

# PORE WATER SALINITIES OF COASTAL SEDIMENTS NORTH HEAD, RICHARDS ISLAND, N.W.T.

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## Abstract

Sediment pore water was analyzed for electrical conductivity and ionic composition from cores obtained at a coastal site on the north end of Richards Island, Mackenzie Delta. Ground electrical conductivity was measured over the site by electromagnetic induction using a Geonics EM-31. Using a horizontal dipole orientation, conductivities of 150 to greater than 500 mmho/m were encountered over lagoon flat and intertidal platform sediments while values less than 50 mmho/m were found over the spit. The results are used to interpret the areal distribution of near-surface (upper 2 m) salinities.

Ground conductivities are correlated with average interstitial pore water salinities within the active layer. Three salinity zones are recognized: a low salinity zone (0-13 ppt) across the spit, a moderate to high salinity zone (13-65 ppt) across much of the intertidal platform, and a very high salinity zone (>65 ppt) across the lagoon flats and part of the intertidal platform.

Low salinities in spit sediments may be attributed to percolation of freshwater through the active layer. Higher salinities below the active layer probably represent marine water which is either relict or has infiltrated during high water levels. High salinities across the intertidal platform may be attributed to solute rejection from seawater into underlying sediments during winter freezing. Very high salinities encountered on the lagoon flats are probably the result of solute rejection during freezing in winter, as well as surface evaporation in summer.

## Résumé

La conductivité électrique et la composition ionique de l'eau interstitielle ont été analysées à partir de carottes de sédiments provenant de la côte nord de l'île Richards, située dans le delta du Mackenzie. La conductivité électrique du sol à travers la région d'étude a été mesurée par induction électromagnétique à l'aide d'un appareil Geonics EM-31. En configuration bipolaire horizontale, des conductivités allant de 150 à plus de 500 mmho/m, ont été obtenues pour les dépôts de zones lagunaires et de plates-formes intertidales tandis que des conductivités de moins de 50 mmho/m ont été obtenues sur la flèche littorale. Les résultats sont utilisés pour interpréter la distribution spatiale de salinité à faible profondeur (0-2m).

Les conductivités du sol sont en corrélation avec les salinités moyennes de l'eau interstitielle à l'intérieur du mollisol. Trois zones de salinité sont identifiées: une zone de faible salinité (0-13 ppt) dans la flèche littorale, une zone de salinité moyenne à forte (13-65 ppt) dans la majeure partie de la plate-forme intertidale, et une zone de très forte salinité (>65 ppt) dans les zones lagunaires et une partie des plates-formes intertidales.

L'infiltration d'eau douce dans le mollisol pourrait expliquer la basse salinité des dépôts de la flèche littorale. Une salinité plus forte sous le mollisol indique probablement la présence d'eau salée relictue ou infiltrée pendant une période de haut niveau d'eau. Un rejet des sels de l'eau de mer dans les dépôts sous-jacents pendant le gel d'hiver pourrait expliquer les fortes salinités retrouvées sous les plates-formes intertidales. Les très fortes salinités mesurées dans les zones lagunaires sont probablement le résultat du rejet des sels pendant le gel d'hiver ainsi que de l'évaporation superficielle en été.

## Introduction

Permafrost, defined on the basis of temperature, is ground which remains below 0°C for two or more years (Harris, 1988). For most practical purposes, however, it is more important to know the extent of ice-bearing ground. Thus, a distinction is often made between ice-bearing

permafrost, in which pore water is frozen, and permafrost defined solely on the basis of temperature. Whether pore water is frozen at 0°C depends, in part, on the solute concentration in the pore water. Increasing concentration of dissolved salts in the soil depresses the freezing point of the pore water. This phenomenon is important wherever pore water is saline and may be particularly significant in controlling ice-bonding of coastal sediments.

Increasing salinity has also been found to decrease frost heaving in soils by inhibiting the growth of ice lenses (Chamberlain, 1983; Lu *et al.*, 1988). Consequently, if sediments encountered are saline, fewer and smaller ice lenses may be present. High salt concentrations also decrease compressive strength and increase creep deformation in frozen ground (Ogata *et al.*, 1983; Pharr and Merwin, 1985; Nixon, 1988).

In coastal regions, high salinities may pose a problem to the maintenance of pipelines and other engineered structures. Freezing point depressions caused by solutes must be taken into account when considering the freezing or thawing that may occur around a structure. In addition, high solute concentrations form a potentially corrosive environment. Thus, the recognition and delineation of saline pore water in permafrost is important for practical applications. The purpose of this study is to define the spatial variation of pore water salinities from a coastal environment in the southern Beaufort Sea using electromagnetic measurement of ground conductivity, and to consider the origin of these saline sediments.

### Study area

The study site, located at 134°24'00" West longitude and 69°43'26" North latitude, is situated at the north end of Richards Island along the Beaufort Sea coast (Fig. 1). Located approximately 60 km northwest of Tuktoyaktuk, it is well within the region of continuous permafrost. The study focuses on a spit, lagoon flat, and intertidal platform on the northeast side of North Head. The area east of the study site is in the vicinity of a potential right-of-way for a high capacity gas pipeline originating in the Beaufort Sea.

The shoreline may be classified as a micro-tidal environment with a tidal range of approximately 25 cm. However, coastal inundation above the mean high water

mark can occur frequently, particularly in late summer, by storm generated surges of one to two metres (Henry, 1975).

The spit is oriented southeast-northwest and is slightly recurved. As shown in Fig. 2 it is approximately 1.0 km long and 200 m wide. It is asymmetric in cross-profile with a gravel storm ridge and driftwood on the seaward side. The main body of the spit is characterized by a dry, sandy to gravelly surface and is partially vegetated by tall grass and sedges. A shallow lagoon occurs on the landward side of the spit and is open to the sea through a narrow channel. Encircling the lagoon is an unvegetated lagoon flat lying just above mean sea level.

A wide platform extends southeast from the spit for an additional 2 km. Near the spit, the platform is intertidal, being totally submerged during wind enhanced high tides. Eastward, the platform slopes gradually seaward, but drops off more abruptly at a water depth of about 50 cm. To the south, the shore rises locally to almost 50 cm above sea level. This raised area is gravelly and partially vegetated with grasses.

### Pore water salinity

#### METHODOLOGY

Pore water samples for electrical conductivity and salinity measurements were obtained from 11 sediment cores in mid-to late August, 1988. Cores were obtained throughout the area using a CRREL corer and a vibracorer. CRREL cores (CC-1 to CC-6) extended into frozen ground while vibracores (VC-1 to VC-5) terminated at the frost table. Cores averaged 1.5 m deep with a maximum of 2 m. A discussion of the operation of these corers may be found in Veillette and Nixon (1980) and Archibald *et al.* (1983).

Core samples were analyzed in the field to determine their physical state as either frozen or thawed. CRREL core samples were placed in plastic freezer containers and sealed with silicone and electrical tape to retain moisture, while vibracore samples were triple wrapped in "ziplock bag" bags. Sediment sampling was based, in part, on sediment texture and active layer depth and so the sampling interval was variable. Samples were placed in sealed metal pails for shipping and were stored in a cold room upon return to Queen's University.

Pore water extraction was conducted on samples returned to the laboratory. The method of extraction was dependent on sediment texture. Pore water was obtained from two fine-grained samples by squeezing with a hydraulic press (Patterson *et al.*, 1978). Water was extracted from remaining sediment samples by a centrifuge method. Samples were centrifuged at 1000 rpm for 15-30 minutes in two-tier plastic containers modified after Edmunds and Bath (1976). With the sample contained in the upper level, water collected in the lower level during centrifuging. The soil sample was subsequently removed and water decanted into sample bottles. This method has been previously used in

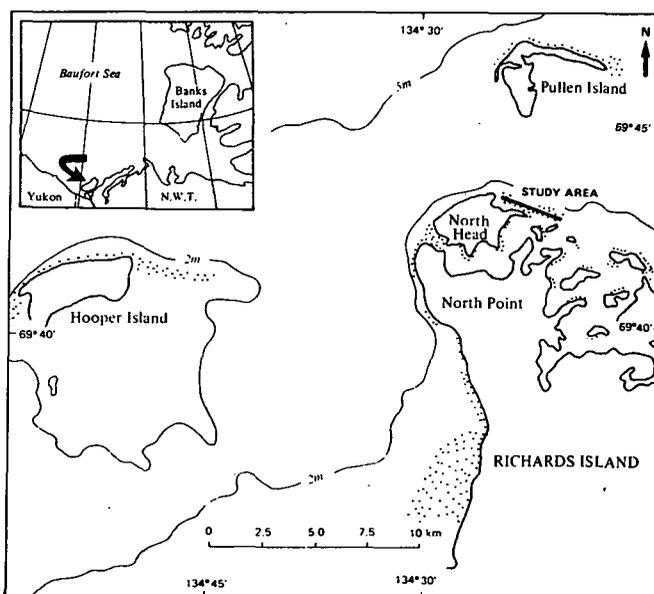


Figure 1. General location map.

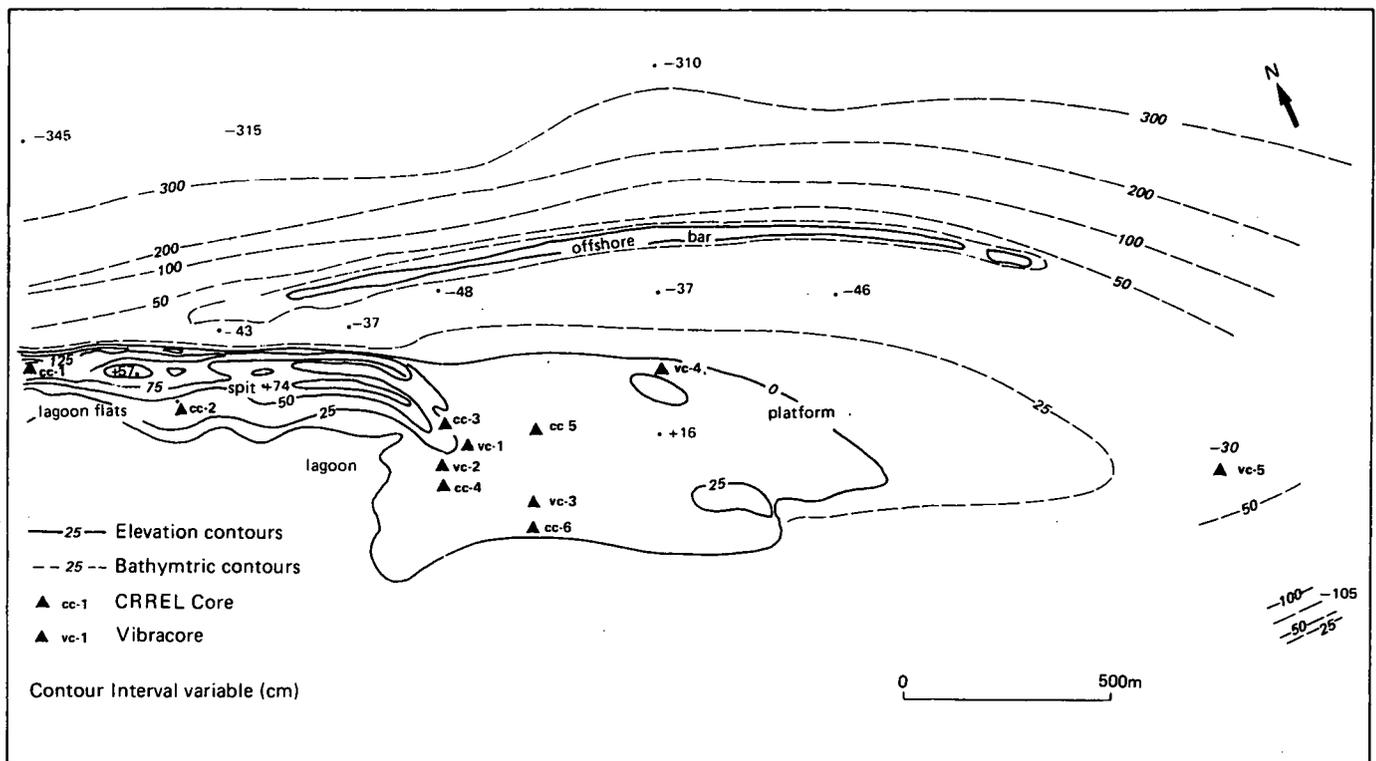


Figure 2. Study site showing elevation and bathymetric contours and CRREL core and vibracore locations (datum taken as mean sea level July 20, 1988).

analysis of saline permafrost sediments (Page and Iskandar, 1978) and provides an easy method of extraction in sandy sediments. Particle size analysis was performed on all sediment samples following pore water extraction.

Salinity measurements were made on all water samples using a salinity-conductivity-temperature (S-C-T) meter. As pore water salinities were high, it was necessary to reduce most concentrations to measurable quantities by dilution with distilled water. Measured salinity is a function of temperature and conductivity and, therefore, the accuracy is also a function of both. Measured salinities are quoted as accurate to within  $\pm 6.5\%$ .

True salinities were calculated by multiplying the measured salinity by the dilution factor. Pore water conductivities were determined from calculated salinities using the empirical relationships obtained from Baker (1987) for seawater and were normalized to 25°C. To check the similarity of pore water samples to seawater, 11 water samples were submitted to the Geological Survey of Canada for major ion determination. Concentrations of chloride, sodium, calcium, magnesium, potassium and sulphate were determined.

## RESULTS

A comparison of salinity measurements based on conductivity and major ion determination is shown in Table I. Salinities based on UNESCO (1966) were determined by multiplying the chloride concentration by 1.80655. Results

from the three methods compare favourably, with measured salinities generally falling within 5% of the average. Salinities determined from summation of ions tend to be the lowest. This is expected as chemical analysis did not include all ions contributing to total salinity (particularly carbonate). Values based on chloride probably overestimate total salinity, as chloride was observed to be enriched with increasing total salinity (a complete discussion of major ion concentrations and a comparison to standard seawater is given by Wolfe (1989)). Most importantly, however, values based on electrical conductivity are reliable measures of salinity.

Table I. Comparison of pore water salinities from selected samples based on: electrical conductivity, \*; summation of major ion concentrations, \$; and chloride concentration, †.

Core	Depth (cm)	Salinity (ppt)			Average
		S-C-T meter	Ion Sum	UNESCO (1966)	
CC-2	50	109.5	105.4	120.4	111.8
CC-2	120-160	105.0	97.5	108.3	103.6
CC-3	105-115	27.0	24.9	25.7	25.9
CC-4	130-140	48.6	48.0	50.1	48.9
CC-5	100-110	84.2	109.5	119.6	104.4
CC-6	100-115	67.5	67.7	71.6	68.9
VC-1	80-110	65.0	59.7	62.8	62.5
VC-2	95-115	58.2	54.9	58.1	57.1
VC-3	110-130	69.6	65.7	67.5	67.6
VC-4	80-100	30.2	28.3	30.2	29.6
VC-5	100-120	51.6	47.6	51.7	50.3

Table II. Sediment texture and pore water characteristics from core samples. Samples frozen at time of coring are denoted by \*. Abbreviations: grvl, snd, silt, cl and lm refer to: gravel, sand, silt, clay and loam, respectively.

Location	Average Pore water Conductivity (mmho/cm)	Apparent Ground Conductivity	
		Horizontal Dipole (mmho/m)	Vertical Dipole (mmho/m)
CC-1	2.8	46	65
CC-2	136.3	610	>1000
CC-3	6.5	90	150
CC-4	71.5	355	790
CC-5	105.4	385	720
CC-6	99.2	530	>1000
VC-1	85.9	---	---
VC-2	89.0	330	630
VC-3	97.8	500	>1000
VC-4	55.1	355	660
VC-5	75.4	---	---

Salinity and conductivity of core samples together with sediment textural descriptions are shown in Table II. The locations of sediment cores are given in Fig. 2. Spit sediments were generally sandy to gravelly near the surface, and sandy loams below 50 cm depth. Pore water salinities within the upper 100 cm of spit sediments are less than 4 ppt (Table II) and correspond to the depth of thaw at time of coring. In deeper sediments, pore water salinity increases rapidly to greater than 24 ppt.

The lagoon flat sediments range in texture from silty clay to sand but are generally loams and sands. Intertidal platform sediments range from sands to clay loams but are also mostly loams and sands. Pore water salinities in the lagoon flats and intertidal platform sediments are well above the value of 35 ppt for standard seawater (Martin, 1971), indicating solute concentration. Pore water salinities in intertidal platform sediments are as high as 84 ppt, but average about 63 ppt. Highest salinities occur on the lagoon flats. Pore water salinities in core CC-2 (Fig. 2) are in excess of 100 ppt, and a salt precipitate was observed on the ground surface in this area. Thaw depths in the lagoon flats and intertidal platform sediments averaged 150 cm during time of coring compared to only 100 cm on the spit. Ground temperatures recorded by Wolfe (1989) indicate that the increased thaw depths are related to freezing point depressions and may be attributed to the high pore water salinities.

## Electromagnetic survey

### BACKGROUND AND METHODOLOGY

A Geonics EM-31 was used to measure ground electrical conductivity. The EM-31 is a lightweight self-contained unit consisting of a transmitter and receiver coil, power source

and readout. The instrument operates at a frequency of 9.8 kHz with a fixed intercoil spacing of 3.66 m (Geonics, 1984). In normal operating mode (vertical dipole orientation) an apparent conductivity is obtained from an area of about 6 m in diameter and to a maximum depth of 6 m. Turning the instrument on its side (horizontal dipole orientation) reduces the effective depth of penetration by approximately one-half.

Soil electrical conductivity is primarily a function of soil type (size, shape and mineralogy of soil particles), moisture content and degree of saturation, concentration of dissolved solutes, and temperature and phase state of the soil moisture (Jurick and McHattie, 1982). In cases where one or two of these parameters is dominant, vertical and lateral variations may be effectively defined.

Electromagnetic induction has been used successfully in permafrost regions to delineate regions of frozen and thawed ground (Arcone *et al.*, 1979; Sartorelli and French, 1982; Sinha and Stephens, 1983; Washburn and Phukan, 1988). This technique relies on the difference in conductivity between frozen and unfrozen soils. Reported EM-31 conductivities over frozen soils are generally less than 2 mmho/m (Sartorelli and French, 1982) and may be more than an order of magnitude less than unfrozen freshwater soils. A thawed active layer therefore results in a high conductivity layer underlain by less conductive frozen ground. Because ground conductivity is primarily electrolytic, the concentration of dissolved salts in pore water also has a strong influence on the conductivity of a soil. EM-31 conductivities may exceed 100 mmho/m over unfrozen saline soils (Cameron *et al.*, 1981). Consequently, the EM-31 has also been previously used to map soil salinity in non-permafrost environments (Cameron *et al.*, 1981; Wollenhaupt *et al.*, 1986).

The EM-31 survey was carried out in areas of the spit, lagoon flats and intertidal platform. Coverage was limited to the area above sea level (Fig. 2). Survey lines were established 100 m apart on the spit and lagoon flats, and 200 m apart across the platform. Readings were taken along lines at 10 m intervals over most of the spit and lagoon flats and at 25 m intervals across the platform. Readings were recorded with the instrument held at a height of 1 m above ground.

### RESULTS

Apparent ground conductivities are mapped in Fig. 3 for horizontal and vertical dipole orientations, respectively. Values shown have been corrected for instrument orientation and high conductivity readings (Geonics, 1984). In addition, apparent ground conductivities obtained over 9 drill cores are marked on the figures.

In the horizontal dipole orientation (Fig. 3a) apparent ground conductivities are lowest over the spit, ranging between 14 and 100 mmho/m. Along most of the vegetated portion of the spit, values are less than 50 mmho/m. Ground conductivities increase towards the lagoon flats and the platform. Highest ground conductivities are observed over the lagoon flats, where conductivities are usually in excess of 500 mmho/m and reach a maximum of 690 mmho/m. Values

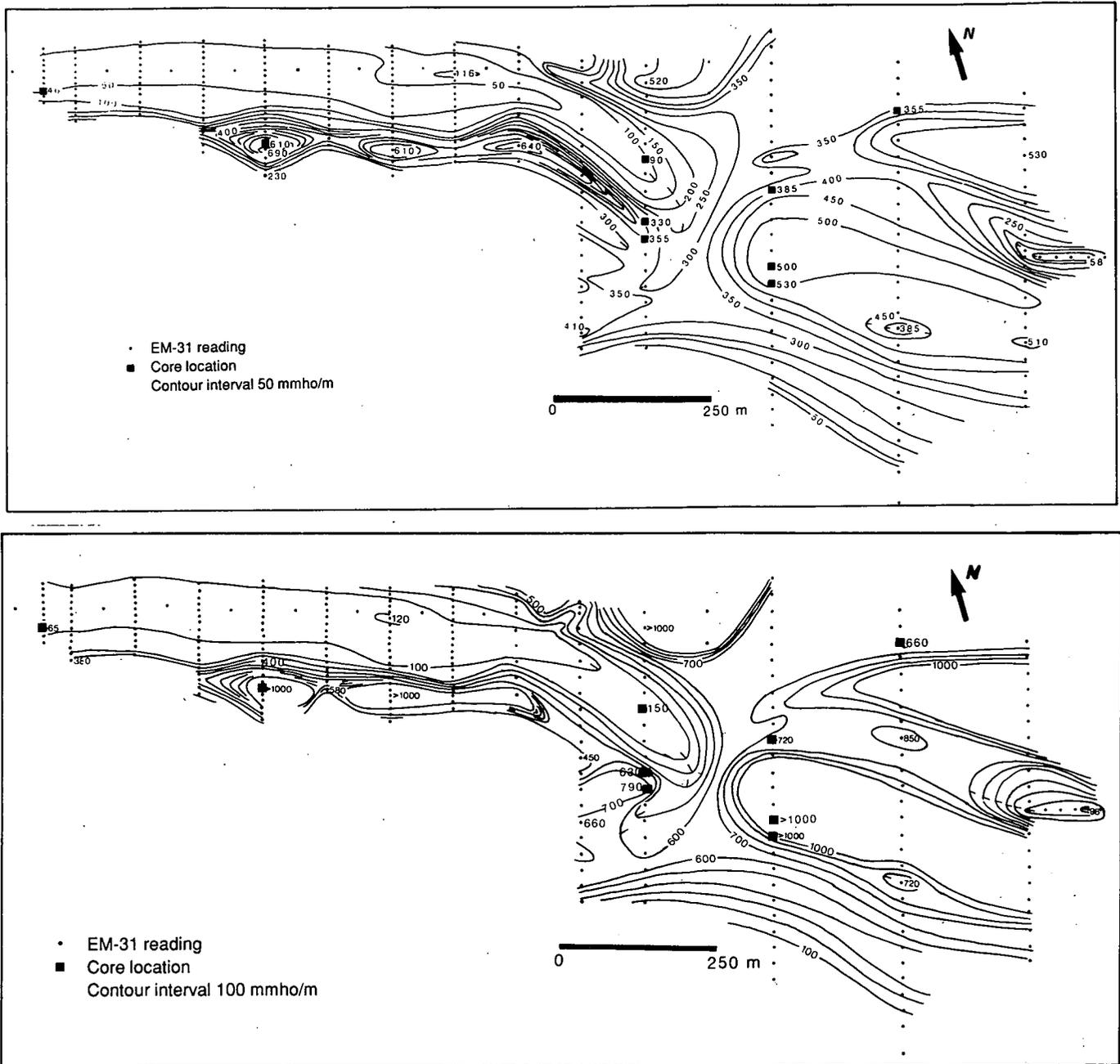


Figure 3. True apparent ground electrical conductivities using EM-31 ; a) horizontal dipole orientation, and b) vertical dipole orientation (includes readings from 9 core locations shown in Fig. 2).

decrease both towards the lagoon to the south and towards the spit to the north. The area of maximum conductivity corresponds to that where the surface salt precipitate was observed.

Ground conductivities across the platform range between 150 and 530 mmho/m. Conductivities decrease southward, towards the shoreline. Values also decrease in the vicinity of the small grass covered rise at the eastern edge of the survey, where a local minimum of 58 mmho/m occurs.

The conductivity distribution for the vertical dipole orientation (Fig. 3b) is similar in pattern to that for the

horizontal dipole. Absolute values, however, are approximately two times greater than those for the horizontal orientation and in many instances are greater than 1000 mmho/m, beyond the instrument range.

### Spatial variation in salinity

The electrical conductivities are generally much higher than those found over freshwater soils or frozen ground, and are comparable to those of Cameron *et al.* (1981) over saline soils. Thus, while soil type and active layer thickness also affect ground conductivity, the observed variations may be

Table III. Average pore water conductivities from active layer samples compared to true apparent ground conductivities from EM-31.

SPIT									
Core	Depth (cm)	Sediment Texture	Salinity (ppt)	Cond. (mmho/cm)	Core	Depth (cm)	Sediment Texture	Salinity (ppt)	Cond. (mmho/cm)
CC-1	25	snd	1.2	2.48	CC-3	50	grvl snd	3.6	6.53
	50	snd	1.2	2.48		104-105*	ice	5.0	8.85
	75-80	snd cl lm	1.8	3.50		105-115*	lm	27.0	42.14
	80-90*	snd cl lm	2.8	5.19					
	90-100*	snd	3.4	6.19					
	150-160*	snd lm	13.2	21.90					
	185-190*	snd lm	25.6	40.17					
LAGOON FLATS									
Core	Depth (cm)	Sediment Texture	Salinity (ppt)	Cond. (mmho/cm)	Core	Depth (cm)	Sediment Texture	Salinity (ppt)	Cond. (mmho/cm)
CC-2	50	snd	109.5	138.48	CC-4	50	snd lm	49.6	72.08
	120-160	slt cl	105.0	134.11		130-140	snd lm	48.6	70.82
						145-150*	snd lm	55.2	78.46
VC-1	0-30	lm snd	25.6	40.17	VC-2	0-15	lm snd	58.4	82.99
	30-60	snd	80.0	107.92		20-25	lm	70.0	96.87
	70-75	snd lm	78.0	105.69		30-40	lm snd	64.0	89.76
	80-110	lm snd	65.0	90.96		60-80	lm	66.4	92.62
	110-130	snd	59.7	84.57		95-115	lm snd	58.2	82.75
INTERTIDAL PLATFORM									
Core	Depth (cm)	Sediment Texture	Salinity (ppt)	Cond. (mmho/cm)	Core	Depth (cm)	Sediment Texture	Salinity (ppt)	Cond. (mmho/cm)
CC-5	50	lm snd	71.2	98.28	CC-6	50	lm	78.0	105.69
	100-110	cl lm	84.2	112.55		100-115	lm	67.5	92.74
	150-160*	snd cl lm	67.2	93.57		160-170*	snd lm	68.4	92.99
VC-3	0-30	cl lm	76.4	103.89	VC-4	0-30	snd	43.2	63.68
	30-40	snd lm	65.0	90.96		80-100	snd	30.2	46.49
	50-60	lm	79.7	105.74	VC-5	45	snd	38.8	58.17
	75-85	snd lm	76.4	103.89		50-70	snd lm	53.6	77.08
	90-105	snd	61.2	86.39		70-90	lm	56.4	80.54
	110-130	snd	69.6	95.70		100-120	lm snd	51.6	74.59
	140-150	cl lm	70.8	97.81					
	125-140	snd lm	61.2	86.39					

primarily a function of the pore water salinity. To test this hypothesis, the approach taken by Cameron *et al.* (1981) in mapping soil salinity with the EM-31 is used. The average pore water electrical conductivities for the core samples obtained within the active layer are compared to the true apparent ground conductivities. Values are shown in Table III while the relationships are plotted in Fig. 4.

Fig. 4a shows good linear correlation ( $r^2 = 0.89$ ) between the average pore water conductivity from active layer samples and apparent ground conductivity. Corresponding salinities are shown on the right axis of Fig. 4a. The relationship suggests that EM-31 readings principally depict near-surface pore water salinities. Results from the vertical

dipole orientation are supportive although the relationship in Fig. 4b is not as strong. Furthermore, for the vertical dipole orientation, three of the drill core sites indicate apparent ground conductivities in excess of 1000 mmho/m, beyond the instrument range. This gives some doubt as to the conductivity relationship at higher values for the vertical orientation. In addition, differences in distribution of salinity with depth, as well as the depth of the active layer, probably account for much of the variability observed in both figures.

Results from the EM-31 survey indicate that ground conductivity measured by electromagnetic induction may be interpreted primarily with respect to salinity. Fig. 5 is an estimated salinity map, illustrating the variation in average

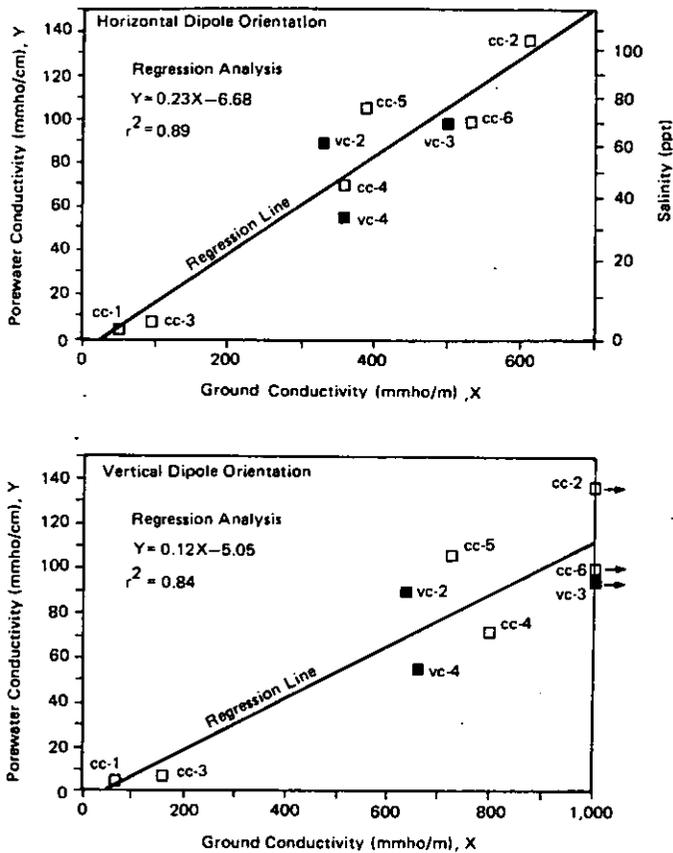


Figure 4. Relationship between apparent ground conductivity and average pore water conductivity for sample cores; a) horizontal dipole orientation with corresponding pore water salinity on right hand axis, and b) vertical dipole orientation (readings beyond instrument range estimated as 1000 mmholm).

active layer pore water salinity across the area, as interpreted from EM-31 readings. The relationship in Fig. 4a, for horizontal dipole orientation, was used in constructing the map.

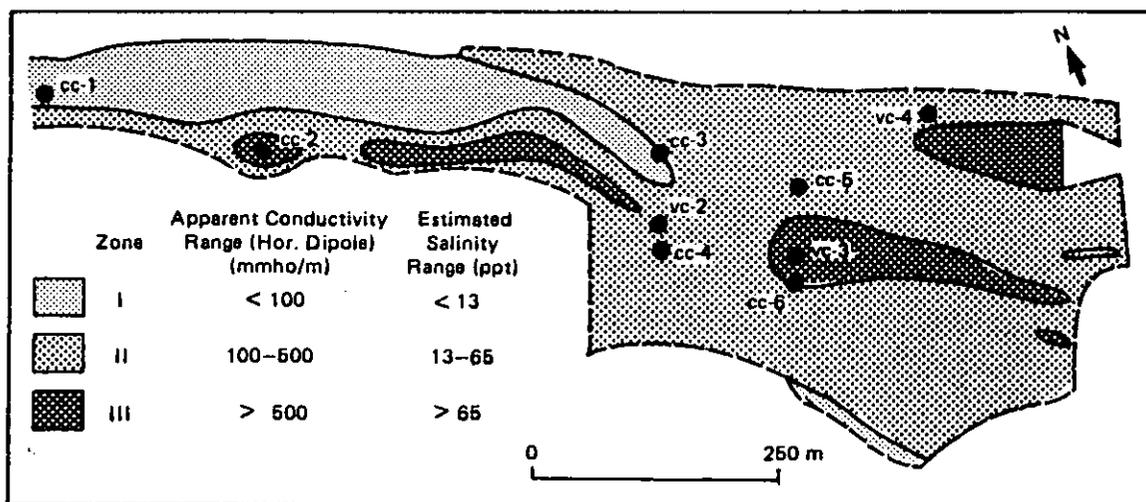


Figure 5. Zonation of study area based on estimated average near-surface pore water salinities from relationship in Fig. 4a.

From Fig. 5, three salinity zones are recognized:

**Zone I:** This salinity zone represents areas of lowest salinity, with less than an average of 13 ppt in the active layer. Apparent ground conductivities are typically less than 100 mmho/m. Included in this zone are the spit, shoreline to the southeast, and small vegetated rise on the platform.

**Zone II:** This zone represents intermediate salinities averaging 13 to 65 ppt in thawed sediments. Apparent ground conductivities range from 100 to 500 mmho/m. Zone II encompasses much of the intertidal platform and borders the spit to the west and the shoreline area to the southeast. High salinities in this zone account for significant freezing point depressions and the presence of poorly-bonded sediment in winter (Wolfe, 1989).

**Zone III:** This zone is primarily one of very high average salinity and is located across the lagoon flats on the southern side of the spit and part of the platform. Average pore water salinities within the zone are expected to exceed 65 ppt. Salinities are high throughout the active layer. Sediments are expected to be poorly-bonded in winter, with freezing point depressions resulting from high solute concentrations.

## Discussion

Pore water analyses and ground electrical conductivity survey indicate that near-surface pore water salinities are variable, and include large areas with salinities in excess of two times the value for standard seawater. This discussion is directed towards examining some of the processes which could account for these conditions.

### SAND SPIT

The subaerial sand spit is generally between 25 and 125 cm above mean high tide level with the frost table in early August situated at a depth of approximately 100 cm.

Low apparent ground electrical conductivities in this area (Zone I) are interpreted as resulting from low pore water salinities in the unfrozen near-surface soils. Salinities determined on core samples obtained from the spit confirm the low salinities in the active layer sediments, with higher salinities, approaching seawater concentrations, in frozen sediments at depth.

The low salinities in the near-surface are thought to be attributed, primarily, to the influence of freshwater percolation through the active layer from rainfall and snowmelt. The spit slopes distinctly towards the lagoon and open ocean, promoting groundwater flow. Since the area is elevated and the top of the ice-bonded layer is near high tide level, there is unlikely to be any inundation by seawater except during exceptional storm surges. An additional factor is the coarse grained nature of spit sediments which would allow passage of solutes during water movement without appreciable soil-water interaction such as would be expected in a silt or clay.

The higher salinities at depth may be due to seepage of seawater during deeper thaw conditions later in the thaw season or due to the fact the sediments and pore water were emplaced with marine waters which have not been freshened by groundwater flow.

#### LAGOON FLATS AND PLATFORM

Boreholes drilled on the lagoon flats and intertidal platform show high salinities at depth. The electromagnetic survey enabled mapping of large areas of high apparent ground conductivities (zone II) and several areas of very high apparent ground conductivities (zone III). Correlation with borehole data suggests that these zones are related to areas of high salinities, generally greater than that of standard seawater.

The presence of precipitated salts on the surface of the lagoon flats in summer indicate that evaporative concentration of salt is active in areas above mean high tide level. Surface evaporation of pore water has been observed in other northern regions. Price *et al.* (1987) attributed a hypersaline band existing landward of the mean high water mark in a coastal marsh along James Bay, Ontario, to primarily near-surface evaporation. At that site, upward diffusion apparently transported saline pore water from relict salt towards the surface of the water table (Price *et al.*, 1989). Evaporation concentrated solutes near the surface while pore water salinities just below the surface decreased markedly. However, the situation is different in the study area as core samples indicate high salinities throughout the profiles to a depth of 1.7 m.

While it is clear that evaporation must result in some elevation of salinity of very near-surface sediments, we feel that it is not the primary process which elevates the salinity at depth in the thawed profile. A more plausible explanation is the process of solute migration experienced during winter freezing. Baker and Osterkamp (1988) suggest that where sea ice freezes annually to underlying sediments, solutes may

be excluded into the sediments. In Alaska, the highest pore water salinities have generally been recorded inside of the 2 m isobath (Lewellen, 1974; Iskandar *et al.*, 1978; Page and Iskandar, 1978). In addition, salinity and conductivity of interstitial water are highest in the first few metres of sediment and then decrease with depth. In our case, sea ice thickness is limited since the study area is at and above the mean tide level. However, the processes of downward migration of solutes in response to a winter freezing front is still considered important. Clearly, if solutes are present in porewater near the surface at the end of the thaw season due to periodic inundation, then as the sediments freeze solutes may be concentrated and migrate downward. Repeated annual freeze-thaw cycles would result in enriched soil salinities at depth. Solutes may be concentrated near the top of ice-bonded sediments, as migration is greatly reduced or even halted by perennially frozen ground. High salinities within Zone II are believed to be attributed to solute migration of marine water into sediments during winter freezing.

The highest salinities (Zone III) were observed in a thin band in the lagoon adjacent to the spit and in the flat area of the platform. Both areas occur just above sea level with zones of lower salinity existing at slightly higher and lower elevations. These areas are probably optimal for especially high near-surface salinities due to summer evaporation since they are exposed to long periods of subaerial exposure with occasional inundation. Higher areas of the spit may be affected by groundwater flow as described previously while lower elevations may not experience the same degree of subaerial exposure, thus limiting evaporation.

#### Conclusions

Pore water salinities of coastal sediments in permafrost regions may be highly variable. Low concentrations were observed in subaerial spit and beach sediments, while concentrations above that of standard seawater were present in most other sediments. High pore water salinities may originate, primarily, from solute exclusion from seawater into sediments during winter freezing. Additional considerations are the potential for surface evaporation and groundwater flow.

In coastal areas where permafrost is present, pore water salinity is an important consideration in the design of marine structures. The results from this study indicate that electromagnetic induction provides an effective means of delineating the near-surface pore water salinity.

#### Acknowledgements

This work was made possible by the encouragement of the Geological Survey of Canada, embodied in the continued advice and review from Scott Dallimore. Polar Continental Shelf Project provided all logistical support from its Tuktoyaktuk base. An NSERC operating grant and NSTP grant provided the remaining funding. The authors also thank S.R. Dallimore and R.B. Taylor for their constructive comments on the manuscript.

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