *et al*. 1999) and the
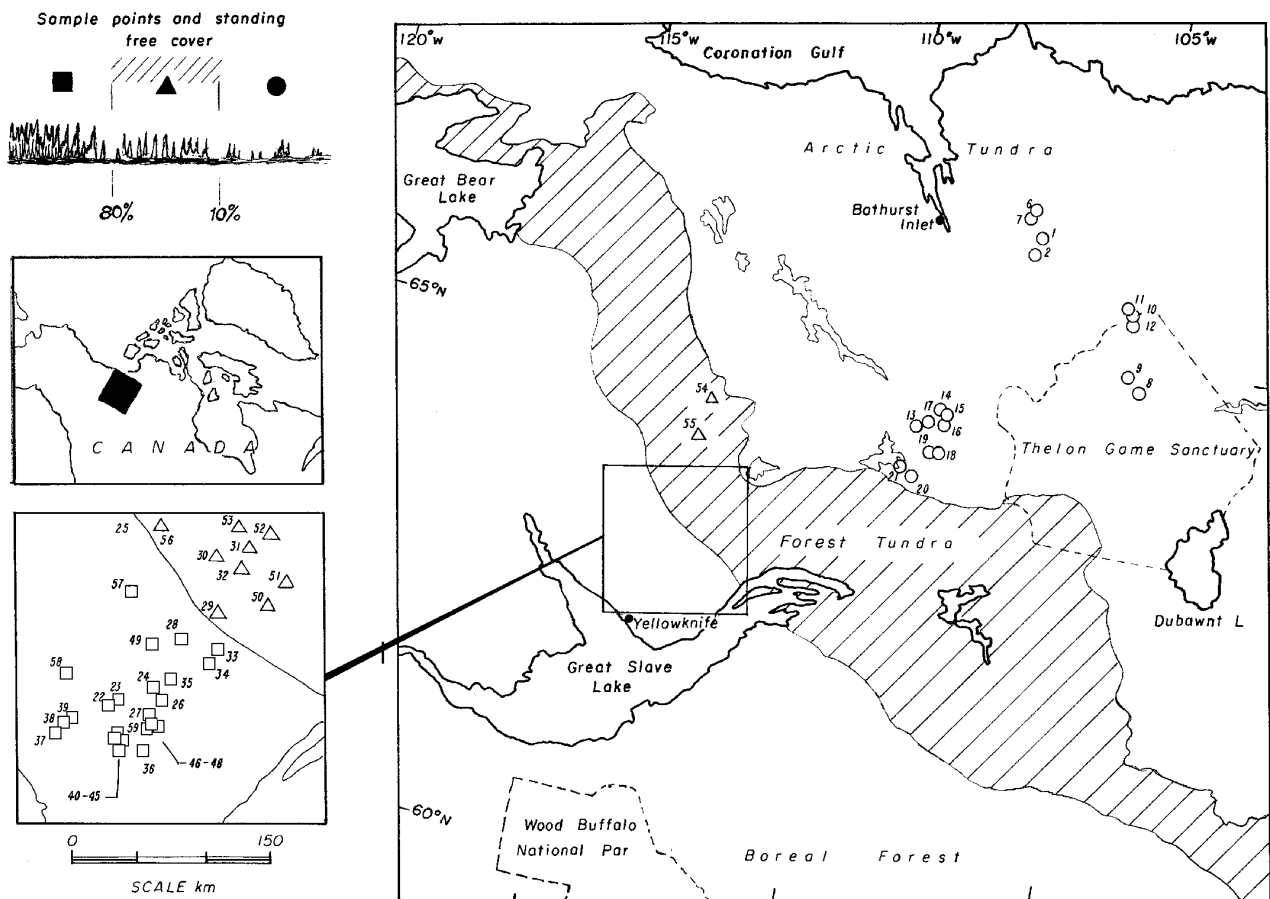
Fig. 1. Location of the 56 study lakes showing their distribution across the three vegetational zones (boreal forest, forest-tundra, and arctic tundra).

Lena and Pechora regions of Siberia (Duff *et al.* 1998). These inconsistencies were likely related to differences in geology, hydrology, human impact, physiographic relief, proximity to the ocean, vegetation, and climate. Similarly, changes in DOC and in nutrient relationships have also been reported (where measured) to be closely related to catchment vegetation (Pienitz 1993) and availability of phosphorus from bedrock materials (Downing & McCauley 1992; Hamilton *et al.* 2001). However, given the vastness of subarctic and arctic regions (approximately six million km^2) in North America (Rouse *et al.* 1997), coupled with the paucity of limnological studies, it is important that research continues in these remote regions to contribute to our understanding of the natural variability of these sensitive freshwater ecosystems and their responses to environmental changes.

This paper explores the relationships between chemical and physical properties of 56 lakes and 27 environmental variables within the central treeline region in Canada's Nunavut and Northwest Territories. Unlike our previous paper (Rühland & Smol 1998), this study includes important additional limnological measurements including nutrients (e.g. TN, total phosphorus

(TP), DIC, and DOC). As the results reported here are part of a more extensive paleoecological study that examines the relationship between diatom distributions and these environmental gradients (Rühland & Smol 2002; Rühland *et al.* 2003), these data are essential for a better understanding of some of the fundamental differences among these arctic lakes, especially as these variables are of great importance to aquatic biota. Our results show that spatial gradients (e.g. temperature, precipitation, vegetation, permafrost) across the central Canadian treeline were often closely reflected in the lakewater chemistry and that distinct limnological differences exist among boreal ecozones. The clear relationships observed among ecozone characteristics and limnological variability along the climatic/vegetational gradient reported here will be compared to other limnological studies of northern treeline regions.

2. STUDY AREA

The 56 study lakes were sampled along a southwest to northeast transect from the Yellowknife area (62°32.72' N, 114°07.13' W) towards Bathurst Inlet (66°41.3' N, 104°55.9' W) in the central Canadian Subarctic (Fig. 1, Tab. 1). This lakeset crosses strong

Tab. 1. Geographical co-ordinates and vegetational zonations of the 56 study sites.
● = Arctic Tundra, Δ = Forest-Tundra, ♦ = Boreal Forest.

	SITE	LAT(N)	LONG(W)		SITE	LAT(N)	LONG(W)
●	TK-1	66°28.58'	104°49.52'	Δ	TK-32	63°29.05'	112°12.63'
●	TK-2	66°20.90'	104°56.45'	♦	TK-33	63°12.97'	112°36.05'
●	TK-6	66°41.31'	104°55.86'	♦	TK-34	63°07.64'	112°47.67'
●	TK-7	66°41.23'	104°55.89'	♦	TK-35	63°02.72'	113°06.46'
●	TK-8	64°41.28'	102°26.42'	♦	TK-36	62°45.75'	113°28.63'
●	TK-9	64°53.37'	102°45.07'	♦	TK-37	62°32.72'	114°07.13'
●	TK-10	65°29.42'	103°22.01'	♦	TK-38	62°33.59'	114°01.34'
●	TK-11	65°33.62'	103°23.25'	♦	TK-39	62°32.89'	113°57.13'
●	TK-12	65°22.50'	103°33.45'	♦	TK-40	62°32.87'	113°56.09'
●	TK-13	64°36.15'	107°26.23'	♦	TK-41	62°34.09'	114°01.74'
●	TK-14	64°35.90'	107°05.93'	♦	TK-42	62°32.75'	113°53.40'
●	TK-15	64°35.74'	107°05.49'	♦	TK-43	62°31.49'	113°50.20'
●	TK-16	64°35.60'	107°05.30'	♦	TK-44	62°31.49'	113°50.20'
●	TK-17	64°35.69'	107°05.01'	♦	TK-45	62°31.01'	113°46.76'
●	TK-18	64°09.39'	107°49.48'	♦	TK-46	62°30.44'	113°39.91'
●	TK-19	64°09.39'	107°49.48'	♦	TK-47	62°40.69'	113°51.03'
●	TK-20	64°09.00'	107°49.00'	♦	TK-48	62°48.27'	113°26.12'
●	TK-21	64°09.00'	107°49.00'	♦	TK-49	63°10.99'	112°22.83'
♦	TK-22	62°42.03'	113°59.19'	Δ	TK-50	63°18.48'	111°58.27'
♦	TK-23	62°43.73'	113°49.53'	Δ	TK-51	63°32.91'	111°42.34'
♦	TK-24	62°54.04'	113°13.15'	Δ	TK-52	63°35.61'	112°25.12'
♦	TK-25	63°04.81'	113°02.88'	Δ	TK-53	63°42.54'	112°34.40'
♦	TK-26	62°54.14'	113°23.22'	Δ	TK-54	64°30.68'	112°41.47'
♦	TK-27	62°49.23'	113°33.75'	Δ	TK-55	64°06.01'	113°01.54'
♦	TK-28	63°15.31'	113°00.22'	Δ	TK-56	63°41.42'	113°26.68'
Δ	TK-29	63°25.25'	112°39.81'	Δ	TK-57	63°20.21'	113°42.30'
Δ	TK-30	63°33.70'	112°21.21'	♦	TK-58	62°53.37'	114°04.24'
Δ	TK-31	63°37.03'	112°17.77'	♦	TK-59	62°30.19'	113°38.20'

vegetational and climatic boundaries from the boreal forest ecozone in the southwest to the arctic tundra ecozone in the northeast (Fig. 1). The region is situated on Canadian Shield bedrock consisting of gneiss, migmatite, granitoid intrusions, and metamorphosed volcanic and sedimentary rocks (Padgham & Fyson 1992). The entire study region is underlain by permafrost and ranges from discontinuous permafrost in the northern boreal forest to continuous permafrost in the arctic tundra zone and thus the boundary approximately follows the position of treeline. The soils are poorly developed as a consequence of the Pleistocene glaciation and from permafrost underlying the region today (Clayton *et al.* 1977).

Temperature and precipitation change sharply from the southern to the northern reaches of the study area, with cooler and drier conditions towards Coronation Gulf (mean January night-time temperatures of -37.5 °C, mean July day-time temperatures of 12.5 °C, and annual precipitation of 200 mm) and warmer, moister conditions towards Yellowknife (mean January night-time temperatures of -30 °C, mean July day-time temperatures of 22.5 °C, and annual precipitation of 267 mm) (Environment Canada 1990; Canada 1991). Lakes are frozen for most of the year with the average open-water period ranging from 90 days at the northernmost locale to 120 days for sites near Yellowknife (Canada 1991).

Three main vegetation zones were recognized, following the vegetational distributions presented by Timoney *et al.* (1993) and Ritchie (1993). These ecozones were delineated according to "percentage treecover" derived from field observations, topographic maps, aerial photographs, and maps derived from satellite imagery (Canada 1996). The forest-tundra transition zone (High Subarctic) lies between 10% and 80% standing tree cover and is characterized by *Picea mariana* (black spruce), *P. glauca* (white spruce), and *Larix laricuna* (larch) (Sirois 1992). The boreal forest (Low Subarctic) lies south of 80% standing tree cover and is characterized by closed-crown, conifer-dominated forest. *Picea mariana*, *P. glauca*, *Abies balsamea* (balsam fir), and *Pinus banksiana* (jackpine) are the most common conifers (Ritchie 1993). The arctic tundra (Low Arctic) lies north of 10% standing tree cover and consists predominantly of dwarf shrub vegetation including *Betula glandulosa* (resin birch), *Salix* (willow) species, and species of heath shrubs (e.g. *Arctostaphylos*, *Ledum*, and *Vaccinium*) (Ritchie 1993).

3. MATERIALS AND METHODS

3.1. Sample Collection and Environmental Data

Lakes were selected within each ecozone with the criteria that the lakes chosen were approximately similar in size and morphometry so that trends observed in en-

vironmental variables along the latitudinal transect would likely reflect changes in ecozone characteristics. Samples were collected between 7 August and 19 August 1996 for TK-1 to TK-36, and between 14 August and 23 August 1998 for TK-37 to TK-59. All lakes are unnamed and so are referred to numerically. The final lakeset consisted of 18 arctic tundra sites, 11 forest-tundra sites and 27 boreal forest sites for a total of 56 lakes (Tab. 1, Fig. 1). As many of these lakes were located in remote areas, the sites were sampled only once and therefore represent a "snapshot" of limnological conditions measured at approximately the same time of the year in two different years.

Limnological measurements were taken from the deepest part of the lake (usually at the lake centre) from an inflatable boat or off the pontoons of a helicopter. Water depth was measured using a weighted graduated rope. Where possible, temperature and conductivity measurements were taken at the surface and at the bottom of the lake using a Yellow Springs Instrument (YSI model 33) salinity, conductivity, temperature meter. Multiple readings for water temperature were taken using hand-held thermometers. Water transparency was determined using a 22 cm diameter Secchi disk. At each lake, several pH measurements were taken using hand-held meters (Hanna) that were frequently calibrated to standard buffers. Due to equipment problems, pH for several lakes were measured shortly after sampling at DIAND laboratories in Yellowknife (TK-47 to TK-59). Lake surface area (AREA) was determined from a series of topographic maps (1:50,000) that were scanned and converted into digital format using the computer program Jandel Sigmascan (v. 3.0).

Water chemistry samples were collected at approximately 30 cm beneath the water surface and were treated in the field according to procedures outlined in the Environment Canada (1994a, b) Analytical Methods Manual. Water samples for major ions and trace metals were collected in 125 ml acid pre-cleaned Nalgene bottles. Nutrient analyses (total nitrogen and total phosphorus) was filtered through Sartorius® (cellulose acetate) filters (pore size = 0.45 µm) and stored in 100 ml glass bottles. For particulate organic carbon (POC) and particulate organic nitrogen (PON), 100 to 400 ml of water was filtered through Whatman® pre-ignited glass microfibre filters (pore size = 0.45 µm). For chlorophyll-*a* (corrected and uncorrected for phaeophytin), a measured volume of water (200 to 500 ml) was filtered through Whatman® glass microfibre filters (pore size = 0.45 µm). The filters for POC, PON and chlorophyll-*a* were folded in half, placed inside plastic Petri dishes, and then wrapped in aluminum foil. The filters and water samples were packed inside storage coolers, and then transported to the National Water Research Institute (Burlington, Ontario) for analyses.

In addition to the environmental measurements mentioned above, the closest distance to 80% standing treecover (DIST) was measured for each site. Distance from treeline was measured from the northern limit of the boreal forest zone. The forest-tundra transitional zone (High Subarctic) in this study region occurs between 10% and 80% standing treecover, the arctic tundra zone (Low Arctic) lies north of 10% standing treecover, and the boreal forest zone (Low Subarctic) lies south of 80% standing treecover.

For each lake, 40 chemical and 6 physical/geographical variables were measured. These variables consisted of total phosphorus filtered (TPF), total phosphorus unfiltered (TPUF), total nitrogen (TN), soluble reactive phosphate-phosphorus (SRP), total Kjeldahl nitrogen (TKN), ammonia (NH_3), nitrite (NO_2), nitrite-nitrate (NO_2-NO_3), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), pH (pH), conductivity (COND), particulate organic carbon (POC), particulate organic nitrogen (PON), chlorophyll-*a* corrected (CHLA-corr), chlorophyll-*a* uncorrected (CHLA), dissolved silica (SiO_2), calcium (Ca), sodium (Na), magnesium (Mg), potassium (K), chloride (Cl), sulphate (SO_4), lithium (Li), barium (Ba), strontium (Sr), silver (Ag), aluminum (Al), beryllium (Be), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), vanadium (V), and zinc (Zn). Physical variables measured on site consisted of maximum lake depth (DEPTH), secchi disk depth (SECCHI), and surface water temperature (TEMP). Geographical variables included distance from treeline (DIST), latitude (LAT), and lake surface area (AREA).

3.2. Data Screening and Analysis

A total of 19 of the original 46 measured variables had numerous sites (19 to 56 sites) with values below the level of detection (BDL). These variables included Ag, Be, Cd, Co, Cr, Cu, Mo, Ni, Pb, V, Zn, NH_3, NO_2-NO_3, NO_2, CHLA-corr, and SRP. POC and PON also fall under this category as 23 of the lakes did not have this information available. Secchi disk depth was also eliminated from the dataset as numerous shallow lakes were clear to the bottom and therefore did not contribute analytically meaningful measurements (see Cumming *et al.* 1995). Three variables (Na, Mn, and Li) were run passively in the statistical analyses as they had fewer sites with values BDL (14-16 sites BDL). Total phosphorus filtered (TPF) displayed highly skewed distributions that could not be corrected through data transformations. However, as this was a potentially important variable, it was retained in the dataset and run passively in the statistical analyses. For all variables, sites that recorded several values below the detection limits were replaced with the measurement of detection for that particular variable (DIC [0.1 mg l^{-1}] one site; Fe [1.0 µg l^{-1}] one site; K [0.2 mg l^{-1}] two sites). For sites that had missing values (e.g. CHLA for boreal forest sites TK-39 and TK-48), the mean CHLA value for that ecozone was used to replace the missing measurements. The fi-

nal environmental dataset consisted of 27 variables, 18 active chemical variables (TPUF, TN, TKN, CHLA, SiO_2, SO_4, DIC, DOC, COND, pH, Ca, Mg, K, Cl, Al, Ba, Fe, and Sr), 5 physical/geographical variables (DIST, LAT, AREA, DEPTH, and TEMP), and 4 passive variables (TPF, Na, Mn, and Li).

The 27 environmental variables were tested for skewness and log transformed (with the exception of pH and TEMP) using the computer program CALIBRATE (Juggins & ter Braak 1993). A Pearson correlation matrix was used to identify the strengths of relationships between these transformed environmental variables. Groups of environmental variables that were significantly correlated ($0.01 \geq p \leq 0.05$) were identified through Bonferroni-adjusted probabilities.

Principal components analysis (PCA), a multivariate ordination technique, was used to interpret the major patterns of variation in the environmental data by examining the strengths of each variable in explaining the principal directions of variation for the 56 sites. Data were centred and standardized to mean zero and unit variance so that all environmental variables were comparable. PCA was carried out using the computer program CANOCO version 4.0 (ter Braak & Šmilauer1998). The aim of this ordination analysis was to determine the interrelationships among the chemical and physical variables across the vegetational gradient. Therefore, the geographical variables (LAT and DIST) were treated as passive variables.

4. RESULTS AND DISCUSSION

Similar to other treeline limnological studies (e.g. Pienitz et al. 1997a, b; Weckström *et al*. 1997a, b; Rühland & Smol 1998; Duff *et al*. 1998; Fallu & Pienitz 1999; Gregory-Eaves *et al*. 2000; Fallu *et al*. 2002), our measured environmental variables followed terrestrial changes across the vegetational gradient. In general, values of major ions, nutrients, DIC, DOC, TEMP, COND, Ba, Li, and Sr were highest for lakes in forested catchments and decreased with increasing latitude (Figs 2, 3, and 4). The majority of the measured variables were significantly different (p <0.05) between ecozones, in particular between the boreal forest and the arctic tundra zones (Tab. 2). The correlation matrix of the 27 environmental variables revealed high correlations among many of the measured variables (Tab. 3). As expected, the two geographic variables (DIST and LAT) were highly negatively correlated to most of the major and minor ions, nutrients, temperature, conductivity, DIC, and DOC. In contrast, Si, Fe, and Al were not significantly correlated to any of the other measured variables. Lake depth (negative correlation) and chlorophyll-*a* (positive correlation) showed significant correlations only to nitrogen (TKN and TN). Although DOC and DIC were not significantly correlated to each other, they were correlated to many of the same variables (TEMP, COND, TN, K, Na, Ca, Mg, Sr, TKN, and Ba).

Unlike DOC, DIC was significantly and positively correlated to pH, TPF, Li, and Cl.

Tab. 2. Comparison of significant differences (two-tailed t-test results) of measured variables across the three vegetational zones [Arctic Tundra (AT), Forest-Tundra (FT), and Boreal Forest (BF)]. * - indicates significantly different (p ≤0.05). Blank cells indicate there was no significant difference between ecozones. TKN = Total Kjeldahl Nitrogen. TN = Total Nitrogen unfiltered (particulate organic nitrogen (PON) + TKN + nitrite-nitrate (NO_3/NO_2). TP-UF = Total Phoshorus unfiltered.

Variable	AT *vs* FT	FT *vs* BF	AT *vs* BF
pH		*	*
DIC (mg l^{-1})		*	*
DOC (mg l^{-1})			*
COND (µS cm^{-1})		*	*
Cl (mg l^{-1})		*	*
Ca (mg l^{-1})	*	*	*
K (mg l^{-1})	*	*	*
Mg (mg l^{-1})		*	*
Na (mg l^{-1})		*	*
SO_4 (mg l^{-1})		*	*
SiO_2 (mg l^{-1})			
Chl-*a* (µg l^{-1})	*		*
TP-UF (µg l^{-1})			
TN (µg l^{-1})	*	*	*
TN:TP	*	*	*
TKN (µg l^{-1})	*	*	*
TEMP (°C)		*	*
Fe (µg l^{-1})			
Ba (mg l^{-1})		*	*
Mn (mg l^{-1})		*	*
Li (mg l^{-1})		*	*
Sr (mg l^{-1})	*	*	*
Al (mg l^{-1})	*	*	*
DEPTH (m)			
AREA (ha)			

4.1. Patterns in physical variables across vegetation zones

The 56 study lakes were generally small (surface area ranged from 0.9 to 36.6 ha; median = 7.9 ha) and shallow (maximum depth ranged from 0.5 to 19.0 m; median = 3.5 m) (Tab. 4). There were no significant differences (p <0.05; Tab. 2) and no pattern was seen in these variables across the three ecozones, as each region contained both deeper and shallower lakes, as well as lakes with both smaller and larger surface areas (Fig. 2a).

Surface lakewater temperature varied from 9.1 °C to 22.0 °C, with a median for the full lakeset of 15.5 °C (Tab. 4). Similar to Pienitz *et al*. (1997a), surface water temperature decreased from south to north along the latitudinal gradient with the warmest temperatures recorded in the boreal forest lakes (median = 17.4 °C), and the coolest in the arctic tundra (median = 13.1 °C) (Fig. 2b). As surface water temperatures in shallower lakes vary considerably within a given season, and from year to year, the data presented here should be considered as a measure of relative differences among zones, as these lakes were sampled within a short time window in August but in two different years.

Tab. 3. Pearson Correlation matrix for measured environmental variables (following transformation) of the 56 lakeset. * and ** indicate significant correlations at $P < 0.05$ and $P < 0.01$, respectively, based on Bonferroni-adjusted probabilities.

	Cl	SO4	SiO2	Chl-a	DOC	DIC	Ba	TKN	Fe	Mn	Al	Sr	Mg	Li	Ca	Na	K	TN	TPUF	TPF	AREA	DEPTH	pH	COND	TEMP	DIST	LAT
Cl	1.00**																										
SO4	0.32	1.00**																									
SiO2	0.22	0.24	1.00**																								
Chl-a	0.18	0.26	-0.07	1.00**																							
DOC	0.42	0.47	0.10	0.34	1.00**																						
DIC	0.73**	0.47	0.21	0.21	0.48	1.00**																					
Ba	0.77**	0.34	0.18	0.31	0.55**	0.77**	1.00**																				
TKN	0.66**	0.53*	0.03	0.51*	0.72**	0.81**	0.82**	1.00**																			
Fe	-0.04	-0.24	0.01	0.01	0.02	-0.29	-0.07	-0.04	1.00**																		
Mn	-0.09	0.02	-0.30	-0.15	0.11	-0.04	-0.02	0.00	0.31	1.00**																	
Al	-0.12	0.27	0.04	0.21	0.26	-0.19	-0.02	0.17	0.31	0.16	1.00**																
Sr	0.71**	0.54*	0.11	0.45	0.72**	0.82**	0.76**	0.91**	-0.23	-0.04	0.07	1.00**															
Mg	0.83**	0.54*	0.23	0.35	0.60**	0.92**	0.83**	0.88**	-0.27	-0.10	-0.07	0.92**	1.00														
Li	0.73**	0.45	0.35	0.06	0.35	0.72**	0.68**	0.64**	-0.09	-0.08	-0.14	0.66**	0.79**	1.00**													
Ca	0.75**	0.5***	0.20	0.31	0.68**	0.91**	0.79**	0.87**	-0.32	0.04	-0.01	0.93**	0.94**	0.69**	1.00**												
Na	0.81**	0.52*	0.21	0.35	0.58**	0.87**	0.81**	0.86**	-0.24	-0.14	-0.05	0.89**	0.95**	0.81**	0.90**	1.00**											
K	0.73**	0.58**	0.27	0.35	0.58**	0.87**	0.80**	0.88**	-0.25	-0.15	0.03	0.89**	0.93**	0.81**	0.89**	0.95**	1.00**										
TN	0.64**	0.52*	0.00	0.50*	0.72**	0.78**	0.82**	0.98**	0.04	0.12	0.18	0.88**	0.84**	0.64**	0.84**	0.83**	0.83**	1.00**									
TPUF	0.29	0.14	-0.10	0.31	0.31	0.31	0.46	0.46	0.39	0.45	0.18	0.35	0.33	0.18	0.31	0.28	0.28	0.54**	1.00**								
TPF	0.57**	0.30	0.21	0.16	0.20	0.49*	0.59**	0.50**	0.19	-0.18	0.06	0.39	0.53**	0.57**	0.37	0.51*	0.53**	0.49**	0.48	1.00**							
AREA	0.07	-0.10	-0.10	0.13	0.06	0.14	0.17	0.08	-0.13	0.14	-0.21	0.17	0.13	0.01	0.19	0.08	0.07	0.08	0.20	-0.05	1.00**						
DEPTH	-0.37	-0.22	0.02	-0.48	-0.22	-0.27	-0.49	-0.55**	-0.34	0.09	-0.22	-0.35	-0.35	-0.32	-0.27	-0.40	-0.41	-0.56**	-0.40	-0.46	0.05	1.00**					
pH	0.45	0.20	-0.10	-0.05	0.31	0.55**	0.40	0.36	-0.11	0.49*	-0.15	0.36	0.49*	0.34	0.52*	0.43	0.35	0.40	0.34	0.11	0.15	0.04	1.00**				
COND	0.81**	0.53*	0.21	0.32	0.52**	0.89**	0.81**	0.83**	-0.30	-0.05	-0.09	0.86**	0.95**	0.73**	0.94**	0.91**	0.89**	0.80**	0.30	0.45	0.14	-0.36	0.50*	1.00**			
TEMP	0.54**	0.44	-0.05	0.22	0.62**	0.58**	0.58**	0.64**	-0.19	0.18	0.20	0.66**	0.65**	0.43	0.70**	0.61**	0.57**	0.65**	0.25	0.29	0.03	-0.13	0.48	0.63**	1.00**		
DIST	-0.39	-0.55**	-0.05	-0.46	-0.76**	-0.69**	-0.56**	-0.80**	0.21	-0.01	-0.24	-0.86**	-0.69**	-0.45	-0.76**	-0.70**	-0.71**	-0.79**	-0.23	-0.21	-0.11	0.30	-0.12	-0.64**	-0.66**	1.00**	
LAT	-0.42	-0.52*	-0.07	-0.45	-0.74**	-0.61**	-0.59**	-0.81**	0.20	-0.01	-0.25	-0.85**	-0.70**	-0.46	-0.76**	-0.70**	-0.72**	-0.80**	-0.26	-0.25	-0.11	0.31	-0.12	-0.65**	-0.64**	0.99**	1.00**

Tab. 4. Limnological measurements for the 56 study sites including minimum, maximum, mean, and median values for each ecozone. D.N.A. data not available.

LAKE	Cl	SO$_4$	SiO$_2$	DOC	DIC	Fe	Mn	Na	Ca	K	Mg	Li	Sr	Ba	Al
			(mg l^{-1})			(µg l^{-1})					(mg l^{-1})				
Arctic Tundra															
TK-1	0.82	0.8	0.51	2.4	2.9	57.0	1.30	0.20	0.9	0.3	0.7	0.001	0.001	0.002	0.020
TK-2	0.64	0.7	0.27	2.0	0.8	80.0	5.30	0.27	0.4	0.2	0.3	0.001	0.001	0.002	0.010
TK-6	0.97	3.5	0.20	1.7	1.7	44.0	1.90	0.20	0.7	0.2	0.6	0.001	0.001	0.002	0.010
TK-7	0.92	1.7	0.12	1.3	1.3	25.0	2.70	0.27	0.5	0.2	0.4	0.001	0.001	0.001	0.010
TK-8	0.60	0.9	0.66	5.9	4.7	89.0	6.50	0.27	2.5	0.3	1.8	0.001	0.002	0.008	0.010
TK-9	6.90	0.2	0.13	2.7	1.5	30.0	6.40	0.60	2.6	0.4	1.4	0.001	0.011	0.010	0.010
TK-10	0.46	1.1	0.31	3.0	1.8	57.0	1.80	0.27	1.2	0.2	0.6	0.001	0.001	0.005	0.010
TK-11	0.51	1.0	0.52	2.4	1.0	52.0	2.40	0.27	0.4	0.2	0.3	0.001	0.001	0.004	0.020
TK-12	0.32	4.1	0.52	1.9	2.2	39.0	1.50	0.27	1.0	0.5	0.8	0.003	0.002	0.001	0.010
TK-13	0.28	5.8	2.47	2.3	1.2	23.0	3.70	0.20	1.0	0.5	0.8	0.003	0.002	0.002	0.050
TK-14	0.21	2.5	0.95	1.7	0.9	37.0	3.60	0.27	0.5	0.3	0.3	0.001	0.001	0.002	0.040
TK-15	0.23	2.4	1.21	1.3	1.2	21.0	1.40	0.27	0.5	0.4	0.3	0.001	0.001	0.002	0.040
TK-16	0.19	1.7	0.26	1.3	0.7	9.0	1.30	0.27	0.3	0.3	0.2	0.001	0.001	0.002	0.010
TK-17	0.21	2.2	0.33	1.7	0.9	9.0	1.60	0.27	0.5	0.4	0.3	0.001	0.001	0.002	0.020
TK-18	0.21	0.8	0.46	3.3	1.8	253.0	2.90	0.27	0.6	0.4	0.4	0.001	0.001	0.006	0.010
TK-19	0.36	1.2	0.29	5.3	2.3	418.0	2.30	0.27	0.7	0.4	0.6	0.001	0.003	0.009	0.020
TK-20	0.16	1.7	0.26	2.3	1.2	23.0	4.10	0.50	0.5	0.3	0.3	0.001	0.001	0.001	0.010
TK-21	0.81	1.9	0.25	10.3	2.9	350.0	4.40	0.50	1.4	0.6	1.1	0.002	0.008	0.007	0.001
Min.	0.16	0.2	0.12	1.3	0.7	9.0	1.30	0.20	0.3	0.2	0.2	0.001	0.001	0.001	0.001
Max.	6.90	5.8	2.47	10.3	4.7	418.0	6.50	0.60	2.6	0.6	1.8	0.003	0.011	0.010	0.050
Mean	0.82	1.9	0.54	2.9	1.7	89.8	3.06	0.60	0.9	0.3	0.6	0.001	0.002	0.004	0.017
Median	0.41	1.7	0.32	2.3	1.4	41.5	2.55	0.27	0.7	0.3	0.5	0.001	0.001	0.002	0.010
Forest-Tundra															
TK-29	0.32	1.1	0.53	138.0	1.8	21.0	6.70	0.20	1.50	0.40	0.60	0.001	0.004	0.003	0.010
TK-30	0.81	3.5	0.56	30.4	0.1	531.0	8.00	0.60	1.20	0.60	0.70	0.002	0.005	0.004	0.260
TK-31	0.85	2.8	0.89	27.3	1.6	623.0	7.60	0.30	1.30	0.40	0.50	0.001	0.004	0.004	0.130
TK-32	0.71	2.7	0.15	17.5	3.2	437.0	5.70	0.30	1.20	0.40	0.60	0.001	0.006	0.003	0.130
TK-50	0.49	1.5	0.70	13.4	2.4	51.0	3.10	0.40	2.80	0.60	1.10	0.001	0.010	0.002	0.030
TK-51	0.39	1.7	0.34	11.0	1.3	42.0	3.10	0.50	1.30	0.70	0.80	0.001	0.009	0.003	0.070
TK-52	0.56	1.9	0.17	14.0	1.0	38.0	0.70	0.50	1.00	0.60	0.80	0.001	0.005	0.002	0.070
TK-53	0.44	2.4	2.04	13.4	1.7	52.0	1.00	0.20	2.50	0.60	1.10	0.001	0.007	0.003	0.110
TK-54	0.19	3.2	0.14	5.8	0.7	4.0	2.70	0.27	1.00	0.40	0.50	0.001	0.005	0.002	0.010
TK-55	0.27	1.5	0.18	10.4	2.8	33.0	3.10	0.80	1.80	0.90	1.00	0.001	0.009	0.003	0.020
TK-56	0.34	1.7	0.72	11.4	2.5	32.0	0.70	1.20	2.80	0.80	1.10	0.001	0.009	0.002	0.020
Min.	0.19	1.1	0.14	5.8	0.1	4.0	0.70	0.20	1.00	0.40	0.50	0.001	0.004	0.002	0.01
Max.	0.85	3.5	2.04	138.0	3.2	623.0	8.00	1.20	2.80	0.90	1.10	0.002	0.010	0.004	0.26
Mean	0.49	2.2	0.58	26.6	1.7	169.5	3.85	0.48	1.67	0.58	0.80	0.001	0.007	0.003	0.08
Median	0.44	1.9	0.53	13.4	1.7	42.0	3.10	0.40	1.30	0.60	0.80	0.001	0.006	0.003	0.07

Tab. 4. Continued

LAKE	TN	TPUF	TKN	CHL*a*	POC	PON	TN:TP	POC:CHL*a*	AREA	DEPTH	pH	COND	TEMP	DIST
			(µg l⁻¹)						(ha)	(m)		(µS cm⁻¹)	(°C)	(km)
Arctic Tundra														
TK-1	208.0	27.1	161.0	0.4	330.0	28.0	7.7	825.0	5.9	9.5	7.7	11.7	17.3	285.0
TK-2	135.0	3.1	93.0	1.0	313.0	32.0	43.5	313.0	2.8	5.5	8.0	9.8	12.9	265.0
TK-6	159.0	4.2	130.0	1.2	204.0	19.0	37.9	170.0	5.3	4.5	8.0	17.0	12.1	320.0
TK-7	165.0	8.4	125.0	1.4	322.0	30.0	19.6	230.0	1.8	9.5	7.6	12.3	12.4	310.0
TK-8	451.0	20.1	323.0	2.2	1190.0	118.0	22.4	540.9	8.5	3.0	7.7	98.8	14.7	115.0
TK-9	228.0	13.4	175.0	1.1	362.0	43.0	17.0	329.1	35.7	5.5	7.5	36.3	14.3	140.0
TK-10	234.0	5.3	181.0	1.5	454.0	43.0	44.2	302.7	36.6	3.0	7.6	14.8	14.0	185.0
TK-11	185.0	5.6	124.0	0.6	527.0	51.0	33.0	878.3	6.3	3.5	6.8	9.7	13.9	192.5
TK-12	198.0	7.4	146.0	0.7	420.0	42.0	26.8	600.0	13.1	6.1	6.9	13.9	10.4	175.0
TK-13	198.0	5.9	155.0	0.4	210.0	25.0	33.6	525.0	2.6	3.1	6.9	16.1	13.0	85.0
TK-14	170.0	4.3	121.0	1.4	301.0	32.0	39.5	215.0	2.8	4.9	6.4	9.2	13.1	100.0
TK-15	146.0	4.6	99.0	0.7	245.0	23.0	31.7	350.0	0.9	3.0	6.6	9.4	12.4	97.5
TK-16	150.0	4.2	106.0	0.7	272.0	32.0	35.7	388.6	4.2	6.0	6.6	7.3	13.7	85.0
TK-17	137.0	2.7	108.0	0.7	190.0	19.0	50.7	271.4	10.3	5.9	6.6	9.3	14.0	95.0
TK-18	258.0	31.3	180.0	1.1	665.0	68.0	8.2	604.5	10.6	7.3	6.6	8.7	11.3	55.0
TK-19	566.0	28.1	499.0	0.7	516.0	56.0	20.1	737.1	8.4	0.8	6.7	9.7	9.1	55.0
TK-20	186.0	6.2	145.0	0.7	337.0	31.0	30.0	481.4	9.7	8.8	7.2	8.7	12.8	35.0
TK-21	793.0	28.3	527.0	6.7	2990.0	256.0	28.0	446.3	9.7	1.0	7.0	17.1	13.5	23.0
Min.	135.0	2.7	93.0	0.4	190.0	19.0	7.7	170.0	0.9	0.8	6.4	7.3	9.1	23.0
Max.	793.0	31.3	527.0	6.7	2990.0	256.0	50.7	878.3	36.6	9.5	8.0	98.8	17.3	320.0
Mean	253.7	11.7	188.8	1.3	547.1	52.7	29.4	456.0	9.7	5.0	7.1	17.8	13.1	145.4
Median	192.0	6.1	145.5	0.9	333.5	32.0	30.9	417.4	7.4	5.2	7.0	10.8	13.1	107.5
Forest-Tundra														
TK-29	287.0	4.20	203.0	0.7	710.0	74.0	68.3	1014.3	18.0	10.1	7.7	14.6	16.1	-65.0
TK-30	593.0	28.50	352.0	4.6	3250.0	231.0	20.8	706.5	10.7	1.5	7.3	15.0	15.8	-45.0
TK-31	403.0	9.20	312.0	1.8	805.0	81.0	43.8	447.2	3.5	5.0	6.8	13.4	16.8	-35.0
TK-32	614.0	24.50	449.0	2.1	1830.0	155.0	25.1	871.4	5.9	1.5	7.5	13.7	16.3	-50.0
TK-50	410.0	4.50	423.0	4.3	D.N.A.	D.N.A.	91.1	0.0	4.3	1.8	6.8	26.2	12.5	-50.0
TK-51	373.0	9.40	357.0	7.9	D.N.A.	D.N.A.	39.7	0.0	8.8	1.8	6.4	18.4	12.0	-22.5
TK-52	413.0	6.00	444.0	4.3	D.N.A.	D.N.A.	68.8	0.0	9.0	1.9	6.2	18.1	12.2	-25.0
TK-53	311.0	4.20	317.0	1.8	D.N.A.	D.N.A.	74.0	0.0	4.6	19.0	6.6	19.8	14.4	-30.0
TK-54	166.0	3.10	167.0	1.8	D.N.A.	D.N.A.	53.5	0.0	9.9	3.4	6.2	12.3	13.0	-10.0
TK-55	395.0	5.30	422.0	3.9	D.N.A.	D.N.A.	74.5	0.0	9.8	2.6	7.0	20.6	13.7	-40.0
TK-56	298.0	7.80	324.0	3.8	D.N.A.	D.N.A.	38.2	0.0	13.2	6.0	6.9	25.2	14.5	-75.0
Min.	166.0	3.10	167.0	0.7	710.0	74.0	20.8	447.2	3.5	1.5	6.2	12.3	12.0	-75.0
Max.	614.0	28.50	449.0	7.9	3250.0	231.0	91.1	1014.3	18.0	19.0	7.7	26.2	16.8	-10.0
Mean	387.5	9.70	342.7	3.4	1648.8	135.3	54.4	759.9	8.9	5.0	6.8	17.9	14.3	-40.7
Median	395.0	6.00	352.0	3.8	1317.5	118.0	53.5	789.0	9.0	2.6	6.8	18.1	14.4	-40.0

Tab. 4. Continued

LAKE	Cl	SO$_4$	SiO$_2$	DOC	DIC	Fe	Mn	Na	Ca	K	Mg	Li	Sr	Ba	Al
			(mg l^{-1})			(µg l^{-1})					(mg l^{-1})				
Boreal Forest															
TK-22	2.0	4.1	0.7	12.8	6.9	50.0	10.30	1.50	8.1	0.9	2.9	0.004	0.037	0.008	0.020
TK-23	0.4	1.6	0.1	15.2	2.8	84.0	6.60	0.40	3.4	0.4	0.9	0.001	0.009	0.002	0.040
TK-24	1.1	8.6	0.2	24.3	9.9	12.0	52.60	1.80	17.9	1.6	3.8	0.003	0.044	0.011	0.030
TK-25	0.7	1.5	0.1	16.5	7.3	40.0	49.50	1.20	8.1	1.2	2.0	0.003	0.025	0.005	0.010
TK-26	0.6	3.9	0.1	6.2	7.3	4.0	7.30	1.10	7.5	1.2	2.5	0.002	0.023	0.002	0.010
TK-27	1.1	4.9	0.5	11.0	7.5	31.0	43.40	1.50	7.1	1.1	3.8	0.003	0.022	0.004	0.030
TK-28	0.7	7.5	1.4	165.0	9.0	22.0	6.90	0.60	15.6	1.0	2.1	0.001	0.019	0.005	0.020
TK-33	0.5	1.6	0.4	116.0	2.3	34.0	3.10	0.40	2.4	0.3	1.0	0.001	0.006	0.003	0.040
TK-34	0.4	0.7	0.2	15.0	2.7	26.0	3.00	0.50	3.3	0.5	1.0	0.001	0.009	0.005	0.050
TK-35	0.6	6.3	0.3	332.0	1.4	21.0	4.70	0.80	6.3	0.6	1.6	0.001	0.019	0.005	0.020
TK-36	1.7	7.0	0.3	80.1	2.1	549.0	16.50	1.50	4.9	1.0	2.1	0.003	0.015	0.006	0.130
TK-37	41.1	3.4	1.4	65.1	41.0	205.0	9.30	39.80	30.7	14.8	32.4	0.028	0.197	0.060	0.010
TK-38	0.9	3.2	0.7	26.5	6.4	21.0	9.30	0.90	7.7	1.4	2.7	0.004	0.021	0.009	0.030
TK-39	15.4	5.8	0.4	69.9	26.1	27.0	22.60	5.40	34.7	6.2	14.7	0.005	0.123	0.061	0.050
TK-40	33.4	6.1	0.9	30.2	13.8	13.0	9.30	5.50	21.1	2.1	12.6	0.005	0.080	0.015	0.010
TK-41	1.8	13.3	0.3	51.6	11.2	52.0	2.70	4.10	19.3	4.2	5.0	0.003	0.058	0.030	0.210
TK-42	1.8	10.5	0.1	44.8	12.2	24.0	4.70	3.20	10.8	3.5	10.5	0.001	0.047	0.017	0.060
TK-43	0.5	2.4	0.1	13.4	3.1	4.0	1.40	0.70	3.4	0.6	2.0	0.001	0.012	0.004	0.010
TK-44	16.6	2.6	0.2	26.2	8.0	21.0	9.30	2.40	10.2	1.9	7.5	0.003	0.048	0.014	0.010
TK-45	7.3	10.3	0.7	24.8	21.7	2.0	9.30	7.50	20.4	3.8	13.6	0.007	0.101	0.025	0.010
TK-46	13.0	3.2	2.3	61.1	42.3	46.0	9.30	31.30	29.3	16.8	32.2	0.022	0.129	0.027	0.010
TK-47	0.4	2.2	0.2	17.4	2.6	5.0	9.30	0.50	3.8	0.6	1.2	0.001	0.012	0.009	0.030
TK-48	0.9	2.7	0.2	24.6	10.1	14.0	12.10	1.80	15.0	2.0	2.7	0.001	0.039	0.007	0.030
TK-49	2.7	5.9	5.7	9.6	9.0	9.0	9.30	2.00	12.5	1.2	3.0	0.001	0.023	0.004	0.010
TK-57	0.7	4.5	0.9	16.4	2.1	59.0	9.30	0.70	2.6	1.0	1.7	0.001	0.014	0.003	0.060
TK-58	1.0	5.1	0.2	26.2	9.1	5.0	9.30	4.00	5.6	2.5	5.2	0.002	0.035	0.008	0.020
TK-59	3.5	4.7	3.4	27.7	35.4	1.0	9.30	12.20	37.0	9.3	23.2	0.010	0.130	0.034	0.010
Min.	0.4	0.7	0.1	6.2	1.4	1.0	1.40	0.40	2.4	0.3	0.9	0.001	0.006	0.002	0.010
Max.	41.1	13.3	5.7	332.0	42.3	549.0	52.60	39.80	37.0	16.8	32.4	0.028	0.197	0.061	0.210
Mean	5.6	4.9	0.8	49.2	11.6	51.1	12.95	4.94	12.9	3.0	7.2	0.004	0.048	0.014	0.036
Median	1.1	4.5	0.3	26.2	8.0	22.0	9.30	1.50	8.1	1.2	2.9	0.003	0.025	0.008	0.020
Full Lakeset (56 lakes)															
Min.	0.16	0.20	0.05	1.30	0.10	1.00	0.70	0.20	0.30	0.20	0.20	0.001	0.001	0.001	0.001
Max.	41.10	13.30	5.72	332.00	42.30	623.00	52.60	39.80	37.00	16.80	32.40	0.028	0.197	0.061	0.260
Mean	3.05	3.43	0.67	29.91	6.49	86.80	7.99	2.57	6.84	1.68	3.82	0.003	0.025	0.009	0.038
Median	0.68	2.55	0.34	13.40	2.55	32.50	0.70	0.20	2.60	0.60	1.10	0.001	0.009	0.004	0.020

Tab. 4. Continued

LAKE	TN	TPUF	TKN	CHL*a*	POC	PON	TN:TP	POC:CHL*a*	AREA	DEPTH	pH	COND	TEMP	DIST
			(µg l⁻¹)						(ha)	(m)		(µS cm⁻¹)	(°C)	(km)

Boreal Forest

LAKE	TN	TPUF	TKN	CHL*a*	POC	PON	TN:TP	POC:CHL*a*	AREA	DEPTH	pH	COND	TEMP	DIST
TK-22	660.0	16.2	472.0	3.5	2050.0	178.0	40.7	585.7	8.8	2.8	7.4	62.0	17.5	-160.0
TK-23	633.0	7.9	553.0	1.9	815.0	70.0	80.1	428.9	6.9	2.0	7.6	24.2	17.4	-155.0
TK-24	1392.0	11.0	1170.0	1.1	3270.0	212.0	126.5	2972.7	16.8	8.0	8.2	102.2	17.1	-135.0
TK-25	966.0	10.0	810.0	1.8	1910.0	146.0	96.6	1061.1	2.7	6.0	7.9	53.9	17.4	-100.0
TK-26	325.0	6.9	275.0	0.6	350.0	40.0	47.1	583.3	20.9	16.0	7.7	56.9	16.9	-130.0
TK-27	672.0	23.0	501.0	2.0	1860.0	161.0	29.2	930.0	10.1	3.0	8.0	64.6	17.8	-170.0
TK-28	512.0	10.8	441.0	1.2	690.0	61.0	47.4	575.0	8.8	6.1	7.8	74.8	16.5	-110.0
TK-33	363.0	6.1	306.0	1.1	426.0	47.0	59.5	387.3	6.1	10.0	7.3	2.5	16.3	-80.0
TK-34	448.0	12.1	355.0	1.3	1010.0	83.0	37.0	776.9	3.6	5.0	7.4	25.9	17.4	-95.0
TK-35	516.0	15.6	433.0	1.2	679.0	64.0	33.1	565.8	4.3	7.0	7.5	44.1	17.2	-135.0
TK-36	996.0	23.3	881.0	4.8	960.0	102.0	42.7	200.0	4.2	1.5	7.2	39.1	17.9	-162.5
TK-37	1790.0	6.4	2460.0	1.3	D.N.A.	D.N.A.	279.7	D.N.A.	6.7	1.3	7.6	478.5	18.3	-180.0
TK-38	883.0	8.7	923.0	5.2	D.N.A.	D.N.A.	101.5	D.N.A.	17.4	2.1	6.3	64.4	18.2	-170.0
TK-39	1590.0	48.6	2270.0	3.1	D.N.A.	D.N.A.	32.7	D.N.A.	14.4	1.0	8.3	271.1	20.2	-155.0
TK-40	889.0	11.2	934.0	1.0	D.N.A.	D.N.A.	79.4	D.N.A.	7.9	2.2	7.0	238.9	18.3	-175.0
TK-41	1930.0	13.0	2120.0	1.5	D.N.A.	D.N.A.	148.5	D.N.A.	4.3	0.5	7.7	149.5	22.0	-180.0
TK-42	1590.0	34.8	1830.0	17.3	D.N.A.	D.N.A.	45.7	D.N.A.	8.4	0.9	7.9	138.5	19.8	-162.5
TK-43	446.0	3.7	461.0	1.5	D.N.A.	D.N.A.	120.5	D.N.A.	7.3	7.3	7.1	42.8	21.5	-160.0
TK-44	883.0	5.7	945.0	2.9	D.N.A.	D.N.A.	154.9	D.N.A.	2.9	1.4	7.1	134.0	20.2	-160.0
TK-45	811.0	8.7	869.0	2.9	D.N.A.	D.N.A.	93.2	D.N.A.	8.0	6.5	7.8	228.9	16.8	-150.0
TK-46	1960.0	10.9	2760.0	1.0	D.N.A.	D.N.A.	179.8	D.N.A.	2.6	0.7	7.8	405.1	15.7	-152.5
TK-47	637.0	8.5	670.0	5.7	D.N.A.	D.N.A.	74.9	D.N.A.	4.6	2.5	6.9	32.8	14.5	-150.0
TK-48	1020.0	22.1	1150.0	3.1	D.N.A.	D.N.A.	46.2	D.N.A.	18.5	1.5	7.4	100.2	13.7	-127.5
TK-49	380.0	5.5	380.0	3.0	D.N.A.	D.N.A.	69.1	D.N.A.	12.2	3.7	7.4	97.4	14.3	-100.0
TK-57	424.0	6.0	428.0	2.8	D.N.A.	D.N.A.	70.7	D.N.A.	3.0	4.6	6.6	27.6	15.2	-107.5
TK-58	1080.0	10.8	1200.0	3.8	D.N.A.	D.N.A.	100.0	D.N.A.	2.6	3.2	7.3	76.9	16.2	-145.0
TK-59	1030.0	10.6	1100.0	5.3	D.N.A.	D.N.A.	97.2	D.N.A.	15.6	4.6	8.1	306.5	19.0	-160.0
Min.	325.0	3.7	275.0	0.6	350.0	40.0	29.2	200.0	2.6	0.5	6.3	2.5	13.7	-180.0
Max.	1960.0	48.6	2760.0	17.3	3270.0	212.0	279.7	2972.7	20.9	16.0	8.3	478.5	22.0	-80.0
Mean	919.5	13.3	988.8	3.0	1274.5	105.8	86.4	824.3	8.5	4.1	7.5	123.8	17.5	-143.2
Median	883.0	10.8	869.0	2.0	960.0	83.0	74.9	583.3	7.3	3.0	7.5	74.8	17.4	-152.5

Full Lakeset (56 lakes)

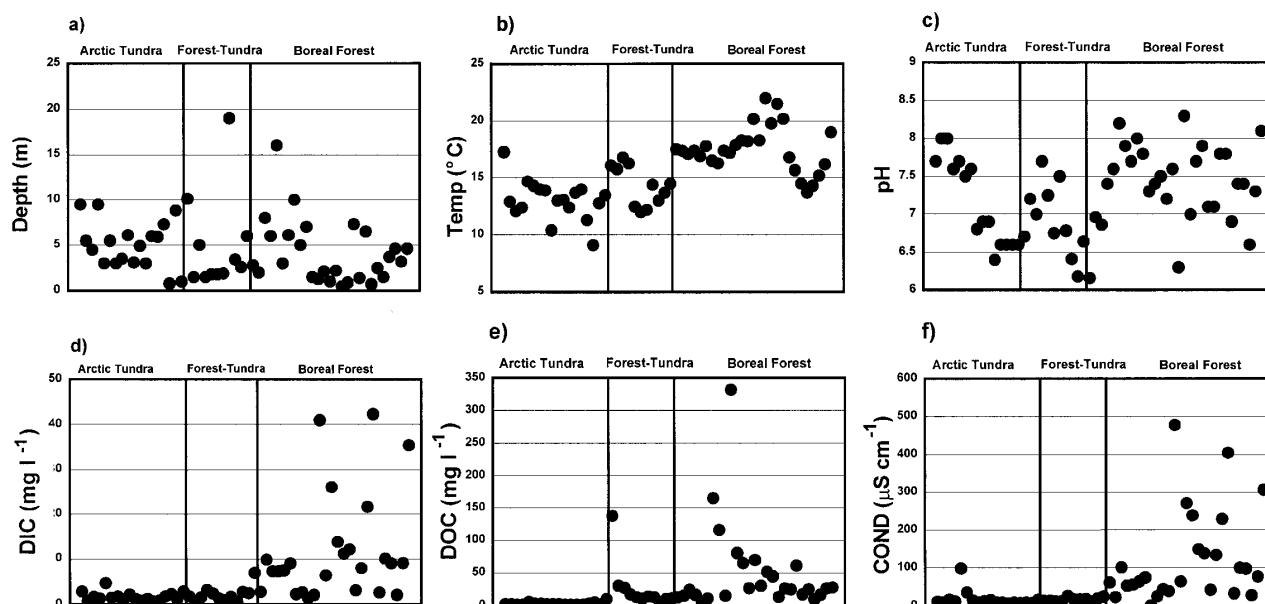| LAKE	TN	TPUF	TKN	CHL*a*	POC	PON	TN:TP	POC:CHL*a*	AREA	DEPTH	pH	COND	TEMP	DIST
Min.	135.0	2.7	93.0	0.4	190.0	19.0	7.7	170.0	0.9	0.5	6.2	2.5	9.1	-180.0
Max.	1960.0	48.6	2760.0	17.3	3270.0	256.0	279.7	2972.7	36.6	19.0	8.3	478.5	22.0	320.0
Mean	601.0	12.1	604.7	2.5	923.1	80.4	61.8	615.6	9.0	4.6	7.2	68.9	15.5	-30.3
Median	435.0	8.6	422.5	1.7	527.0	56.0	44.9	540.9	7.9	3.5	7.3	25.6	15.5	-70.0

Fig. 2. Trends in selected environmental variables across vegetation zones. Sites are classified into vegetational zones along the x-axis, the value of the measured environmental variable for each lake is given along the y-axis.

It is well known that relatively shallow lakes with small surface areas will be less likely to stratify than deeper larger lakes (Gorham & Boyce 1989) especially in arctic environments where wind activity can play a major role in lakewater mixing. Thermal stratification may influence (among other things) nutrient distributions within a lake (Gorham & Boyce 1989). Due to logistical constraints, temperature profiles (surface and bottom) were measured for only 33 (TK-1 to TK-36) of the 56 lakes. Twenty eight of these 33 lakes were weakly to strongly stratified with temperature differences (t.d.) between the surface waters and the bottom waters ranging from 0.2 to 12.4 °C. The majority of lakes in the arctic tundra zone were weakly stratified (mean t.d. = 1.1 °C) and 5 of the lakes were isothermal (TK-6, TK-16, TK-19, TK-20, and TK-21). All lakes in the boreal forest and in the forest-tundra showed varying degrees of stratification, six of which were strongly stratified (TK-25 - t.d.= 5.7 °C, TK-26 - t.d. = 11.6 °C, TK-28 - t.d. = 9.0 °C, TK-29 - t.d. = 8.7 °C, TK-33 - t.d. = 12.4 °C, and TK-35 - t.d. = 10.9 °C). These differences in thermal stratification patterns across the climatic ecozones may be important factors with respect to future climatic warming through changes in the composition of lakewater biota and their habitats.

4.2. Trends in pH across vegetation zones

Trends in pH across ecozones were quite variable, with boreal forest lakes generally recording higher pH values (89% of pH values higher than 7.0) than arctic tundra lakes (50% of pH values higher than 7.0) (Fig. 2c). The pH range (6.2 to 8.3 with a median of 7.3) was

somewhat smaller than that recorded in previous studies of this area (Puznicki 1996; Rühland & Smol 1998) and is likely due to the more uniform nature of the bedrock geology across the sampling transect for this lakeset. It may also indicate that catchment vegetation does not play a major role in affecting lakewater pH in this lakeset. As expected, pH was significantly correlated ($p \leq 0.05$) to DIC ($r = 0.55$,), Mn ($r = 0.40$), Mg ($r = 0.49$), Ca ($r = 0.52$), and COND ($r = 0.50$) (Tab. 3).

4.3. Trends in major ions, DIC, and conductivity across vegetation zones

The surface waters of this lakeset were generally dilute with conductivity measurements varying from 2.5 to 478.5 µS cm^{-1}, with a median of 10.8 µS cm^{-1} in the arctic tundra zone, 18.1 µS cm^{-1} in the forest-tundra zone, and 74.8 µS cm^{-1} in the boreal forest zone (Tab. 4). Despite the dilute nature of these lakes, there was a clear trend in major ions and related variables (such as DIC) across the vegetational gradient (Fig. 2d). Boreal forest lakes were significantly different ($p \leq 0.05$; Tab. 2) and had higher concentrations of Ca, Mg, Na, K, Cl, SO$_4$, DIC and COND than both arctic tundra and forest-tundra lakes. DIC (which partially reflects trends in major ion concentrations) varied from 0.1 to 42.3 mg l^{-1} with a median of 1.4 mg l^{-1} in the arctic tundra zone, 1.7 mg l^{-1} in the forest-tundra zone, and 8.0 mg l^{-1} in the boreal forest zone (Tab. 4). This trend of increasing ionic concentrations from arctic tundra to boreal forest lakes has been reported in other treeline studies (Pienitz *et al.* 1997a, b; Rühland & Smol 1998; Duff *et al.* 1998; Fallu & Pienitz 1999; Gregory-Eaves *et al.* 2000; Fallu *et al.*

2002). This variability in major ion concentrations among zones is likely due to differences in climate-related factors such as hydrology, degree of permafrost, and duration of ice cover (see below).

Patterns in conductivity closely follow those for major ions and DIC (Fig. 2f). For example, Na, K, Ca, Mg, Cl, as well as DIC, displayed high and significant ($p \leq 0.01$) correlations with COND (Tab. 3). Sites with higher COND measurements (100.2 to 478.5 μS cm^{-1}) had consistently higher DIC (8.0 to 42.3 mg l^{-1}), Ca (7.7 to 34.7 mg l^{-1}), Mg (2.7 to 32.4 mg l^{-1}), K (1.6 to 16.8 mg l^{-1}), Cl (1.1 to 33.4 mg l^{-1}), Na (1.8 to 39.8 mg l^{-1}), and SO$_4$ (2.6 to 13.3 mg l^{-1}) values, all of which were located in the boreal forest zone. Lakes with particularly high COND values (>150 μS cm^{-1}) were located in proximity to each other and to the city of Yellowknife (TK-37, TK-39, TK-40. TK-45, TK-46, TK-59), likely as a result of their location closer to human activity. The correlation between COND and DIC is particularly strong ($r = 0.89$, $p \leq 0.01$). Similar to other arctic studies (Pienitz *et al*. 1997a, b; Rühland & Smol 1998; Gregory-Eaves *et al*. 2000; Lim *et al*. 2001), the general trend in relative concentrations of cations was Ca>Mg>Na>K with mean values of 6.8 mg l^{-1}, 3.8 mg l^{-1}, 2.6 mg l^{-1}, and 1.7 mg l^{-1}, respectively (Tab. 4). The relative concentrations in major anions followed similar trends to Lim *et al*. (2001) with DIC (most of which is bicarbonate (HCO$_3$) given the circumneutral pH range of this dataset)> SO$_4$ >Cl with mean values of 6.5 mg l^{-1}, 3.4 mg l^{-1}, and 3.1 mg l^{-1}, respectively (Tab. 4).

The decrease in ionic concentrations from south to north may be indirectly related to climatic factors. As bedrock geology across this vegetational gradient is relatively uniform, other factors are likely responsible for differences in major ion variations across the climatic gradient. Lakes situated in the continuous permafrost zone (arctic tundra sites) will have much more restricted groundwater inflow resulting in a lower net yield of base cations entering the lakes than those situated on discontinuous permafrost to the south. Higher values in DIC, and related variables in boreal forest lakes may also be related to higher precipitation and runoff than in arctic tundra sites (Schindler *et al*. 1996; Henriksen *et al*. 1998). Pienitz *et al*. (1997a, b) have found similar trends in their lakesets spanning treeline in both the Yukon and the Northwest Territories. They attributed the higher values in the forested catchments to increased weathering and ion supply from the catchment as a result of higher precipitation. Thicker and more highly developed soils in the boreal forest also contribute to the higher ionic concentrations in this vegetation zone. In addition, in-lake alkalinity generation, such as from increased biological productivity and sulfate reduction processes, are more pronounced in warmer climates (Webster *et al*. 1990; Psenner & Schmidt 1992; Schindler *et al*. 1996) such as is found in the boreal forest zone.

4.4. Trends in DOC across vegetation zones

A wide range in DOC concentrations was measured in this lakeset with a minimum of 1.3 mg l^{-1} to a maximum of 332.0 mg l^{-1}, with a median of 13.4 mg l^{-1} (Tab. 4). This range was about an order of magnitude greater than those reported by Pienitz *et al*. (1997a, b), Moser *et al*. (1998), Duff *et al*. (1998), and Fallu & Pienitz (1999), but similar to Alaskan values reported by Gregory-Eaves *et al*. (2000).

Lower DOC values were recorded in arctic tundra lakes (median = 2.3 mg l^{-1}), than in lakes within the boreal forest zone (median = 26.2 mg l^{-1}) (Fig. 2e). This trend of increasing DOC concentrations from forest to tundra was expected as waters draining the catchments of coniferous leaf litter bring high amounts of allochthonous DOC into lakewaters (Wetzel 1983; Cronan & Aiken 1985; Forsberg 1992; Schindler *et al*. 1992; Hongve 1999). Additionally, wetlands, commonly found in the study region provide another important allochthonous source of DOC (Henriksen *et al*. 1998). Water colour in many of the boreal forest and forest-tundra lakes was commonly tea-coloured to dark chocolate-coloured, a strong indication of high levels of catchment-derived DOC comprised of coloured humic substances (Meili 1992). For example, boreal forest lakes that were reported to be very darkly coloured (TK-35, TK-28, TK-33, TK-36, TK-37, TK-39, TK-41, TK-46) had corresponding high levels of DOC (51.6 to 332.0 mg l^{-1}). This large gradient in lakewater DOC between treeless and forested catchments suggest that potentially this variable may track past changes in coniferous forests in this region.

4.5. Trends in nutrients and chlorophyll-a across the vegetational gradient

Nutrients were expected to track changes in the different vegetation zones as one primary source of nutrients to lakes is from terrestrial sources (Guildford & Hecky 2000). Higher allochthonous sources of nutrients entering into forest lakes probably result from higher runoff, higher precipitation, and denser vegetation. In this forested zone, increased breakdown of terrestrial litter, a longer growing season (i.e. shorter duration of ice cover) in combination with warmer temperatures would elevate primary productivity and intensify nutrient circulation. In the arctic tundra, shorter growing seasons, cooler conditions, restricted hydrological processes, continuous permafrost, and diminished catchment-derived nutrients would likely reflect lower primary productivity.

The majority of our study lakes were oligotrophic but did display a moderate range in trophic status (North American standards) from ultra-oligotrophic (TPUF <5.0 μg l^{-1}, 11 lakes) to eutrophic (TPUF >30 μg l^{-1}, 3 lakes). In general, boreal forest lakes had higher TPUF concentrations (median = 10.8 μg l^{-1} and a range of 3.7 to 48.6 μg l^{-1}) than arctic tundra lakes (median = 6.1 μg l^{-1}
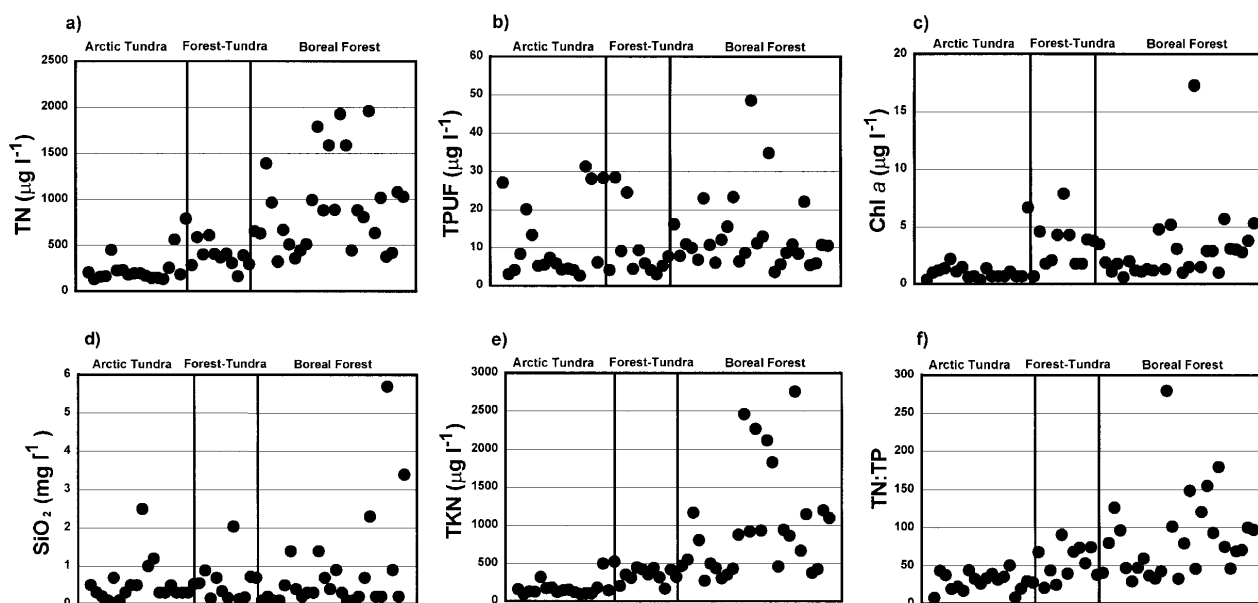
Fig. 3. Trends in nutrients and CHLA across vegetation zones. Sites are classified into zones along the x-axis, the value of the measured environmental value for each lake is given along the y-axis.

Fig. 4. Trends in metal elements across vegetation zones. Sites are classified into zones along the x-axis, the value of the measured environmental variable for each lake is given along the y-axis.
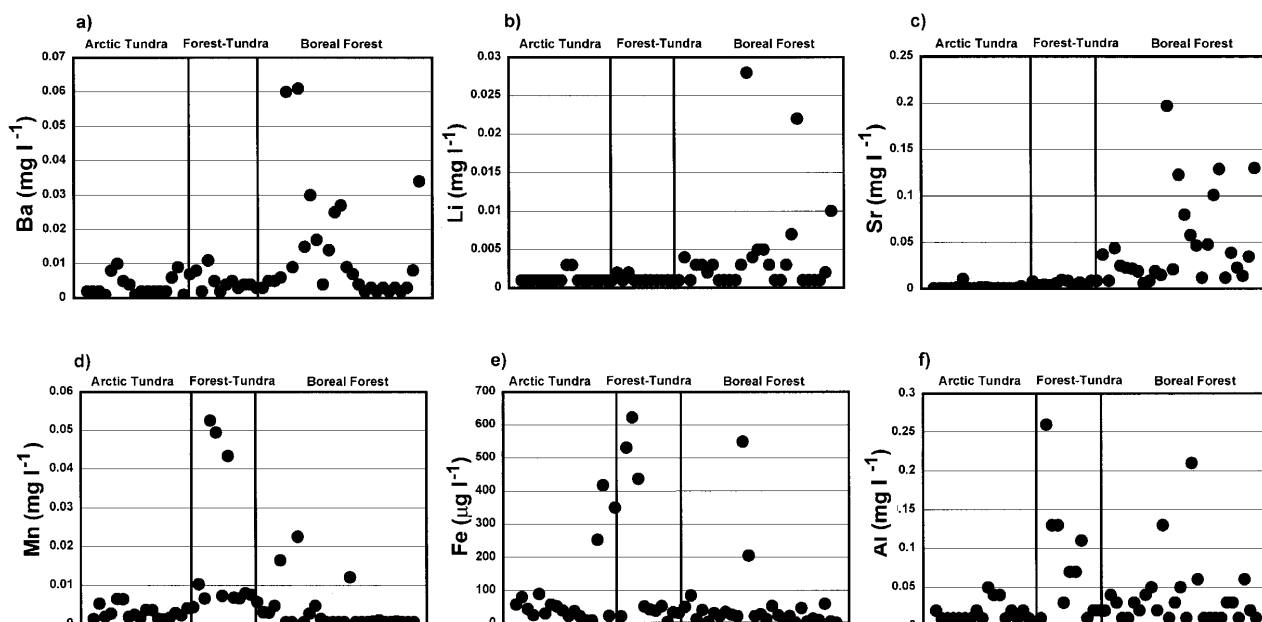
and a range of 2.7 to 31.3 µg l⁻¹) and forest-tundra lakes (median = 6.0 µg l⁻¹ and a range of 3.1 to 28.5 µg l⁻¹) (Tab. 4, Fig. 3b). According to this classification system, three lakes were classified as eutrophic, two of which were located in the boreal forest (TK-39: 48.6 µg l⁻¹ & TK-42: 34.8 µg l⁻¹) and one in the arctic tundra (TK-18: 31.3 µg l⁻¹). Both boreal forest lakes were very shallow (about 1.0 m in depth) and were relatively close to the city of Yellowknife (approximately 25 km). Reasons for the higher phosphorus values are not clear, but

may be related to the possibility that these lakes receive water from nearby Prelude Lake to the north, which has a small lodge (accommodates 15 people) and a small community campsite (28 sites) (Wedel *et al.* 1990) that may be a potential source of nutrients. The CHLA value for TK-42 (17.3 µg l⁻¹) was the highest recorded for the entire lakeset, but for TK-39 CHLA levels were moderately low (3.1 µg l⁻¹). The higher value for TPUF in the arctic tundra lake (TK-18) as well as in a lake a few meters away (TK-19) may be related to the relatively

high iron concentrations (253.0 and 418.0 µg l⁻¹). Both lakes were dark red in colour. Iron is known to form complexes with phosphorus, leaving the measured phosphorus unavailable for biological uptake (Jones *et al*. 1988). This appears to be the case for these lakes, as low algal biomass, as inferred from CHLA, were also recorded (TK-18: CHLA = 1.1 µg l⁻¹; TK-19: CHLA = 0.7 µg l⁻¹). Therefore, even though the phosphorus levels are high, the lakes are still not very productive.

Nutrient concentrations and CHLA followed similar spatial trends, as expected, with higher concentrations in SiO_2, CHLA, TKN, TN, and TPUF measured in boreal forest lakes (medians of 0.3 mg l⁻¹, 2.0 µg l⁻¹, 869.0 µg l⁻¹, 883.0 µg l⁻¹, and 10.8 µg l⁻¹, respectively) than in arctic tundra lakes (medians of 0.3 mg l⁻¹, 0.9 µg l⁻¹, 145.5 µg l⁻¹, 192.0 µg l⁻¹, and 6.1 µg l⁻¹, respectively) (Tab. 4, Fig. 3). Our values were similar to those reported by Lim *et al*. (2001) and by Gregory-Eaves *et al*. (2000), but had substantially higher concentrations of TKN, TN, and TPUF than other Canadian treeline studies (Pienitz *et al*. 1997a; Fallu & Pienitz 1999).

CHLA was not significantly correlated to other measured variables with the exception of nitrogen (TKN and TN) (Tab. 3). TPUF and CHLA were only weakly correlated (r = 0.31) suggesting that productivity in some of these lakes may be limited by other factors, such as nitrogen.

To determine whether the POC of our lakes was primarily derived from allochthonous versus autochthonous sources, a ratio of POC (particulate organic carbon) to CHLA (representing algal biomass) was calculated for all lakes where POC measurements were available (n = 33). These ratios were also explored by Lim *et al*. (2001) and by Hamilton *et al*. (2001) for Canadian high arctic sites. In our reduced lakeset of 33 sites, the POC:CHLA ratios ranged from 170:1 to 2973:1, with a mean of 616:1 (Tab. 4). Eppley *et al*. (1977) suggested that ratios greater than 100 are indicative of higher loading of detrital POC coming into the lake from external sources (i.e. not from algal sources within the lake). To further explore the relationship between these two indicators of production, linear regressions between CHLA and POC for boreal forest lakes and for arctic tundra lakes (only 4 sites in the forest-tundra had POC data available and was therefore not included here) were generated (Fig. 5a-c). Weak relationships were found between POC and CHLA for lakes in the arctic tundra ecozone (r^2 = 0.02, n = 16 after the removal of two outliers), as well as for lakes in the boreal forest (r^2 = 0.20, n = 10 after the removal of one outlier). The higher ratio of POC:CHLA in our boreal forest lakes (mean = 824.3) than our arctic tundra lakes (mean = 456.0) together with the poor relationships observed suggest that lakes in our forested catchments have higher loadings of detrital matter than do arctic tundra lakes. This would be expected, as increased catchment vegetation and richer soils can contribute significant amounts of detrital POC in comparison to the more sparsely vegetated catchments with poorly developed soils of arctic tundra sites.

The relationship between POC and CHLA in the arctic tundra zone can be compared to the ratios calculated by other researchers in the Canadian Arctic and Subarctic (Pienitz *et al*. 1997a, b; Lim *et al*. 2001; Hamilton *et al*. 2001) and in Alaska (Gregory-Eaves *et al*. 2000). As in this dataset, the majority of lakes in these studies (98%, n = 91) had POC:CHLA ratios well above 100, suggesting that even these tundra lakes received much of their detrital loading from allochthonous sources. Much like this study, linear regressions of the data from these other studies did not reveal strong relationships between these two variables for lakes in the arctic tundra, with the exception of lakes in Alaska (r^2 = 0.87, n = 9).

To assess whether our lakes were primarily limited by phosphorus or by nitrogen, TN:TP ratios were calculated. TN:TP ratios for this lakeset ranged from 7.7 to 279.7 with a mean of 61.8 (Tab. 4). Nitrogen limitation may be common in lakes with TN:TP ratios less than 14 (especially if TP was high) (Downing & McCauley 1992) and tend to be phosphorus-limited in lakes with ratios greater than 17 (Sakomoto 1966). Using these criteria, only two lakes from this study (TK-1 and TK-18; both in the arctic tundra zone) were classified as possibly nitrogen-limited and both had TPUF concentrations well above the mean (27.1 µg l⁻¹ and 31.3 µg l⁻¹, respectively). All other lakes were classified as phosphorus-limited. The findings reported here agree with Pienitz *et al*. (1997a), Gregory-Eaves *et al*. (2000), and Hamilton *et al*. (2001). There is a clear spatial trend in this ratio with an increase in TN:TP from the arctic tundra to the boreal forest (Fig. 3f). This is not surprising, as higher TN:TP values are to be expected in lakes receiving runoff from undisturbed forested watersheds than lakes that depend more on inputs from precipitation such as in the arctic tundra (Downing & McCauley 1992). However, these calculations should be viewed with caution, as this dataset does not provide extensive year-round sampling, but only one snapshot sample for each lake collected in August.

4.6. Trends in trace metals across vegetation zones

Concentrations of aluminum, barium, iron, lithium, manganese and strontium were all within the range considered common for natural surface waters in Canada (<1000 µg l⁻¹, <1000 µg l⁻¹, <500 µg l⁻¹, <200 µg l⁻¹, <1000 µg l⁻¹, respectively; McNeely *et al*. 1979). All of these metals (with the exception of Fe) had significantly higher (p <0.05) concentrations in boreal forest lakes than in forest-tundra or arctic tundra lakes (Tab. 2), and closely followed the trends in major ions and related variables (Fig. 4).

Concentrations of Ba, Sr, and Li were significantly higher (p <0.05) in the boreal forest (medians of 0.008 mg l⁻¹, 0.025 mg l⁻¹, and 0.003 mg l⁻¹, respectively) and
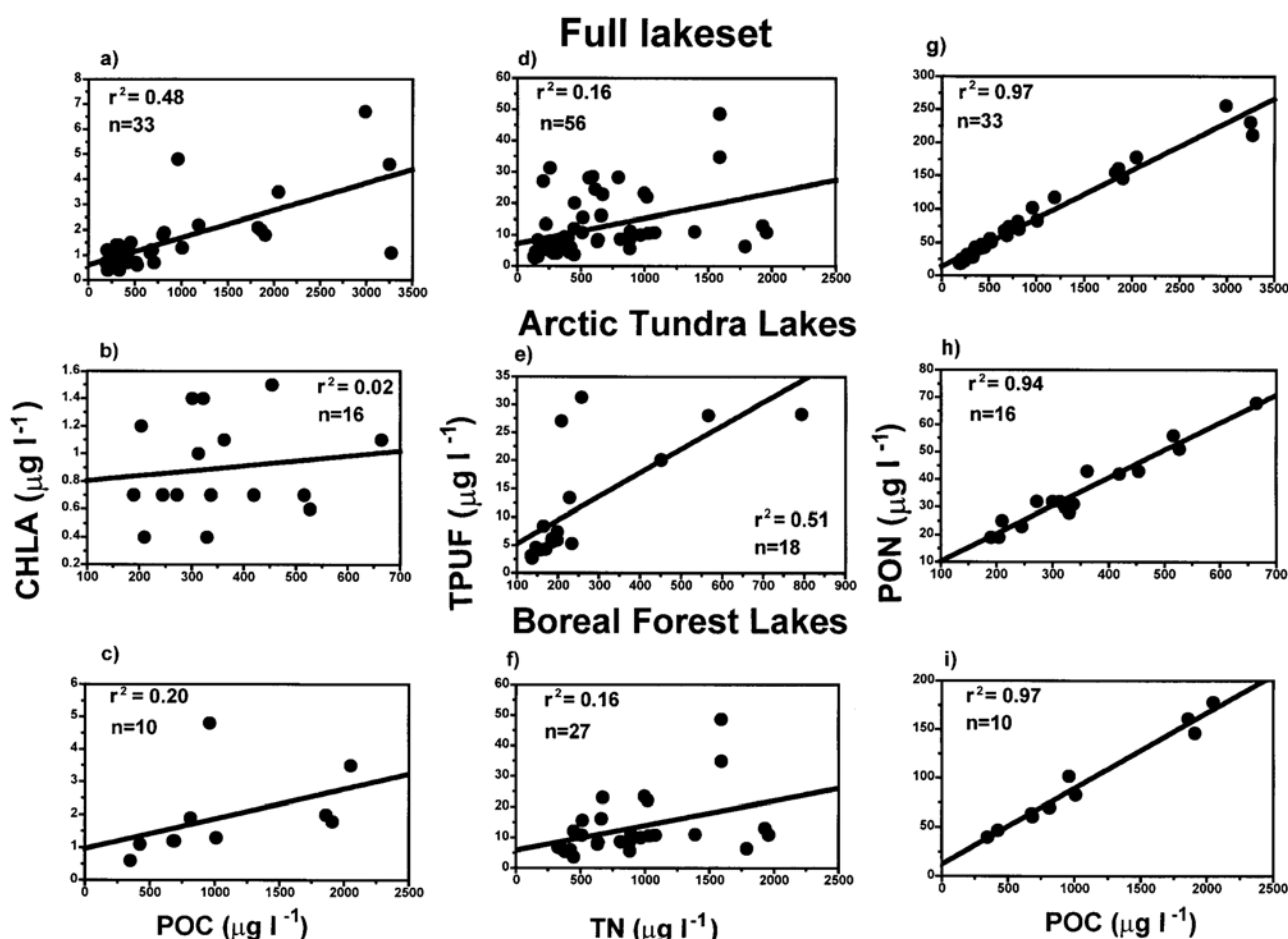
Fig. 5. Comparison of selected nutrient relationships between arctic tundra and boreal forest lakes.

lower in the arctic tundra (medians of 0.002 mg l^{-1}, 0.001 mg l^{-1}, and 0.001 mg l^{-1}, respectively) (Tab. 2, Tab. 4). All three of these metallic elements had significant and positive correlations to major ions and DIC (Tab. 3). The values for Li were consistent with values reported by Puznicki (1996), Moser *et al*. (1998), Gregory-Eaves *et al*. (2000), and Lim *et al*. (2001). Not surprisingly, Li was most highly correlated to Na and K (r = 0.81, p ≤0.01; Tab. 3), as all three are univalent alkali metals. However, concentrations of Ba and Sr were substantially lower in this lakeset than values reported previously. This may be due to the scarcity of calcium-carbonate and magnesium-rich deposits and the more granitic nature of the surrounding bedrock, as higher values of these metals are expected in lakes whose catchments drain rocks richer in calcium carbonate. Puznicki (1996) reported notably higher concentrations of Ba and Sr (maximum of 0.083 mg l^{-1} and 0.177 mg l^{-1}, respectively) in lakes around Great Bear Lake, where calcium carbonate-rich deposits are more predominant. Unlike our study, calcium carbonate-rich deposits were also reported in many of the sites studied by the other researchers mentioned above.

Although iron concentrations were within the range commonly found in Canadian surface waters (McNeely *et al*. 1979), several lakes (TK-18, TK-19, TK-21, TK-30, TK-31, TK-32, TK-36, TK-37) were dark orangy/ reddish-brown in colour and had iron values (205.0 - 623.0 µg l^{-1}) well above the lakeset mean (86.8 µg l^{-1}). As DOC concentrations were relatively low for most of these lakes (mean 29.9 mg l^{-1}), the coloured nature of these lakes may be a consequence of iron-rich deposits within their catchments. Fe and Mn are often linked to high concentrations of humic materials and therefore, lakes with high concentrations of DOC often record higher values of Fe and Mn (e.g. Moser *et al*. 1998; Fallu & Pienitz 1999). Unlike these other arctic studies, no such relationship was observed in this lakeset (r = 0.02, r = 0.11, respectively; Tab. 3). The only measured variable that was significantly correlated to Mn was pH (r = 0.49, p ≤0.05; Tab. 3). This is likely due to Mn being brought into solution through weathering processes such as acid leaching (McNeely *et al*. 1979).
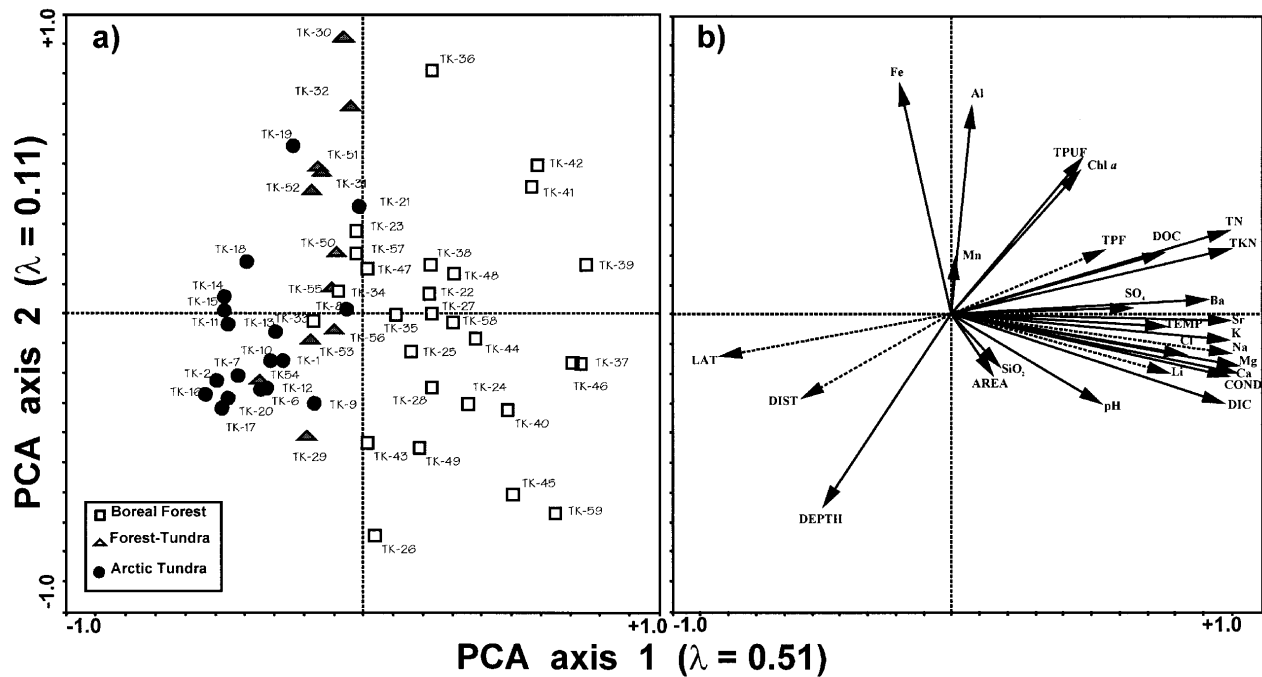
Fig. 6. Principal Components Analysis (PCA) of the 56 study sites and environmental variables. Dashed lines represent environmental variables that were run passively in the ordination.

4.7. Ordination (PCA)

The distribution of variables and sites in the ordination closely tracked the patterns across vegetational zones discussed earlier. PCA revealed two main directions of variation, with axis 1 explaining 51% of the total variance and axis 2 explaining an additional 11% (Fig. 6). An examination of the inter-set correlations of the 20 active environmental variables, together with the position and length of the arrows, revealed that the strongest direction of variation (axis 1) was primarily a gradient of major ions and nitrogen consisting of Ca, Mg, K, Cl, SO4, COND, pH, DIC, DOC, nitrogen TKN, TN, Ba, Sr, and TEMP. All of these variables had high positive correlations with PCA axis 1 and to each other (Tab. 3), and plotted towards the right of the ordination. The second gradient (axis 2) was characterized by strong inter-set correlations to Al, Fe, TPUF, and DEPTH. Al and Fe were positively correlated to PCA axis 2 and to each other, and negatively correlated to DEPTH (Tab. 3, Fig. 6).

The 56 sites were clearly separated into the three ecozones along the first PCA gradient, with boreal forest lakes plotting almost exclusively on the right hand side of the ordination, indicating that these sites were characterized by higher concentrations of major and minor ions (and related variables) and nitrogen (Fig. 6a). Arctic tundra sites, on the other hand, plotted exclusively on the left hand side of the ordination, and were associated with more dilute lakewater chemistry. Boreal forest sites showed greater dispersal in the PCA ordina-

tion space than did the arctic tundra sites, reflecting greater variability in lakewater chemistry within this ecozone. The second direction of variation was less obviously related to the vegetational gradient. Here, deeper lakes plotted towards the lower half of the ordination, and lakes with higher concentrations in Fe and Al plotted towards the upper half of the plot. As there were no obvious spatial trends for DEPTH, Fe or Al, (Fig. 2a, Fig. 4ef), sites that plotted near these environmental arrows in the PCA did not show any clear association to vegetation zones (Fig. 6a, b).

4.8. Some implications of treeline spatial trends in terms of predicted climatic warming

The spatial gradient of climate-related factors (e.g. temperature, vegetation, precipitation, degree of permafrost) across treeline was often closely reflected in the lakewater chemistry of the 56 study lakes. Therefore, these limnological trends may provide important information on possible future changes with additional climatic warming. For example, warmer climates will shorten the duration of ice cover on lakes. This could result in some currently polymictic or isothermal lakes to thermally stratify, and dimictic lakes to have longer and more stable periods of thermal stratification (De Stasio *et al.* 1996). The length of the growing season will also increase with diminished ice and snow cover, extending the photosynthetically active period and increasing algal production rates (Smol 1983, 1988; Douglas & Smol 1999). A warmer and drier climate will affect the hydrological regime, as increases in evapora-

tion will not likely be compensated for by increases in precipitation (Schindler *et al.* 1997). Changes in the extent of permafrost (deeper active layer and continuous permafrost becoming discontinuous in northern regions) will also have a profound effect on the hydrological system through increased groundwater flow and runoff from the catchment to the lake.

The above physical changes brought about by climatic warming will have important implications on lakewater chemistry. Increased runoff and groundwater flow should increase the input of nutrients to lakes, resulting in higher production. The net yield of base cations entering the lakes should increase as a result greater groundwater inputs, which should also increase pH (Webster *et al.* 1990; Schindler *et al.* 1996). Increases in pH are also expected during warmer temperatures through enhanced in-lake alkalinity generation processes such as increased biological productivity and stronger sulfate reduction processes (Psenner & Schmidt 1992; Schindler *et al.* 1996). These physical and chemical changes, will undoubtedly have important impacts on aquatic habitats and species composition in freshwater ecosystems.

5. CONCLUSIONS

The chemical characteristics of the 56 study lakes appear to be strongly influenced by climatic and climate-related factors (e.g. degree of permafrost, vegetation, weathering, duration of snow and ice cover). Our results show that: 1) distinct limnological differences exist among treeline ecozones; 2) of all the measured limnological variables, ionic and nutrient concentrations displayed the greatest changes from the subarctic boreal forest to the arctic tundra; and 3) arctic tundra lakes were more chemically dilute than subarctic forested lakes.

Comparisons with other circumpolar treeline regions indicate that some global patterns are emerging, suggesting that climatic warming will impact the chemistry of freshwater treeline lakes. However, because lakewater chemistry can also be related to factors other than climate (e.g. local geology, vegetation, human disturbances and physiographic relief) and due to the vastness of this ecotone on a global scale, more studies of this kind are needed to refine our understanding of baseline limnological conditions at circumpolar treeline. Future research should include monitoring of treeline lakes to examine the changing patterns of ice cover duration, thermal stratification, and the associated changes in lakewater limnology. From a paleoclimatic perspective, studies of this kind, coupled with paleolimnological analyses, have the potential to be used to track past shifts in the arctic treeline and other climate-related characteristics. These data will provide important information needed to better understand these changing ecosystems under a climatic warming scenario.

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