

# Mineralogy, lithostratigraphy, and inferred geochemical history of North Ingebrigt lake, Saskatchewan

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*Shang, Y. and Last, W.M., 1999: Mineralogy, lithostratigraphy, and inferred geochemical history of North Ingebrigt lake, Saskatchewan; in Holocene Climate and Environmental Change in the Palliser Triangle: A Geoscientific Context for Evaluating the Impacts of Climate Change on the Southern Canadian Prairies, (ed.) D.S. Lemmen and R.E. Vance; Geological Survey of Canada, Bulletin 534, p. 95–110.*

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**Abstract:** North Ingebrigt lake, a small, hypersaline playa basin in the Great Sand Hills of southwestern Saskatchewan, contains one of Canada's thickest Holocene terrestrial salt sequences. The 10 000-year long lacustrine sequence from the basin consists of well indurated salt, with only minor mud and organic debris. Cores lack obvious bedding, colour variation, or other visible sedimentary structures. The mineral suite consists mainly of hydrated Na-, Mg-, Ca-, and (Na+Mg)-sulphates, -carbonates, and -chlorides. This long and apparently uninterrupted sequence of soluble salts implies that the lake was characterized by high salinity throughout its Holocene history. Preliminary chronostratigraphy indicates that accumulation rates have varied greatly in the past. Similarly, variations in salt mineralogy suggest that the basin experienced significant changes in brine composition. These evaporites permit reconstruction of specific ion activities and ratios in the brine through time, providing the first detailed evidence of the complexity of brine evolution in a closed-basin lacustrine environment in western Canada.

**Résumé :** Le lac North Ingebrigt, petit bassin à playa hypersalin dans les dunes Great Sand Hills du sud-ouest de la Saskatchewan, contient une des plus épaisses séquences de sels continentaux holocènes au Canada. La séquence lacustre du bassin, longue de 10 000 ans, se compose de sel très induré renfermant de faibles quantités de boue et de débris organiques. Les carottes ne présentent ni stratification manifeste, ni variation de couleur, ni autre structure sédimentaire visible. La suite minérale est composée essentiellement de sulfates, de carbonates et de chlorures hydratés de Na, Mg, Ca et Na+Mg. L'existence de cette longue séquence apparemment ininterrompue de sels solubles permet de supposer que le lac se caractérisait par une forte salinité pendant l'ensemble de son histoire holocène. Les études chronostratigraphiques préliminaires indiquent que les taux d'accumulation ont fortement varié par le passé. De même, les variations de la minéralogie des sels laissent penser que le bassin a subi des changements importants quant à la composition des saumures. Ces évaporites permettent la reconstitution dans le temps des activités et des rapports ioniques spécifiques de la saumure, fournissant ainsi les premières indications détaillées sur la complexité de l'évolution des saumures dans un milieu lacustre de bassin fermé dans l'Ouest du Canada.

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## INTRODUCTION

Mineralogical and lithostratigraphic investigations of lake sediments have traditionally provided paleolimnologists with an important but usually nonquantitative understanding of such factors as water depth, drainage-basin weathering conditions, tectonic setting, and sediment provenance (Gierlowski-Kordesch and Kelts, 1994; Dearing, 1997). In contrast, paleobiological parameters have often been called upon to contribute a somewhat more quantitative perception of the lake. This is still true in many lacustrine settings: biological indicators such as ostracodes, chrysophytes, diatoms, chironomids, and plant macrofossils can provide exceptional quantitative information on past water salinity, major-ion chemistry, nutrient level, temperature, and depth in most fresh and marginally saline lakes (e.g. Berglund, 1986; Davis, 1990; Sullivan and Charles, 1994).

However, in large areas of western North America as well as many other regions of the world, saline to hypersaline surface waters dominate the landscape. Climatic and hydrological conditions during much of the mid- to early Holocene in western Canada gave rise to greatly elevated water salinities, even in lakes where modern ionic concentrations are low. These high-salinity brines are often accompanied by strongly alkaline conditions which curtail the use of siliceous microfossils (Evans, 1993; Gell et al., 1994). Shallow water and associated high-energy oxidizing conditions at the sediment-water interface further limit the potential of paleobiological work by creating poor preservation conditions for pollen and macrofossils. At the same time, these saline and hypersaline lacustrine settings can provide investigators with an extraordinarily explicit record of past changes in water chemistry through the endogenic and authigenic minerals preserved in the sediment. As emphasized by Teller and Last (1990), the evaporites are particularly useful because their mere presence (versus abundance) can provide unambiguous data on the thermodynamic conditions of the precipitating solution.

Evaporite formation and related physicochemical conditions have been subjects of long-standing sedimentological interest and study over the last two centuries (Eugster, 1971; Multhauf, 1978). Numerous chemical models have been established to predict the sequence of salts precipitated during evaporative concentration of a brine. In general, two approaches have been used to determine the stable mineral assemblages and solution composition: direct evaporation experiments and thermodynamic and solubility calculations. Since the experimental work of Van't Hoff and his successors in the early part of this century, a large amount of data has accumulated on the solubility of salts in different aqueous systems (Assarsson, 1950a, b, c; Stewart, 1963; Braitsch, 1971; Eugster, 1971). These data have been successfully used to graphically predict the sequence of major minerals precipitated from evaporating brines by means of concentration-temperature diagrams and phase (or Jänecke) diagrams (Harvie et al., 1982). This graphical approach is best applied to relatively simple binary and common-ion aqueous systems, and cannot readily manage the more complex ionic systems that commonly occur in natural brines (Hardie, 1984).

To solve this problem, several generations of computer models based on equilibrium thermodynamics have emerged over the past two decades. Although many of these models are limited to dilute aqueous solutions with ionic strengths less than 0.7, some are valid to high ionic strengths (Harvie et al., 1984; Weare, 1987).

Experimental and theoretical geochemical models provide a powerful tool that can assist in deciphering past chemical and hydrological conditions and depositional processes during evaporite formation in a sedimentary basin. In this paper, we use these mineral solubility models as the theoretical basis for interpreting the observed evaporite mineral assemblages and chemical compositions of brines in North Ingebrigt lake, Saskatchewan, and the hydrological conditions under which these evaporites were deposited. Although commonly applied to brine reconstruction in marine and lacustrine settings elsewhere, this was the first such effort to apply these models to lake deposits of the Great Plains of North America.

## METHODS

This paper is based on mineralogical and lithostratigraphic analyses of a single 23 m long sediment core retrieved from the North Ingebrigt lake basin in February 1994. As most of the sedimentary fill in the North Ingebrigt basin consists of highly indurated salt, conventional paleolimnological coring techniques (e.g. Livingstone piston coring, Vibracoring, hollow-stem Shelby-tube augering) were not able to penetrate and/or recover the sediment. A specially modified, air-cooled diamond-drilling/coring technique was used to retrieve core. Details regarding this drilling equipment and unique coring technique, not previously used in Quaternary paleolimnology in Canada, are found in Shang (1999). The diamond drilling afforded excellent recovery of large-diameter (6 cm), undisturbed sediment cores. Because a compressed air (rather than water) circulation system was used, the highly soluble salts experienced little chemical modification or dissolution during retrieval. In addition to the 23 m core reported in this paper, cores and auger samples were also collected from other sites in North Ingebrigt lake. Analytical results from these other sections and intrabasinal correlations are presented elsewhere (Shang, 1999).

The core was extruded in the field, cut into sections approximately 2 m long, wrapped in plastic, and transported to the University of Manitoba, where it was stored in a cold room (4°C) until sampled. In the laboratory, core sections were cut longitudinally using a rock saw, photographed, and one of the halves was subsampled at 2 cm intervals for various physical, chemical, and mineralogical analyses. Subsamples for <sup>14</sup>C dating and other analyses were taken at irregular intervals. Subsampling was done in a cold room and subsamples were stored at 4°C to minimize postcollection modification of the mineral suite.

Mineralogical analyses were conducted using X-ray diffraction (XRD) techniques (Last, 1996; Shang, 1999). A nonaqueous medium was used in sample preparation, and subsamples were stored in a temperature- and humidity-

controlled environment until analyzed. Mineral identification was aided by the use of an automated search-match computer program (Marquart, 1986). Percentages of the various minerals were estimated from the bulk mineral diffractograms using the intensity of the strongest peak for each mineral, as outlined by Schultz (1964) and Last (1980). Nonstoichiometry of the dolomite and calcite was determined by examining the displacement of the  $d_{104}$  peak on a detailed (slow) XRD scan (Goldsmith and Graf, 1958) and calculated according to Hardy and Tucker (1988). All detailed evaporite and carbonate mineralogy was deciphered from detailed (slow) XRD scans. Moisture content, organic matter content, and total carbonate mineral content were evaluated by weight loss on heating to temperatures of 45°C, 500°C, and 1000°C, respectively (Dean, 1974). Duplicate samples were prepared and analyzed for both mineralogy and weight loss every 50 cm. These replicate analyses indicate that precision of the data reported here is approximately  $\pm 1\%$  for weight loss and  $\pm 7\%$  for mineralogy.

Various statistical analyses were performed on the mineralogical and lithostratigraphic data in order to evaluate parameter interrelationships (Pearson product-moment linear correlation analysis and R-mode factor analysis), and to define stratigraphic units (cluster analysis). All statistical evaluation was done using the computer program SAS (SAS Institute Inc., 1989). Details regarding these statistical procedures are provided in Sheskin (1997) and Shang (1999). Modified versions of the computer programs WATEQF (Truesdell and Jones, 1974; Rollins, 1989), MIX2 (Plummer et al., 1975), and PHRQPITZ (Plummer et al., 1988; Shang, 1999) were used to help determine the thermodynamic activity and molar ratios of the chemical species.

## MODERN NORTH INGEBRIGT LAKE

### General setting

North Ingebrigt lake (lat. 50°24.5'N, long. 109°22.5'W, elev. 695 m a.s.l.) occupies a narrow riverine basin in the Great Sand Hills of southwestern Saskatchewan (Fig. 1), about 100 km west of Swift Current. The basin probably originated about 14 000–13 000 BP as a glacial meltwater spillway superposed on the buried preglacial Johnsborough Valley (David, 1964; Christiansen, 1979). The area is underlain by up to 60 m of till and glaciofluvial sediments, which in turn overlie about 3 km of Phanerozoic sedimentary rocks. The approximately 300 km<sup>2</sup> watershed of the lake is characterized by poorly integrated drainage and hummocky to gently rolling topography consisting mainly of sand flats, undulating moraine, and stabilized sand dunes (Epp and Townley-Smith, 1980; Saskatchewan Research Council, 1985).

The closed basin of North Ingebrigt lake is about 3 km long and 750 m wide, with a high-stage surface area of 1.25 km<sup>2</sup>. The lake is located in the most arid portion of the northern Great Plains. The Sand Hills area experiences a cold continental climate characterized by extreme temperature

(-46° to 45°C) and precipitation variations. Fox Valley, 20 km north of the basin, receives approximately 300 mm of precipitation annually, and has a mean daily temperature of -14°C in January and +21°C in July.

Salts have been commercially extracted from numerous saline wetlands and playas in the vicinity of North Ingebrigt lake for more than 70 years (Tomkins, 1953, 1954; Last and Slezak, 1987). One of North America's largest sodium sulphate mines and processing plants is located a few kilometres south at Ingebrigt Lake. Salts have also been extracted from Chain (local name), Snakehole, Corral, Boot (local name), Verlo (local name), and Vincent lakes, all within 30 km of the North Ingebrigt basin. Although North Ingebrigt has, to date, not been mined, the lake is presently under mineral lease, and Cole (1926) identified a total anhydrous Na<sub>2</sub>SO<sub>4</sub> reserve of about  $3 \times 10^6$  t.

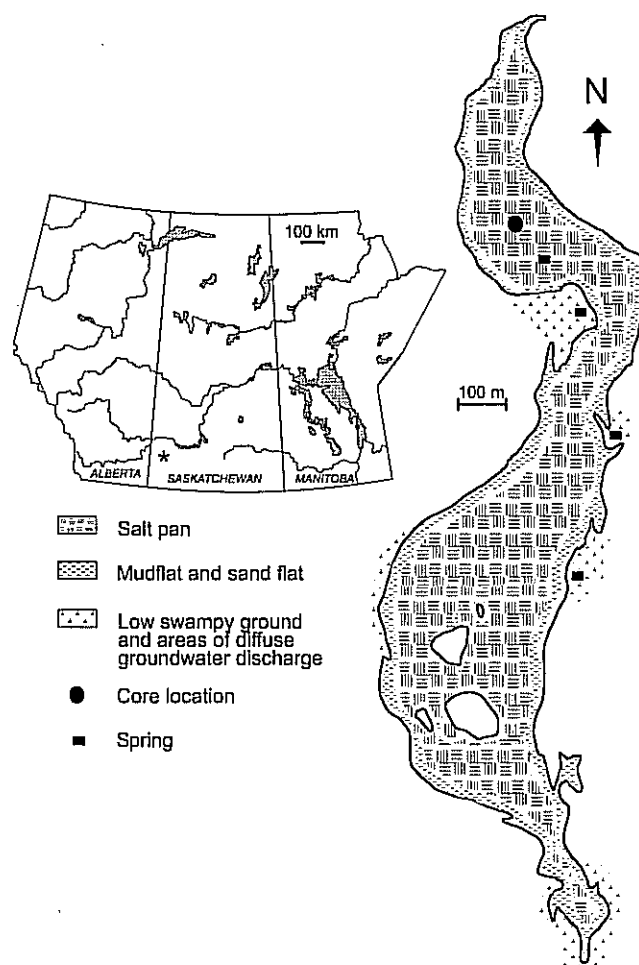


Figure 1. Generalized distribution of modern sedimentary facies and location of springs in North Ingebrigt lake. Inset shows location of the lake within the northern Great Plains of western Canada.

### Hydrogeology and hydrological setting

North Ingebrigt lake is one of a series of distinct, separate, riverine salt playas occupying this 50 km long, north-trending meltwater channel. Closure of the North Ingebrigt basin is small and a water level of more than approximately 1.5 m above the present-day surface will spill over to Ingebrigt Lake, less than 1 km to the south. The spill point for the entire Ingebrigt–North Ingebrigt chain of lake basins is approximately 20 m above the present-day surface of the valley floor.

The modern hydrology and hydrochemistry of North Ingebrigt lake and surrounding drainage basin were discussed by Shang (1999), although David (1964), Ruffel (1968), and Rutherford (1967, 1970) also provided important regional and local groundwater and hydrochemical data. Typical of most of the shallow, salt-dominated playas in western Canada, the hydrological budget of North Ingebrigt lake is dominated by groundwater inflow and evaporation. There is no perennial streamflow into this topographically closed basin, and evaporation exceeds mean annual precipitation by a factor of 3 (Canadian National Committee for the International Hydrologic Decade, 1978). Groundwater enters the lake via both diffuse inflow and several discrete springs. The lake exhibits typical playa characteristics, filling with water during the spring and early summer and usually drying completely by late summer or early fall. Maximum water depth is generally less than 50 cm.

North Ingebrigt lake water is usually hypersaline, with salinities in the range 100–300 g·L<sup>-1</sup> total dissolved solids (TDS). Although strong seasonal variation occurs in brine chemistry, the water is alkaline (pH > 8), strongly dominated by Na<sup>+</sup> and SO<sub>4</sub><sup>2-</sup>, and nearly depleted of Ca<sup>2+</sup> and HCO<sub>3</sub><sup>-</sup> (Fig. 2). Inflowing groundwater is relatively dilute (less than 5 g·L<sup>-1</sup> TDS), with higher proportions of Ca<sup>2+</sup> and HCO<sub>3</sub><sup>-</sup>.

### Modern sedimentology

North Ingebrigt lake is a salt-dominated playa. Except for a narrow, nearshore fringe of organic-rich, fine-grained and poorly sorted clastic sediments, the modern lake sediments are almost entirely very soluble evaporitic salts (Fig. 1). These endogenic precipitates of the modern salt-pan sedimentary facies comprise mainly hydrated Na- and Mg-sulphates, including mirabilite (Na<sub>2</sub>SO<sub>4</sub>·10H<sub>2</sub>O), bloedite (Na<sub>2</sub>Mg(SO<sub>4</sub>)<sub>2</sub>·4H<sub>2</sub>O), epsomite (MgSO<sub>4</sub>·7H<sub>2</sub>O), and leonhardite (MgSO<sub>4</sub>·4H<sub>2</sub>O). Gypsum (CaSO<sub>4</sub>·2H<sub>2</sub>O), halite (NaCl), despujolsite (Ca<sub>3</sub>Mn(SO<sub>4</sub>)<sub>2</sub>(OH)<sub>6</sub>·3H<sub>2</sub>O), and protodolomite (disordered, nonstoichiometric MgCa(CO<sub>3</sub>)<sub>2</sub>) are commonly present in small to trace amounts in the upper few centimetres. The inorganic fraction of the detrital sediments of the mud flat, sand flat, and surrounding colluvium facies are composed of clay minerals (mostly illite and expandable lattice clays), feldspars, carbonate minerals (mainly dolomite), quartz, and ferromagnesian minerals.

Modern sedimentation in North Ingebrigt lake is controlled largely by the seasonal (or periodic) sequence of flooding, evaporative concentration, and desiccation of the playa surface. Like many other saline playas in the region, sedimentary processes are dominated by: 1) formation of salt crusts, efflorescent crusts, spring deposits, and intra-sedimentary salts; 2) subaqueous cumulate and bottom salt precipitation; 3) physical reworking and redistribution of clastic salt and accretionary salt grains; 4) formation of salt cements; 5) irregular dissolution of surface salt crusts and formation of solution pits on the playa surface and within the near-surface sediment; 6) formation of karst chimneys; and 7) mud diapirism and subsequent reworking of fine-grained siliciclastic material. These processes were discussed in detail by Last (1984, 1989a) and Shang (1999). The salt

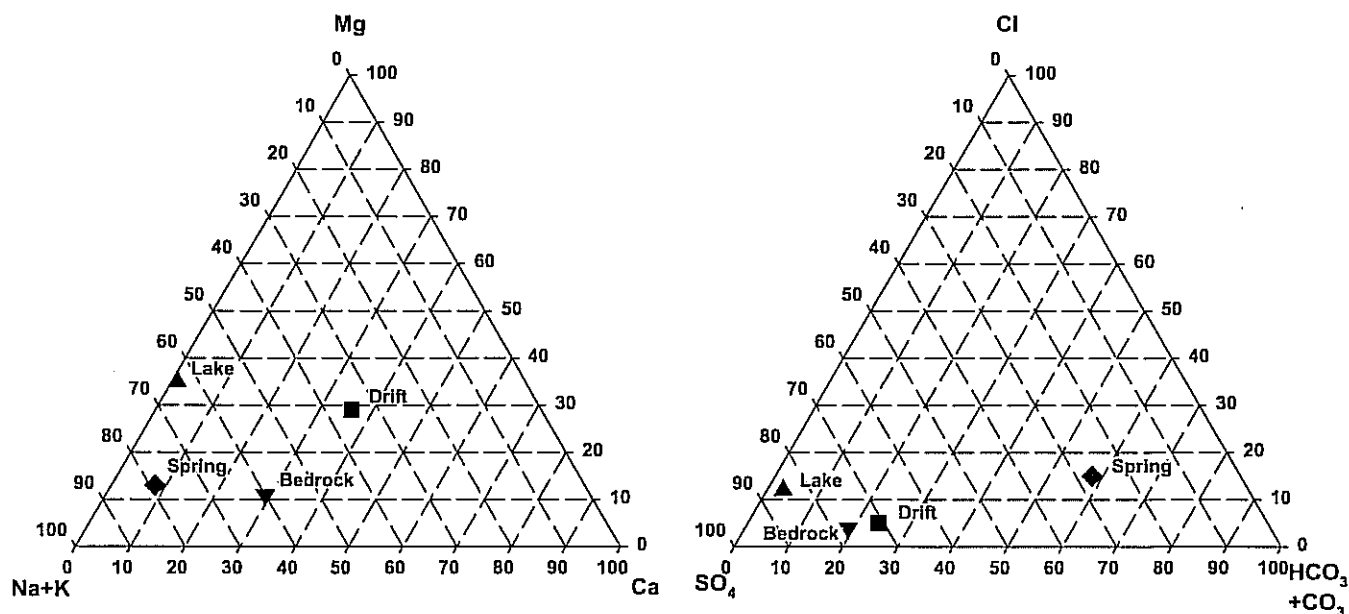


Figure 2. Mean water composition (milli-equivalent %) of North Ingebrigt lake (▲), inflowing springs (◆), and groundwater from near-surface Cretaceous bedrock (▼) and glacial deposits (■).

playas in the Ingebrig chain contain several of the largest Holocene saline karst features identified in the northern Great Plains (Last, 1993a).

The paragenesis of the mineral suite in North Ingebrig lake is complex. In a groundwater-dominated, hypersaline salt pan/playa environment such as that found in today's basin, the distinction between endogenic and authigenic mineral components is obscure (*see also* Sonnenfeld, 1984; Smoot and Lowenstein, 1991). Salts that may have formed as true endogenic precipitates (i.e. derived from within the water column of the lake) are very likely dissolved and reprecipitated numerous times at the sediment-water interface as the composition of the overlying brine changes during the year, or at the surface of the playa upon subaerial exposure and desiccation. Likewise, both fresh and saline pore waters within the upper few centimetres of the playa surface can readily modify the precipitated salts. Although seasonal and longer term mineralogical changes and accompanying diagenesis of the nondetrital suite in North Ingebrig sediment are complex processes, observations from numerous other saline playas in western Canada and other parts of North

America (e.g. Smith and Friedman, 1986; Last, 1989b) indicate that the evaporite mineral suite is largely stabilized within a few tens of centimetres below the playa surface.

## STRATIGRAPHY

### General description

The stratigraphic sequence recovered from North Ingebrig lake consists almost entirely of massive, coarsely crystalline, well indurated salt. The sediment of the upper few metres of the section is somewhat more friable, with slightly finer crystal size, than deeper parts of the core. Minor amounts of fine-grained mud occur sporadically throughout the section. Organic matter content is low, averaging less than 2% (Fig. 3; Table 1). The salt is generally translucent but ranges from opaque to clear. The sediment varies from colourless to white (N8; Munsell™ Colour Chart), grey (N4 to N7), pale yellow (5Y8/4), light olive grey (5Y6/2), and pale red (7.5R6/2). Except for subtle changes in clarity, colour, and degree of

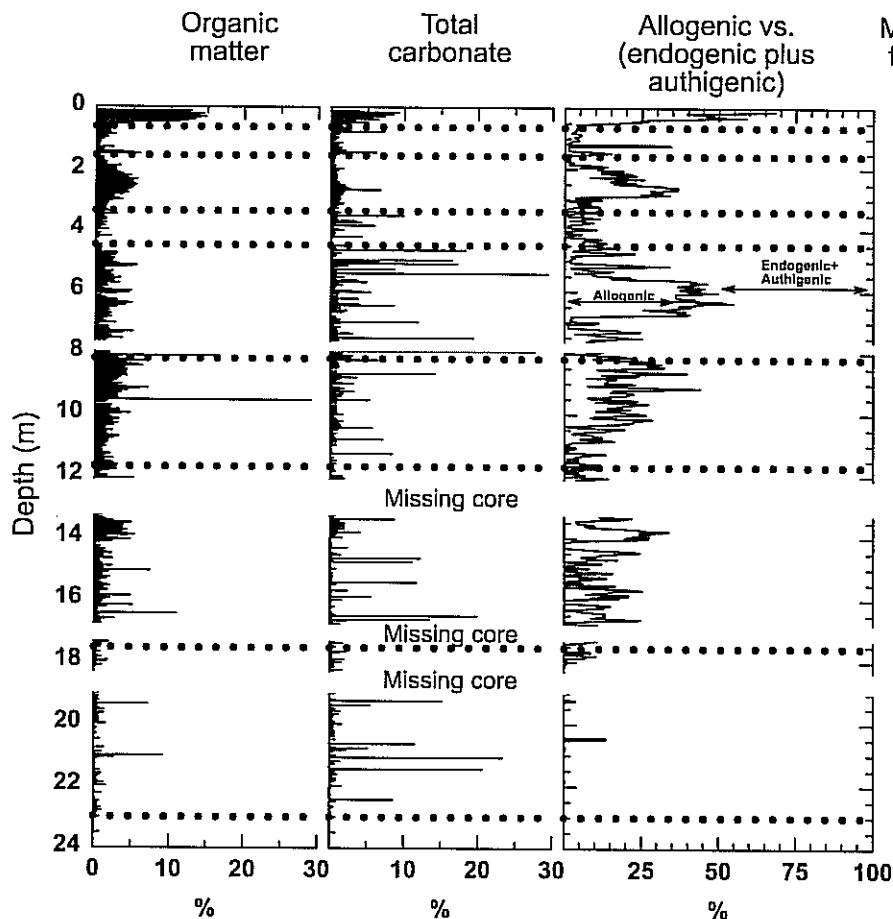


Figure 3. Stratigraphic variation in percentages of organic matter, total carbonate content, and proportion of total inorganic allogenic material versus endogenic+authigenic components in North Ingebrig lake core. Heavy horizontal dotted lines delineate mineral facies (*see* Table 1). Gaps in plots represent sections in which there is missing core.

**Table 1.** Summary of average characteristics of mineral facies from North Ingebrigt lake core.

	Mineral facies						Core average
	1 Na-SO <sub>4</sub> facies	2 Mg-CO <sub>3</sub> - Na-SO <sub>4</sub> facies	3 Ca-SO <sub>4</sub> - Na-SO <sub>4</sub> facies	4 Muddy Na-SO <sub>4</sub> facies	5 Muddy Mg-calcite- Na-SO <sub>4</sub> facies	6 Dolomitic Na-SO <sub>4</sub> facies	
Total clay minerals (%)	0.4	6.7	12.2	9.1	9.9	3.4	5.2
Quartz (%)	0.5	0.6	1.1	2.5	3.5	9.9	2.6
Total feldspar minerals (%)	0.6	1.8	0.5	11.7	3	2.7	3.1
Potassic feldspars (%)	<0.1	0.1	0.1	0.4	1.4	1.7	0.4
Plagioclase (%)	0.5	1.7	0.4	11.3	1.5	0.9	2.7
Total calcite (%)	<0.1	0.1	<0.1	0.1	0.7	0.3	0.2
Low-Mg calcite (%)	<0.1	0.1	<0.1	0.1	0.1	<0.1	<0.1
Magnesian calcite (%)	<0.1	0.1	0.1	0.1	0.6	0.3	0.2
MgCO <sub>3</sub> in Mg-calcite (mol%)	n.c.	8.7	6.3	9.4	12.2	13.4	10.4
Total dolomite (%)	0.1	1.5	1.9	1.2	3.3	11.8	3.1
Stoichiometric dolomite (%)	0.1	0.3	0.5	0.5	1.7	2	0.8
Protodolomite (%)	0.1	1.2	1.3	1.6	1.5	9.8	2.3
CaCO <sub>3</sub> in protodolomite (mol%)	n.c.	62.6	63.8	62.5	60.3	54.3	60.9
Magnesite (%)	<0.1	1	1	0.3	0.1	<0.1	0.3
Aragonite (%)	0.1	0.3	0.2	0.1	0.1	<0.1	0.1
Ca sulphates (%)	0.3	3.4	17.2	5.5	6.8	1.7	5.1
Na sulphates (%)	97.9	83.9	65.5	72	76.2	65.7	79.5
Mg sulphates (%)	<0.1	0.4	0.1	n.d.	0.2	4.1	0.7
Chlorides (%)	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Pyrite (%)	n.d.	0.1	n.d.	n.d.	n.d.	n.d.	<0.1
Allogenic fraction (%)	1.7	10.7	15.8	24.6	20.4	28.1	11.6
(Endogenic+authigenic) fraction (%)	98.3	89.3	84.2	75.4	79.6	71.9	88.2
Total organic matter (%)	0.3	1.3	2.5	1.9	2.4	5.3	2.1

n.c. – not calculated

n.d. – not detected

**Table 2.** Endogenic and authigenic mineralogy of North Ingebrigt lake core.

Mineral name	Composition	Occurrence <sup>1</sup>	Mineral name	Composition	Occurrence <sup>1</sup>
<b>Carbonate minerals</b>			<b>Sulphate minerals (cont.)</b>		
Aragonite	CaCO <sub>3</sub>	Common	Polyhalite	K <sub>2</sub> Ca <sub>2</sub> Mg(SO <sub>4</sub> ) <sub>4</sub> ·2H <sub>2</sub> O	Rare
Arlinite	Mg <sub>2</sub> CO <sub>3</sub> (OH) <sub>2</sub> ·3H <sub>2</sub> O	Very rare	Potassium alum	KAl(SO <sub>4</sub> ) <sub>2</sub> ·12H <sub>2</sub> O	Very rare
Ankerite	Ca(Fe,Mg)(CO <sub>3</sub> ) <sub>2</sub>	Rare	Leonhardite	MgSO <sub>4</sub> ·4H <sub>2</sub> O	Very rare
Banstonite	Ca <sub>2</sub> Ba <sub>4</sub> (CO <sub>3</sub> ) <sub>13</sub>	Very rare	Thenardite	Na <sub>2</sub> SO <sub>4</sub>	Very common
Calcite	CaCO <sub>3</sub>	Rare	Wallerite	Na <sub>2</sub> Ca(SO <sub>4</sub> ) <sub>2</sub> ·4H <sub>2</sub> O	Very rare
Gaylussite	Na <sub>2</sub> Ca(CO <sub>3</sub> ) <sub>2</sub> ·5H <sub>2</sub> O	Very rare	<b>Carbonate-sulphate, carbonate-sulphate-chloride, and carbonate-phosphate minerals</b>		
Kutnohorite	Ca(Mn,Mg)(CO <sub>3</sub> ) <sub>2</sub>	Very rare	Bonshiedite	Na <sub>3</sub> Fe(PO <sub>4</sub> )(CO <sub>3</sub> )	Very rare
Magnesite <sup>2</sup>	MgCO <sub>3</sub>	Common	Bradleyite	Na <sub>3</sub> Mg(PO <sub>4</sub> )(CO <sub>3</sub> )	Very rare
Magnesian calcite	(Mg,Ca <sub>1-x</sub> )CO <sub>3</sub>	Common	Burkeite	Na <sub>4</sub> (SO <sub>4</sub> )CO <sub>3</sub>	Very rare
Minrecordite	CaZn(CO <sub>3</sub> ) <sub>2</sub>	Very rare	Hanksite	KNa <sub>22</sub> (CO <sub>3</sub> ) <sub>2</sub> (SO <sub>4</sub> ) <sub>2</sub> Cl	Common
Protodolomite	(Mg,Ca <sub>1-x</sub> )(CO <sub>3</sub> ) <sub>2</sub>	Very common	Rapidcreekite	Ca <sub>2</sub> (CO <sub>3</sub> )SO <sub>4</sub> ·4H <sub>2</sub> O	Very rare
Zemkorite	Na <sub>2</sub> Ca(CO <sub>3</sub> ) <sub>2</sub>	Very rare	Tychite	Na <sub>2</sub> Mg <sub>2</sub> SO <sub>4</sub> (CO <sub>3</sub> )	Very rare
<b>Sulphate minerals</b>			<b>Chloride minerals</b>		
Arcanite	(K,NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	Rare	Bischofite	MgCl <sub>2</sub> ·6H <sub>2</sub> O	Very rare
Bloedite	Na <sub>2</sub> Mg(SO <sub>4</sub> ) <sub>2</sub> ·4H <sub>2</sub> O	Very common	Carnallite	KMgCl <sub>3</sub> ·6H <sub>2</sub> O	Very rare
Despujolite	Ca <sub>2</sub> Mn(SO <sub>4</sub> ) <sub>2</sub> (OH)·3H <sub>2</sub> O	Rare	Douglasite	KFeCl <sub>2</sub> ·2H <sub>2</sub> O	Very rare
Epsomite	MgSO <sub>4</sub> ·7H <sub>2</sub> O	Common	Halite	NaCl	Rare
Eugsterite	Na <sub>2</sub> Ca(SO <sub>4</sub> ) <sub>2</sub> ·2H <sub>2</sub> O	Very rare	<b>Nitrate and borate minerals</b>		
Görgavite	K <sub>2</sub> Ca <sub>2</sub> (SO <sub>4</sub> ) <sub>6</sub> ·H <sub>2</sub> O	Very rare	Inderborite	CaMgB <sub>2</sub> O <sub>11</sub> ·H <sub>2</sub> O	Rare
Gypsum	CaSO <sub>4</sub> ·2H <sub>2</sub> O	Very common	Niter	KNO <sub>3</sub>	Very rare
Hexahydrite	MgSO <sub>4</sub> ·4H <sub>2</sub> O	Common	Soda Niter	NaNO <sub>3</sub>	Very rare
Kieserite	MgSO <sub>4</sub> ·H <sub>2</sub> O	Rare	Nitrobarite	Ba(NO <sub>3</sub> ) <sub>2</sub>	Rare
Krausite	Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> ·2H <sub>2</sub> O	Very rare	<b>Other minerals</b>		
Leightonite	K <sub>2</sub> Ca <sub>2</sub> Cu(SO <sub>4</sub> ) <sub>4</sub> ·2H <sub>2</sub> O	Very rare	Pyrite	FeS <sub>2</sub>	Very rare
Mercallite	KHSO <sub>4</sub>	Very rare	Sepiolite	Mg <sub>3</sub> Si <sub>6</sub> O <sub>15</sub> (OH) <sub>2</sub> ·6H <sub>2</sub> O	Very rare
Mirabilite <sup>3</sup>	Na <sub>2</sub> SO <sub>4</sub> ·10H <sub>2</sub> O	Very common(?)			

<sup>1</sup> Very common – mineral occurs in greater than 75% of the samples analyzed. Common – mineral occurs in 25–75% of the samples analyzed. Rare – mineral occurs in 10–25% of the samples analyzed. Very rare – mineral occurs in less than 10% of the samples analyzed. These characterizations apply only to occurrence within the core and are not meant to imply any information about the relative abundance of the particular mineral. For example, some of the phases that are listed as being rare or very rare can, nonetheless, be relatively abundant in a particular sample, and minerals that may be listed as common can have very low abundances.

<sup>2</sup> Includes hydromagnesite and pseudohydromagnesite.

<sup>3</sup> Because of its extreme instability and very rapid dehydration, mirabilite was rarely identified by X-ray diffraction.

induration of the salts, due mainly to slight variations in mud and organic matter content, there is an absence of visible bedding in the 23 m of recovered section.

The inorganic mineral suite in North Ingebrigt lake comprises three genetic types: allogenic (i.e. derived from weathering and erosion of the surrounding glacial drift, soils, and bedrock in the watershed), endogenic (i.e. originating from processes occurring within the water column of the lake), and authigenic (i.e. originating from processes occurring once the sediment has been deposited). The endogenic+authigenic fraction dominates the sedimentary sequence (average 88%; Fig. 3; Table 1) and consists of a complex assemblage of mainly hydrated Na-, Mg-, (Na+Mg)-, and Ca-sulphate minerals, with smaller amounts of Mg-, (Ca+Mg)-, Na-, and Ca-carbonate and -chloride minerals (Table 2). Although the entire stratigraphic section is dominated by sulphate minerals, the relative proportion of Na-sulphates decreases upward corresponding to a complementary increase in Mg- and Ca-sulphates. Most of the endogenic and authigenic carbonate minerals show little stratigraphic variation. Magnesium carbonates (magnesite, hydromagnesite, and pseudohydromagnesite) are most abundant between about 8 and 18 m depth, whereas the carbonates in the upper metre of section are dominated by disordered, nonstoichiometric dolomite (Fig. 4).

In contrast, the minor amount of allogenic sediment (average 12%) is composed of a relatively simple mixture of clay minerals, feldspar minerals, carbonate minerals, and quartz (Fig. 5). This allogenic fraction closely reflects the composition of glacial deposits in the surrounding drainage basin (cf. David, 1964). These detrital components are most abundant in the upper metre of the section and at 5–7 m and 8.5–10 m depths in the core.

Linear correlation coefficient analysis of the mineralogical and lithostratigraphic data shows, as expected, that variations in the allogenic components are significantly correlated (at  $\alpha=0.005$  confidence level) with changes in organic matter content, and inversely correlated with variations in most of the endogenic and authigenic components. Within the endogenic and authigenic minerals, the changes in sulphate and carbonate fractions show an inverse correlation, the variation in sulphates and chlorides exhibit a strong positive correlation, and fluctuations in the Na-sulphate salts are inversely correlated with the Ca- and Mg-sulphates.

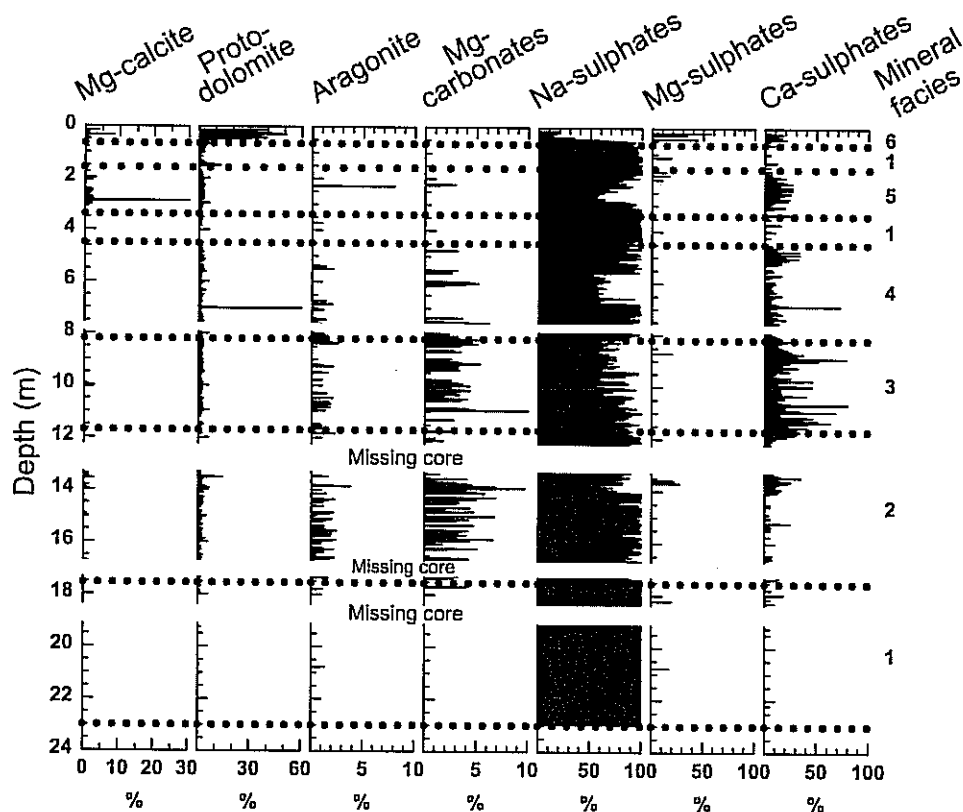


Figure 4. Stratigraphic variation in percentages of Mg-calcite, protodolomite, aragonite, Mg-carbonate minerals, Na-sulphate minerals, Mg-sulphate minerals, and Ca-sulphate minerals in North Ingebrigt lake core. Heavy horizontal dotted lines delineate mineral facies (see Table 1). Gaps in plots represent sections in which there is missing core.

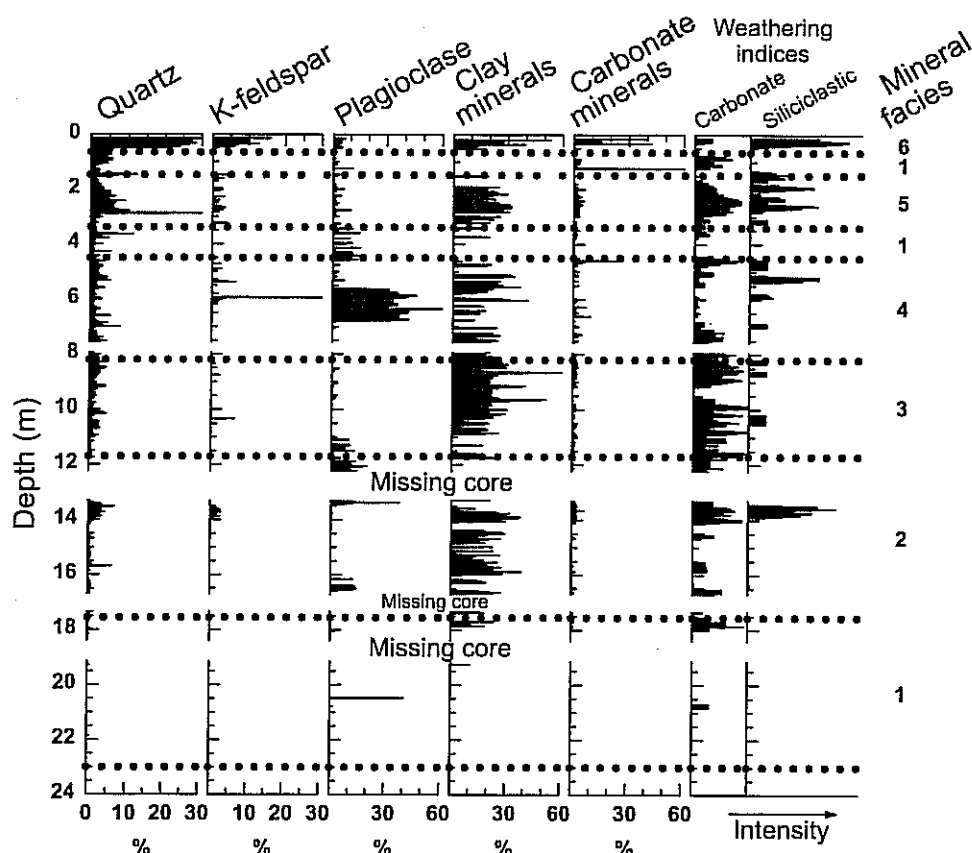


Figure 5. Stratigraphic variation in percentages of quartz, K-feldspar, plagioclase, total clay minerals, and allogenic carbonate minerals in North Ingebrigt lake core. The carbonate weathering index is the ratio of detrital dolomite to calcite, and the siliciclastic weathering index is the ratio of total detrital siliciclastic minerals to total detrital carbonate minerals. An increase in these ratios suggests more intense weathering within the watershed. Heavy horizontal dotted lines delineate mineral facies (see Table 1). Gaps in plots represent sections in which there is missing core.

### Mineral facies

Based mainly on the occurrence and relative abundance of endogenic and authigenic mineral phases in the core, the recovered stratigraphic section from the lake was divided into six mineralogical facies by means of average linkage cluster analyses using a distance coefficient of greater than 0.2 (Jöreskog et al., 1976; Beaumont and Gatrell, 1982; SAS Institute Inc., 1989). It must be emphasized that the contacts between these mineralogical facies are not visually distinctive and are commonly gradational over several tens of centimetres. Table 1 summarizes the average major mineral composition of these six facies. The stratigraphic positions of these facies are shown in Figures 3–5.

Although sulphate and carbonate minerals are the dominant soluble and sparingly soluble components in the inorganic fraction of North Ingebrigt lake sediment, the specific mineralogy of these endogenic and authigenic precipitates is

complex (Table 2). Further subdivision of the mineral facies into mineral zones was based on the detailed composition of the samples in each facies. A total of 31 individual zones were recognized in the 23 m long core, with each zone distinguished by a specific suite of inorganic components (Table 3).

#### Facies 1 – Na-sulphate (17.6 m to base of core, 3.4–4.5 m, and 0.8–1.6 m depth)

The most commonly occurring mineral facies in North Ingebrigt lake is characterized by a relatively simple mineral assemblage comprising mainly Na-sulphate salts with only minor amounts of gypsum, magnesite, protodolomite, aragonite, and halite. This facies is also identified by the presence of nitrate salts. The ratio of (endogenic+authigenic) to allogenic components is very high, and the organic matter content extremely low (Table 1).



Table 3. Stratigraphic sequence of mineral facies and mineral zones in North Ingebrigt lake core.

Mineral facies	Mineral zone	Depth (m)	Salt mineral assemblages		
			Major	Ancillary	Minor & trace
6 Dolomitic Na-sulphate	2	0.1–0.4	Bloedite, protodolomite, thenardite	Gypsum, Mg-calcite	Ankerite, benstonite, despujolsite, douglasite, leightonite, minrecordite
	1	0.4–0.8	Protodolomite, thenardite	Gypsum, Mg-calcite	Bischofite
1 Na-sulphate	2	0.8–1.2	Thenardite	Bloedite, Mg-calcite, protodolomite	Hanksite, niter
	1	1.2–1.6	Protodolomite, thenardite	Gypsum, Mg-calcite	Arcanite, artinite, hanksite
5 Muddy Mg-calcite– Na-sulphate	2	1.6–2.4	Gypsum, thenardite	Aragonite, bloedite, gypsum, magnesite, protodolomite	Arcanite, despujolsite, hanksite, leightonite, mercurite, rapidcreekite
	1	2.4–3.4	Gypsum, thenardite	Mg-calcite, protodolomite	Bensonite, epsomite, görgeyite, hanksite, mercurite, polyhalite
1 Na-sulphate	3	3.4–3.9	Thenardite	Aragonite, gypsum, protodolomite	Hanksite, tychite
	2	3.9–4.1	Thenardite	Gypsum, protodolomite	Niter
	1	4.1–4.5	Thenardite	Protodolomite	Hanksite, niter
4 Muddy Na-sulphate	5	4.5–4.9	Thenardite	Mg-calcite, magnesite, protodolomite	Hanksite
	4	4.9–5.6	Gypsum, thenardite	Aragonite, Mg-calcite, protodolomite	Arcanite, hanksite, Inderborite
	3	5.6–6.2	Thenardite	Gypsum, magnesite, protodolomite	Arcanite, gaylussite, hanksite, hexahydrate, sepiolite, watterite
	2	6.2–7.2	Gypsum, thenardite	Aragonite, protodolomite	Arcanite, hanksite, polyhalite, sepiolite
	1	7.2–8.2	Gypsum, protodolomite, thenardite	Aragonite, magnesite, Mg-calcite	Burkeite, epsomite, hanksite, leonhardtite, mercurite, görgeyite, sepiolite
3 Ca-sulphate– Na-sulphate	5	8.2–9.4	Gypsum, thenardite	Aragonite, gypsum, magnesite, protodolomite	Carnallite, hanksite, polyhalite
	4	9.4–10.2	Gypsum, magnesite, thenardite	Aragonite, halite, Mg-calcite, protodolomite	Hanksite, mercurite, polyhalite, görgeyite, rapidcreekite, sepiolite
	3	10.2–10.5	Gypsum, thenardite	Aragonite, magnesite, protodolomite	Hanksite, mercurite, polyhalite
	2	10.5–11.2	Gypsum, thenardite	Aragonite, magnesite, protodolomite	Hanksite, leonhardtite, polyhalite
	1	11.2–11.7	Gypsum, thenardite	Aragonite, halite, magnesite, Mg-calcite, protodolomite	Hanksite, rapidcreekite, sepiolite
2 Mg– carbonate– Na-sulphate	7	11.7–13.4	Gypsum, magnesite, thenardite	Aragonite, protodolomite	Hanksite
	6	13.4–14.1	Gypsum, magnesite, thenardite	Aragonite, bloedite, halite, Mg-calcite, protodolomite	Arcanite, despujolsite, eugsterite, hanksite, rapidcreekite
	5	14.1–15.1	Gypsum, protodolomite, thenardite	Aragonite, magnesite	Hanksite, görgeyite, leonhardtite
	4	15.1–15.8	Gypsum, thenardite	Aragonite, magnesite, protodolomite	Gaylussite
	3	15.8–16.4	Magnesite, thenardite	Aragonite, protodolomite	Bonshtedite, bradleyite, hanksite, pyrite
	2	16.4–17.4	Gypsum, magnesite, protodolomite, thenardite	Mg-calcite	Hanksite, leonhardtite, rapidcreekite
	1	17.4–17.6	Thenardite		Görgeyite
1 Na-sulphate	5	17.6–19.5	Thenardite	Magnesite, protodolomite	Hanksite
	4	19.5–20.6	Thenardite	Halite	Hanksite, nitrate, nitrobarite
	3	20.6–21.1	Thenardite	Gypsum	Nitrate, protodolomite
	2	21.1–22.2	Thenardite	Gypsum	
	1	22.2–23.0	Thenardite	Gypsum	Hanksite, nitrate

### Facies 2 – Mg-carbonate–Na-sulphate (11.7–17.6 m depth)

Facies 2 is recognized by a relatively high content of magnesite, aragonite, and gypsum (Table 1). Both magnesite and gypsum increase upward over the 6 m of stratigraphic section in which this facies occurs. Facies 2 is also distinguished by the presence of pyrite and a wide array of ancillary sulphate minerals and carbonate-sulphate double salts.

### Facies 3 – Ca-sulphate–Na-sulphate (8.2–11.7 m)

Facies 3 has the highest gypsum content in the stratigraphic sequence and is also characterized by very low amounts of Mg-sulphate salts (Table 1). Both the organic matter and the allogenic fraction of the sediment show an upward increase in abundance over the 2.5 m of core in which this facies is found.

#### Facies 4 – muddy Na-sulphate (4.5–8.2 m depth)

Facies 4 is the most detrital-rich facies of the sedimentary sequence, with nonevaporite minerals constituting up to 50% of the sediment. The endogenic and authigenic precipitates are mainly Na- and Ca-sulphates, with relatively low proportions of carbonates and no Mg-sulphate salts (Table 1).

#### Facies 5 – muddy Mg-calcite–Na-sulphate (1.6–3.4 m depth)

Facies 5 also has a relatively high content of detrital clastic minerals and associated medium to dark grey colour. The endogenic+authigenic fraction is further characterized by a high proportion of Mg-calcite, gypsum, and magnesite, and an absence of Mg-sulphates (Table 1). The salts of facies 5 are less well indurated than those in the other parts of the section.

#### Facies 6 – dolomitic Na-sulphate (0.1–0.8 m depth)

The least commonly encountered facies in the stratigraphic record is marked by relatively high proportions of disordered, nonstoichiometric dolomite associated with a complex mixture of Na-, (Na+Mg)-, and Ca-sulphate salts and halite (Table 1). Facies 6 is only found in the upper metre of the section. Like facies 5, it is poorly indurated and dark coloured.

#### Chronostratigraphy

The chronostratigraphy of the North Ingebrigt lake salt sequence is poorly constrained owing to a paucity of material suitable for dating. Large quantities of core were processed and examined in an unsuccessful attempt to find datable, well preserved upland and shoreline macrofossils. Therefore, finely disseminated organic matter from two samples was used to establish a preliminary chronostratigraphy for the recovered sedimentary sequence. A  $^{14}\text{C}$  age of  $5544 \pm 66$  BP (5912 calendar years before present) was determined on a sample from the base of facies 5 at 3.2–3.4 m depth, and a sample from near the base of the core (22.1–22.9 m) yielded an age of  $10\,250 \pm 150$  BP (12 181 calendar years before present). In addition, a sample of endogenic carbonate material from facies 3 at the base of a 9 m long core in the southern part of the basin yielded a date of  $8240 \pm 120$  BP (9176 calendar years before present). Further temporal control is provided by the presence of a borate mineral zone (inderborite) at 5.6 m depth, which may be an indication of a diagenetically altered volcanic ash corresponding to the 6800 BP Mazama eruption. Petrographic and geochemical analysis of this borate zone is continuing, but it must be emphasized that the interpretation of this zone as an altered volcanic ash is still equivocal.

## DISCUSSION

### *General paleolimnology of North Ingebrigt lake*

The 23 m of salt-rich sediment recovered from the North Ingebrigt lake basin was deposited in a saline to hypersaline environment. The predominance of Na-sulphate salts and paucity of nonevaporitic sediments indicate that a saturated brine, high in  $\text{Na}^+$  and  $\text{SO}_4^{2-}$  ions, existed in the basin for nearly all of the Holocene. However, the complex assemblage of evaporites, including a diverse array of Ca-, Mg-, Na-, and K-sulphates and -carbonates, suggests that the lake experienced considerable short-term fluctuation in brine composition. The common occurrence of chlorides and Mg- and K-sulphates in the evaporitic deposits of the lake implies that the salinity of the water periodically reached, and probably exceeded, values of  $350 \text{ g}\cdot\text{L}^{-1}$  TDS. In contrast, the presence of Mg-calcite and aragonite indicates that lower salinity, Ca-bicarbonate waters were also present. Dramatic fluctuations in brine chemistry and salinity such as these are not unusual in modern saline playas of the region. For example, Ceylon Lake in south-central Saskatchewan has, over the past several decades, ranged from a freshwater Ca-bicarbonate lake (TDS of less than  $5 \text{ g}\cdot\text{L}^{-1}$ ) to a sulphate and chloride mineral precipitating basin with a salinity of nearly  $400 \text{ g}\cdot\text{L}^{-1}$  TDS (Last, 1987, 1989b, 1990).

Although many saline lakes and playas in the northern Great Plains of western Canada and elsewhere are characterized by relatively high levels of organic productivity (Warren, 1986; Hammer, 1986; Slezak and Last, 1987; Lyons et al., 1994), the sediments recovered from North Ingebrigt lake are remarkably low in organic content. This scarcity of organic matter in the stratigraphic record is most likely a reflection of a combination of factors, including 1) high salinities experienced in the lake, which curtail both organism diversity and productivity; 2) strongly oxidizing conditions at the sediment-water interface; and 3) only small amounts of terrestrial organic debris reaching the centre of the basin due to negligible stream flow.

Changes in the depth of brine and long-term fluctuations in water level in the North Ingebrigt basin undoubtedly occurred over the past 10 000 years, but are difficult to assess from the preserved lithostratigraphic record. In contrast to the salt-dominated stratigraphic records in nearby Ingebrigt, Chappice, and Freefight lakes, and Little Manitou Lake in central Saskatchewan (Ruffel, 1968; Last, 1993b; Vance et al., 1993; Sack and Last, 1994), there is no compelling petrographic, lithostratigraphic, or geochemical evidence that North Ingebrigt lake was ever a deep-water basin. Indeed, shallow-water hypersaline playa conditions, probably similar to those of today, existed throughout most of the Holocene. However, the absence of pedogenic horizons, recognizable erosional and solution-modified contacts and bedding planes, and relatively coarse-grained allogenic sediment suggests that the basin probably never experienced significant or extended periods of complete dryness and subaerial desiccation.

Although absolute age dating of the North Ingebrigt lake record has provided only a very preliminary chronostratigraphic framework, it nonetheless suggests that there have been considerable changes in sediment accumulation rates during the Holocene. Deposition of the sediments of facies 1 and facies 2 in the lower half of the sequence appears to have been rapid, with accumulation rates approaching  $50 \text{ cm} \cdot 100\text{a}^{-1}$ . During the mid- and late Holocene, this rapid rate of salt accumulation decreased significantly, and extrapolated linear sedimentation rates averaged an order of magnitude less than those exhibited in the early part of the record.

### *Geochemical conditions of sedimentation*

A basic tenet of chemical sedimentology is that, in a hydrologically closed system undergoing evaporative concentration, a complete assemblage of nondetrital minerals must have the same bulk ionic composition as the original water (Hardie, 1984). As discussed elsewhere (Wasson et al., 1984; Torgersen et al., 1986; Teller and Last, 1990; Last, 1994), there are many assumptions and limitations that must be accepted in the application of this straightforward principle to paleolimnology. Nonetheless, North Ingebrigt lake, a topographically and hydrologically closed basin having a relatively small catchment and a long and apparently continuous record of chemical sedimentation from hypersaline brines, is ideally suited for paleochemical reconstructions based on these types of thermodynamic and mass balance calculations.

Our ability to deduce the composition of a brine from the preserved mineral record in a lacustrine basin has been improved by significant advances in thermodynamic models of salt dissolution and mineral precipitation from concentrated solutions (Harvie and Weare, 1980; Harvie et al., 1982, 1984; Greenberg and Møller, 1989; Spencer, et al., 1990). The theoretical framework for this brine reconstruction follows discussions by Garrels and Christ (1965), Eugster and Smith (1965), Wood (1975), Smith (1979), and Wasson et al. (1984). Figure 6 shows changes in the relative chemical activities of the major dissolved components in the precipitating brine in North Ingebrigt lake through the Holocene.

The salts of facies 1 (Na-sulphate facies) were precipitated from a geochemically simple brine with a cation content dominated by sodium and the anions comprising mainly sulphate and nitrate. The source for the increased relative chemical activity of nitrate (the chemical activity of a major dissolved component is indicated by a superscript 'a' preceding the formula for the component, thus  $^a\text{NO}_3^-$ ) in the precipitating brine compared to the rest of the Holocene stratigraphic sequence is not known with certainty. Rutherford (1967) reported elevated  $\text{NO}_3^-$  levels in some of the shallow (glacial drift) groundwater of the area. Shang (1999) showed that evaporative concentration of these glacial drift groundwaters can result in niter and soda niter precipitation. Similarly, it is well known that oxidation of organic matter in a strongly alkaline environment under relatively arid conditions can result in the formation of Na- and K-nitrate salts (Clarke, 1924).

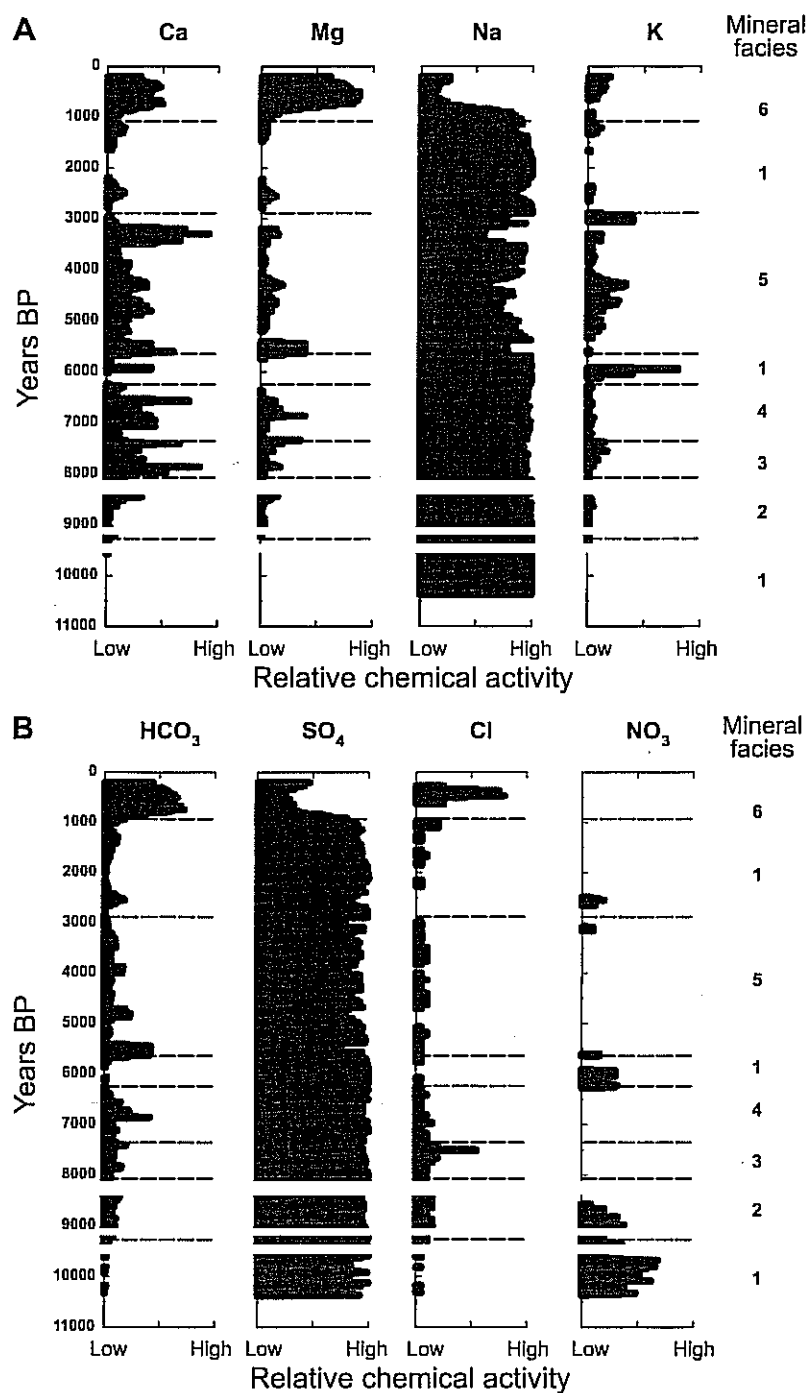
During deposition of facies 2 (Mg-carbonate-Na-sulphate facies) between about 9200 and 8000 BP, the relative chemical activities of  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ , and  $\text{HCO}_3^-$  increased,  $^a\text{SO}_4^{2-}$  remained high, and  $^a\text{NO}_3^-$  gradually decreased. The resulting brine was thus considerably more complex than that which occupied the basin during the first 1000–1500 years of the record. This facies marks the earliest significant occurrence of carbonate in the lake water. The presence of gaylussite rather than pirssonite suggests relatively low temperatures, high pH, and high  $^a\text{H}_2\text{O}$  conditions. The occurrence of eugsterite, a (Na+Ca)-sulphate, together with gypsum and bloedite, indicates a precipitating solution with a varying but generally very high molar Na:Ca ratio (Vergouwen, 1981; Van Doesburg et al., 1982).

The salts of facies 3 (Ca-sulphate-Na-sulphate facies) indicate deposition in a brine with higher  $^a\text{Ca}^{2+}$  values than existed previously. The widespread occurrence of minor amounts of hanksite and polyhalite, interpreted as penecontemporaneous diagenetic products of gypsum, suggests that this brine was commonly elevated in  $\text{Cl}^-$  and  $\text{K}^+$ , and was highly alkaline.

Deposition of facies 4 (muddy Na-sulphate facies) between about 7300 and 6200 BP and facies 5 (muddy Mg-calcite-Na-sulphate facies) between 5600 and 2900 BP represents significant freshening episodes of the brine. However, the lake still remained saline to hypersaline. The  $^a\text{Ca}^{2+}$  and  $^a\text{HCO}_3^-$  values show an increase relative to facies 1–3, and there are complementary decreases in  $^a\text{Mg}^{2+}$ ,  $^a\text{Na}^+$ , and  $^a\text{Cl}^-$  coincident with brine dilution.

One of the most dramatic changes in water composition in the North Ingebrigt record occurred about 1000 years ago. Although the transition from facies 5 to facies 4 was gradual over the period ca. 4000–2000 BP, the chemical conditions responsible for facies 4 ended abruptly ca. 1000 years ago. After this time, there was a major increase in relative  $^a\text{Mg}^{2+}$  and  $^a\text{HCO}_3^-$  values and a decrease in  $^a\text{SO}_4^{2-}$ ,  $^a\text{Ca}^{2+}$ , and  $^a\text{Na}^+$ . Although this uppermost dolomitic Na-sulphate facies may represent an overall freshening of the brine, hypersaline conditions remained common, as indicated by the occurrence of halides and Mg-sulphates. Facies 6 is unusual, with no known modern analogues among today's saline playas of western Canada.

Any discussion of water-level fluctuations or lake-depth changes in a basin that annually or periodically undergoes complete drying is meaningless. Likewise, it is difficult to evaluate or summarize brine solute concentration changes in a water body that regularly experiences great ranges of salinity associated with playa flooding and desiccation. However, the mineralogical record does provide some important information about the changes in mean atmospheric relative humidity. As discussed elsewhere (Harbeck, 1955; Langbein, 1961; Hosler, 1979), evaporation and evaporative concentration of a water body leading to mineral precipitation is a complex process. The effective, long-term average atmospheric relative humidity of the location plays a pivotal role in helping to determine the ultimate suite of evaporites that is



**Figure 6.** Relative chemical activities of major dissolved (A) cation and (B) anion components of lake (or interstitial) brines versus time, based on the endogenic+authigenic mineral suite in North Ingebrig lake. Relative activity values increase to the right; heavy horizontal dashed lines delineate mineral facies (see Table 1). Temporal scale is in <sup>14</sup>C years BP and was established by simple linear interpolation.

formed (Kinsman, 1976; Sonnenfeld, 1984). Regardless of the actual mechanism of evaporite mineral formation, the presence of a particular mineral or suite of minerals is an indication that the brine was thermodynamically saturated with respect to that inorganic precipitate. The chemical activity of the water ( $a_{H_2O}$ ) in the precipitating solution is directly proportional to the water vapour pressure of the atmosphere, which in turn is related to the mean atmospheric relative humidity (Kinsman, 1976). Thus, the wealth of experimental and theoretical data on thermodynamic conditions of salt mineral formation (Eugster and Smith, 1965; Bradley and

Eugster, 1969; Hardie and Eugster, 1970; Braitsch, 1971; Smith and Stuiver, 1979; Eugster et al., 1980) can be used to estimate  $a_{H_2O}$ , and hence the relative humidity of the basin.

During the periods 10 350–8700 BP, 6500–5500 BP, and 1500–1000 BP, the North Ingebrigt lake basin experienced climatic conditions in which the mean relative humidity was considerably lower than that of today (Fig. 7). In contrast, comparatively humid conditions (but not wet enough to cause a basic change in the hydrological setting of the playa) are suggested by higher relative humidity during the periods 7200–6500 BP and 5500–3000 BP. Finally, the millennium between 8000 and 7000 BP was characterized by considerable variability, with rapid, short-term fluctuations between high and low relative humidity.

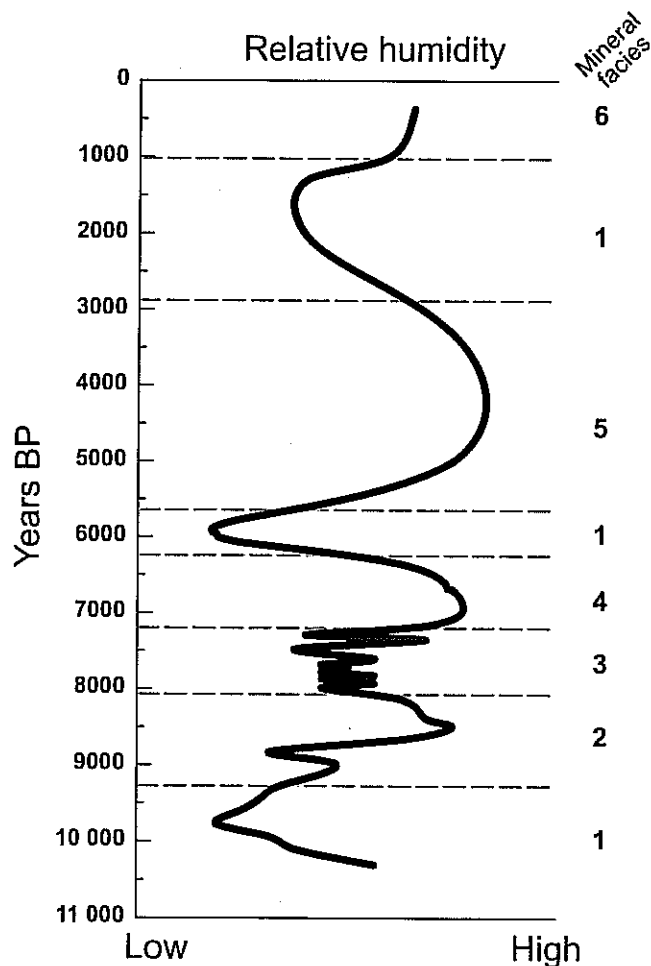


Figure 7. Variation in mean atmospheric relative humidity at North Ingebrigt lake as estimated by the evaporitic mineral suite. Numbers on the right refer to the mineral facies (see Table 1). Temporal scale is in  $^{14}C$  years BP and was established by simple linear interpolation.

#### *North Ingebrigt lake relative to other Holocene lacustrine records*

Although it is not our intent in this paper to reconstruct the regional climatic history, it is nonetheless tempting to compare the changes in mean atmospheric relative humidity interpreted for North Ingebrigt lake with paleolimnological fluctuations at other sites in the region with long Holocene records (Table 4).

The 7500-year long sediment record from Chappice Lake, Alberta, a hypersaline playa located about 80 km west of North Ingebrigt lake, is one of the longest and best documented lacustrine paleohydrological records in the entire northern Great Plains region (Vance et al., 1992, 1993, 1995). Although temporal control of the North Ingebrigt lake record is much less tightly constrained than that of Chappice Lake, broad similarities exist. Both basins show an early Holocene episode of significant fluctuation in relative humidity and in water level and salinity conditions (prior to 6000 BP at Chappice Lake; 8500–7000 BP at North Ingebrigt lake). Similar early Holocene periods of rapidly changing conditions, from high to low water levels and from hypersaline to fresh water, were noted in stratigraphic records from Ceylon lake, about 400 km southeast of Ingebrigt Lake (Last, 1990), and from Clearwater Lake, 100 km to the northeast (Last et al., 1998). Similarly, a mid-Holocene interval of low-water, saline to hypersaline conditions correlative to the very low mean atmospheric relative humidity at 6000–5000 BP at North Ingebrigt lake has also been documented at Chappice and Ceylon lakes as well as several other lacustrine sites in the Prairie region (Vance et al., 1995). Finally, the lengthy period of stable and relatively moist conditions between about 5000 and 2000 BP is recorded in numerous other basins on the northern Great Plains (see overviews in Lemmen, 1996; Xia et al., 1997; Vance, 1997).

**Table 4.** Comparison of mean relative humidity at North Ingebrigt lake to interpreted water levels and salinities at Chappice Lake, Alberta, and Clearwater and Ceylon lakes, Saskatchewan.

<sup>14</sup> C age (years BP)	North Ingebrigt lake – Mean relative humidity	Chappice Lake – Water level and salinity	Clearwater Lake – Water level and salinity	Ceylon lake – Water level and salinity
Present		Fluctuation from low to high and fresh to saline		Low and hypersaline
	High			High and fresh water
1000		Low water		Stable conditions – low water and hypersaline
	Low		Stable conditions – deep and fresh water	
2000		Deep and relatively fresh water		High and fresh water
3000	High			Stable conditions – low water and hypersaline
4000		Stable conditions – low water and hypersaline	Missing section	Very low to dry and hypersaline
5000	Very low			
6000	High	Repeated fluctuation from dry to deep and fresh to hypersaline		Repeated fluctuation from shallow to deep and fresh to hypersaline
7000	Repeated fluctuation from low to high	Base of record		
8000			Deep and fresh water	
9000	High		Deep to shallow (dry at 8200 BP) and saline to hypersaline	
			Shallow and hypersaline	
10000	Very low to low		Shallow and fresh water saline	Deep and fresh water

## CONCLUSION

There are many salt-dominated playa basins in the Great Plains of North America whose sediment records are conducive to paleolimnological study. North Ingebrigt lake is one of the first of these lakes to undergo detailed mineralogical and lithostratigraphic investigations. Obviously, deciphering all the intricate processes that control the relationships between lake hydrology, regional climate, and the chemistry of a brine is an arduous task even in a small, presumably rather simple evaporating pan like North Ingebrigt lake. It has been repeatedly shown that there is relatively little relationship between brine chemistry of modern lakes in the northern Great Plains and their specific climatic setting (e.g. Last, 1989c, 1992; Lambert, 1989; LaBaugh and Swanson, 1992). This suggests that any linkage between water composition and climate on a regional basis is extremely tenuous. Indeed, the Holocene mineralogical record preserved in North Ingebrigt basin emphasizes the complexity, rather than the simplicity, of long-term brine composition changes and the interplay between the many intrinsic processes that are operating within the basin itself and the various extrinsic factors that help control the geochemical aspects of the lake.

## ACKNOWLEDGMENTS

This research was made possible through funding from the Geological Survey of Canada's Palliser Triangle Global Change Project, the Natural Sciences and Engineering Research Council of Canada (NSERC), and the University of Manitoba. Anne Ross and Grant Caresle provided valuable assistance in the laboratory. We thank J. Donovan, R.A. Klassen, and D.S. Lemmen for their helpful comments and suggestions on an earlier draft of this manuscript.

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