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A review of published literature on the effects of permafrost on the hydrogeochemistry of bedrock

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April 2000

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Keywords: permafrost, groundwater chemistry, salinity, salt-rejection, isotopes, glaciation.

Abstract

Salt-rejection into the aqueous phase from permafrost growth ('aggradation') during the onset of cold-climate conditions in the Pleistocene period is a mechanism that could account for the presence of saline groundwaters in the Fennoscandian Shield. This report describes the results of a review of scientific literature on the subject of permafrost, to search for and evaluate information which may indicate whether this mechanism is feasible for sites such as Olkiluoto and Äspö on the Baltic Sea coast.

The geomorphological characteristics of permafrost (such as development of patterned ground, ice wedging, pingo growth) have been studied in detail in the literature and provide an understanding of the effects of pore water expulsion and saline water formation. Evidence of salt-rejection during permafrost aggradation is found in results of analyses of the chemical and isotopic compositions of water in pingos and open taliks published in North American, Chinese and Russian literature over the last fifty years. While most studies have concentrated on shallow permafrost in soils and sediments, deep-drilling by the oil and gas industry has shown that permafrost may extend both laterally and to considerable depth. For instance, permafrost on the north slope of Alaska is laterally continuous over an area of at least 1000 km^2 and is associated with fluids of salinities up to 130 g/L. Also, in northern Siberia, permafrost has been observed to depths of over 900 m.

Saline waters are ubiquitous in coastal areas that are currently underlain by permafrost. However, it is not clear how much of the salinity has been produced by the freezing process and how much is simply due to leaching of saline soils and sediments by groundwaters and the presence of residual seawater in the sediments. Possible indicators of concentration by freezing include the presence of brines (i.e. waters of greater salinity than seawater), mineral precipitates (e.g. mirabilite) that are formed on freezing of seawater, enhanced or depleted sulphate concentrations in certain groundwaters, and lighter isotopic signature of the saline waters caused by the ice-water isotopic fractionation.

This review has found that salt-rejection processes undoubtedly will have occurred in groundwaters in the marine sediments and bedrock of the Baltic coast during the Pleistocene. Deeply penetrating permafrost in the bedrock would cause relatively pure water to form as ice in fractures and displace residual saline fluids, under density flow, to greater depths. The process could have occurred to a sufficient extent that large volumes of saline water were generated, some of which may currently remain in the fractured rock. In these waters, loss of sulphate by mirabilite precipitation would be expected to have occurred but, on warming and degradation of the permafrost, lower-salinity meltwaters would re-dissolve the mirabilite, giving rise to a SO_4-rich groundwater. This may be the origin of groundwater that is currently identified as Litorina Sea water at the Äspö and Olkiluoto sites.

This mechanism differs from that suggested by Israeli workers who propose freezing of open seawater and infiltration of residual brines into the bedrock followed by lateral migration inland. The hypothesis presented here, of formation of saline waters and brines by permafrost aggradation and salt-rejection is more acceptable from a hydrogeological standpoint because the saline waters are formed in situ and need not migrate laterally. Further field evidence, coupled with modelling of depths of permafrost penetration, could be used to assess the volume and concentration of saline groundwater formed as a result of downward advancement of permafrost in the crystalline bedrock.

Preface

This study forms a part of the research programmes for spent nuclear fuel disposal in the bedrock of Finland and Sweden and was jointly funded by Posiva Oy and SKB.

The author would like to thank Margit Snellman and Peter Wikberg for supervising and reviewing this work. Reviews from T Äikäs, A Hautojarvi, L Wikstrom, and L Moren are also gratefully appreciated.

Discussions with Robert van Everdingen and correspondence from J Ross Mackay considerably helped the direction and content of this review. Conversations and e-mail communications with S Alexeev, M Allard, G Brown, M Burgess, G Bursey, I Clark, L Dike, S Gehor, M Ferrick, E Galimov, A Huertas, D Kane, P Kurfurst, Y Kouznetsov, E S Melnikov, N Morgenstern, A B Ptitzyn, V Shepelev, J Sivitski, C Smart, G Thorne, V Vozhov and H Woo, are also gratefully acknowledged.

Contents

1 Introduction

The origin of the salinity of intermediate depth groundwaters at sites such as Olkiluoto (Finland) and Äspö (Sweden) has been considered in detail by a number of geoscientists in each country over the last 10 years, as part of the work performed for the program of deep geologic disposal of nuclear fuel waste /Nurmi et al, 1988; Rhen et al, 1997; Glynn and Voss, 1999; Laaksoharju et al, 1999; Pitkänen et al, 1999/. The unusual composition of some of these groundwaters has led researchers to propose that these were formed by the penetration of paleoseawater into the fractured rock. Subsequently, the composition of that water was modified by interaction with the bedrock and mixing with groundwaters from other sources, including glacial meltwater /Herut et al, 1990; Bein and Arad, 1992/. Aspects of this hypothesis are briefly examined here but a detailed analysis is not performed as it lies outside the scope of this review.

The work described here examines an alternative and relatively unique origin for these groundwaters; namely that they could be formed as residual fluids resulting from the rejection of salts during ice formation under conditions of ‘aggrading’ (advancing) permafrost. The aim of this review is to search for and present existing scientific literature on the topic of salinity generation by permafrost formation in order to determine if there is sufficient basis for continuing with further research into this process and the possibility of initiating or supporting laboratory or field studies to investigate it in more detail.

2 Characteristics of permafrost

Permafrost is the term that defines ground that is at or below 0°C for at least two consecutive years /van Everdingen, 1998/. It is also used to describe more loosely ground is perennially frozen (i.e. ice is present). Permafrost is the result of long periods of continuous cold climate as occurred frequently over the Pleistocene epoch, i.e. the last ~2 million years. Permafrost occurrences, distribution and thicknesses are expected to increase during periods of colder temperatures (such as those associated with onset of glaciation) and to decrease during warm intervals (e.g. interglacials). The term 'cryotic' has recently become accepted as being more rigorous than permafrost in defining ground that is below 0°C whether or not it is frozen. Permafrost is usually overlain by an 'active' layer which is subject to seasonal freezing and thawing. The relationship between temperature and depth for a typical permafrost site is shown in Figure 2-1, together with the terms that describe the state of the ground /van Everdingen, 1990/.

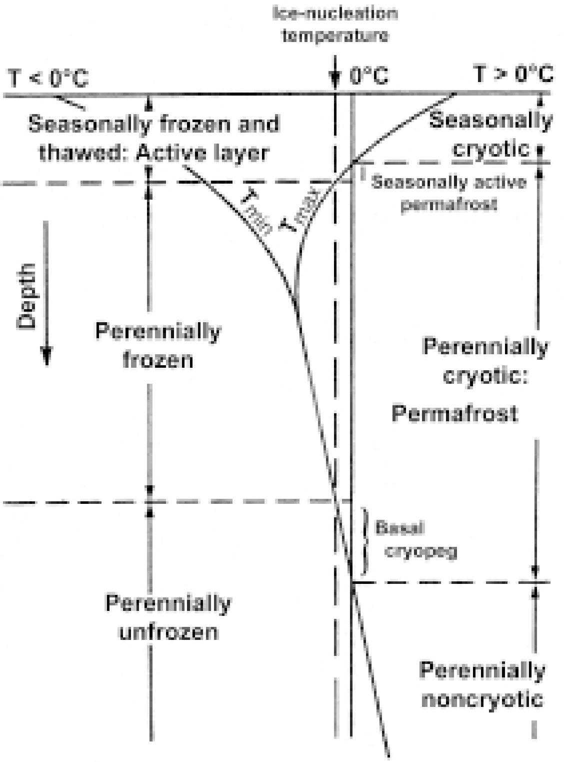

Figure 2-1. *Schematic representation of variation of temperature with depth in permafrost showing terms indicating temperature relative to 0°C and presence or absence of ice /from van Everdingen, 1990/.*

2.1 Distribution and thickness

Permafrost occurs abundantly in northern areas of Canada, Alaska, Russia and China (see summaries in /Hivon and Sego, 1993; Lewellen, 1973; Mel'nikov, 1983; Guoqing and Guodong, 1995/ respectively). Literature on the occurrence of permafrost and its characteristics goes back for over 50 years.

Permafrost areas typically retain a snow and ice cover for at least eight months of the year /Woo, 1990/ and in the northern hemisphere, they are divided into the High Arctic (largely barren with some tundra vegetation), Middle Arctic (tundra with some bare ground) and Low Arctic (continuous tundra cover). South of these areas is usually a zone of discontinuous permafrost which is covered with boreal forests and wetlands and where snow cover persists for at least six months of the year. In the main areas of permafrost, characteristic geomorphological features can usually be recognised, such as patterned ground, palsas (ice-cored peat mounds), ice lenses and wedges, frost shattered rock, shallow drained lakes containing taliks (unfrozen areas), and pingos (symmetrical hills in a flat landscape), /Mackay, 1977, 1978, 1990, Seppala, 1982; Michaud et al, 1989; Mackay and Dallimore, 1992/. Examples of some of these features and the resulting effects on the hydrogeology of the land are illustrated in Figure 2-2 for hilly and flat inland topographies, and for a coastal environment.

At present, permafrost exists both at high altitudes (e.g. in parts of Canada and Russia) as alpine permafrost, as well as at lower elevations in northern latitudes (e.g. in Scandinavia, the Arctic Islands). The climatic variations of these two types of regime are quite different due, in part, to differences in seasonal temperature range, amount of precipitation, abundance of surface water bodies and local geothermal gradient. These factors are important in determining the extent of permafrost that develops in a region during the onset of a glacial cycle.

The depth or thickness of permafrost at the present time can range from a few meters in the Low Arctic areas, to as much as 600 m into bedrock or sediments in the High Arctic islands in Canada /Collett and Bird, 1988/, and up to 900 m in the northern part of Siberia /Schwartsev et al, 1988/. Most data for the deep subsurface have been obtained from deep-drilling of permafrost in sediments during the search for oil and gas and relatively few instances have been reported of permafrost occurring in fractured rock. However, some work has been done in this regard and is described in section 5.

In the last ten years there has been a concerted effort to document the occurrences and characteristics of permafrost around the world by the International Permafrost Association's Data and Information Working Group, to aid climate-change studies, engineering design, environmental planning and protection, and to generally advance the knowledge of permafrost /Clark and Barry, 1998/. In particular, attempts are being made to construct a database of parameters such as the extent and depth of permafrost, temperature regimes, moisture content and chemistry. A CD-ROM of this data is currently available and it includes a circum-Arctic permafrost map, a bibliography of literature going back to 1978, a glossary of terms, an index of over 730 Russian permafrost maps, and selected data sets of permafrost sites /Clark and Barry, 1998/.

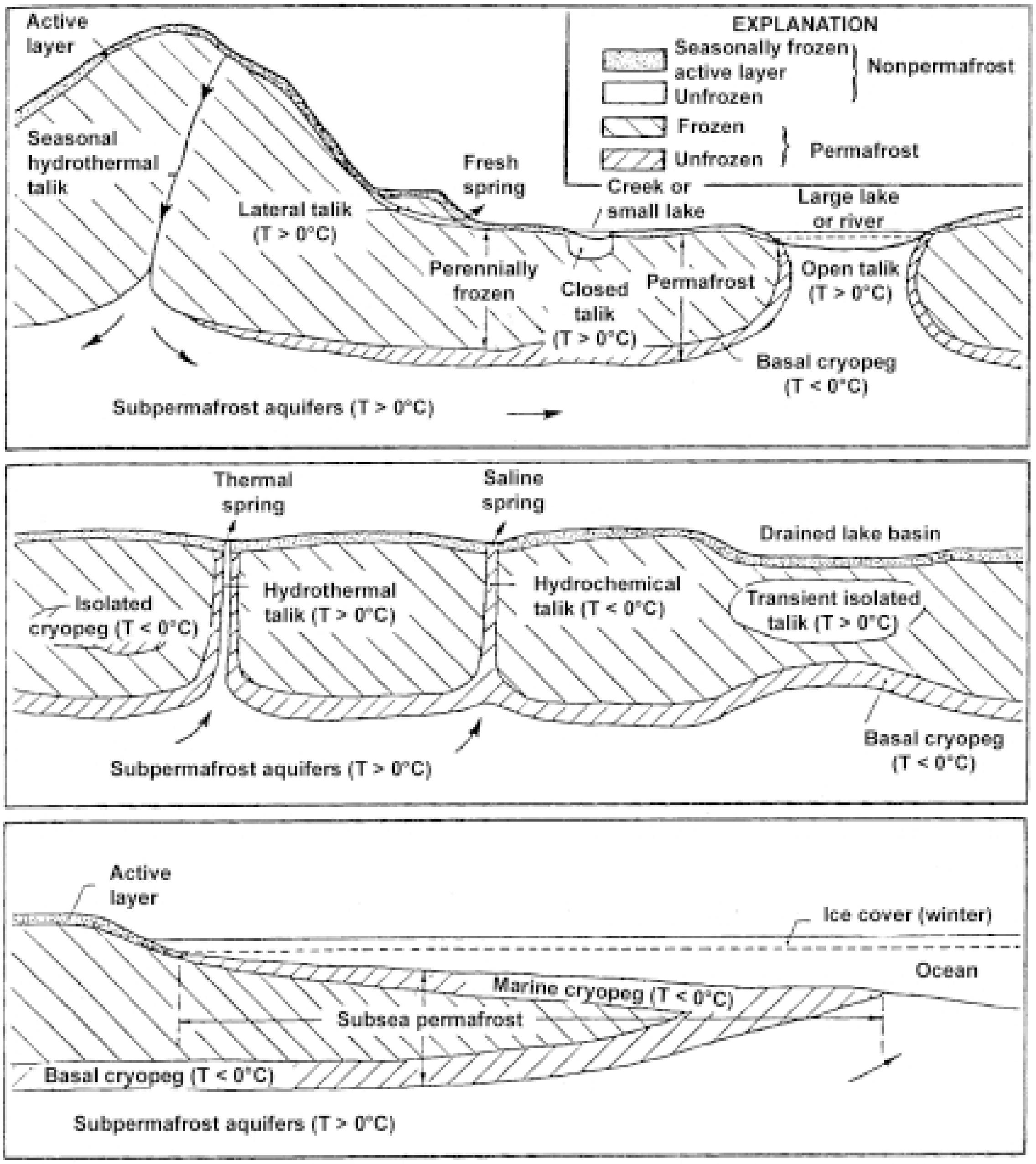

Figure 2-2. *Representation of groundwater aquifers in permafrost areas: upper – suprapermafrost aquifers in the active layer with closed taliks; middle – intrapermafrost aquifers in open, lateral and transient/isolated taliks; and lower – subpermafrost aquifers isolated, basal and marine cryopegs (modified from /van Everdingen, 1990/). 'Cryopeg' refers to ground that is below O°C but is unfrozen due to the presence of saline waters.*

2.2 Water content

Permafrost may contain small amounts of liquid water whose quantities vary depending on the temperature, pressure, surface area of the soil or sediment particles, the mineralogy, chemical composition and packing arrangement of the soil particles, and the concentration, density and composition of the unfrozen fluid /Hivon and Sego, 1995/. This fluid is adsorbed onto the surfaces of soil or sediment particles, and is liquid even when the temperature is well below the initial freezing point. The relationship between unfrozen water content and ground temperature is shown in Figure 2-3 and the terminology describing temperature, water content and phase conditions is given in Table 2-1 /van Everdingen, 1976, 1990/.

In non-saline soils, the amount of unfrozen water is largely a function of surface area and grain arrangement (which control capillary and adsorption forces) and, therefore, the free-water content of these soils, particularly if the grain size is large, tends to be low. In saline soils and sediments, which typically occur in coastal areas, particle sizes are smaller and groundwater freezes progressively during permafrost aggradation, rejecting dissolved salts into the remaining unfrozen liquid. This ground (known as 'cryopeg') gradually becomes more saline and undergoes a continuous decrease in freezing point until the eutectic composition is reached, at about 240 g/L and –22°C (in the case of NaCl), as shown in Figure 2-4 /Biggar and Sego, 1993/.

The freezing of saline water results in two phenomena, as concisely summarized by /Anisimova, 1980/: 1) cryogenic concentration of readily dissolved salts (mainly chlorides) with a low eutectic temperature and 2) precipitation of salts with a high eutectic temperature (mainly carbonates and sulphates). The phenomenon of salt-rejection during freezing has been described in detail by /Terwilliger and Dizio, 1970/ using both theoretical modelling and laboratory experiments to examine the Na-Cl rich boundary layer at the solid-liquid interface, and to study the solute redistribution process during freezing.

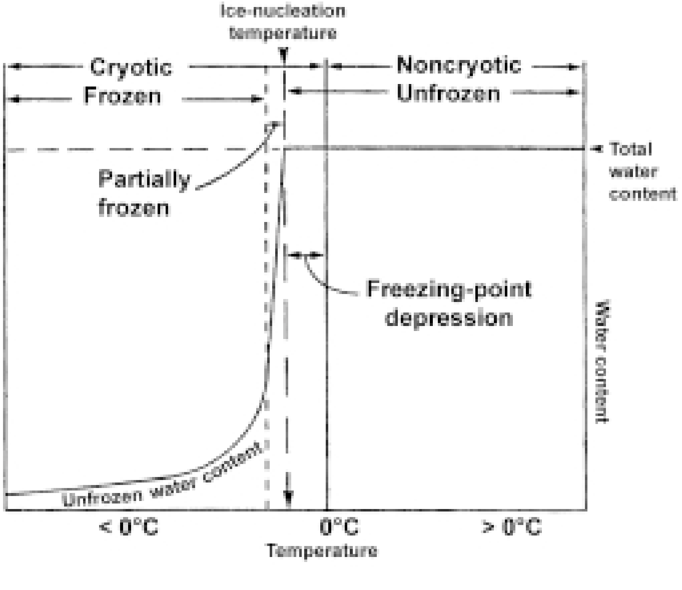

Figure 2-3. Hypothetical relationship between unfrozen water content and ground temperature showing the terminology used for near-zero temperatures /from van Everdingen, 1990/.

Table 2-1. Terminology describing ground temperature, water content and phase conditions in ground materials /after van Everdingen, 1976/.

H_2O content ► Temperature ▼	No H_2O (except chemically bound and adsorbed)		Some H_2O (less than porosity)		Pore spaces filled with H_2O		Containing "excess H_2O"		Zone descriptions	
									Phase	Temp.
T > 0°C	Dry, noncryotic		Moist or unsaturated, noncryotic		Wet or saturated, noncryotic		- - -		Nonfrozen	Noncryotic
0°C — Cryo point										
T < 0°C	Dry, cryotic	Dry permafrost	Moist or unsaturated, cryotic	Moist permafrost	Wet or saturated, cryotic	Wet permafrost	- - -	- -		Cryotic
Initial freezing point of soil system										
T < 0°C			Ice-poor, partially frozen	Ice-poor permafrost	Partially frozen	Permafrost	Ice-rich, partially frozen	Ice-rich permafrost	Partially frozen	
			Ice-poor, frozen		Frozen		Ice-rich, frozen		Frozen	

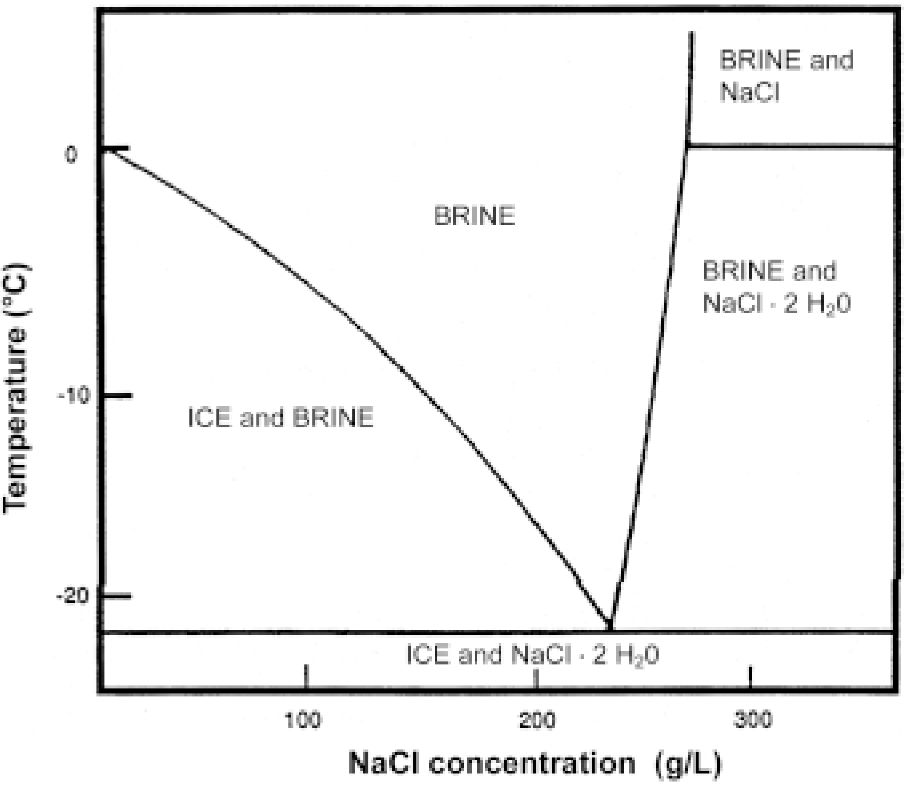

Figure 2-4. *Phase diagram for NaCl – water solutions /from Biggar and Sego, 1993/.*

The importance of grain size of the soil or sediment and its role in the process of ice nucleation and salt rejection is shown in Figure 2-5 for various salinities and grain sizes /Hivon and Sego, 1995/. Experimental studies /Anderson and Morgenstern, 1973/ have shown that ice-water interfaces develop during freezing and a thin liquid film probably exists at contact surfaces because the ice does not bind strongly to the soil. The ice crystal is then able to grow away from the particle surface into the pore space and reject solutes which then concentrate within the void space as brine 'islands' /Hivon and Sego, 1995/. Depending on the grain size of the sediments, these brines may then migrate away from the freezing surface driven by density and capillary forces, and coalesce to form separate and possibly extensive saline water phases (cryopegs) as described further below. A more detailed discussion of solute redistribution during permafrost formation has been given by /Hallet, 1978/.

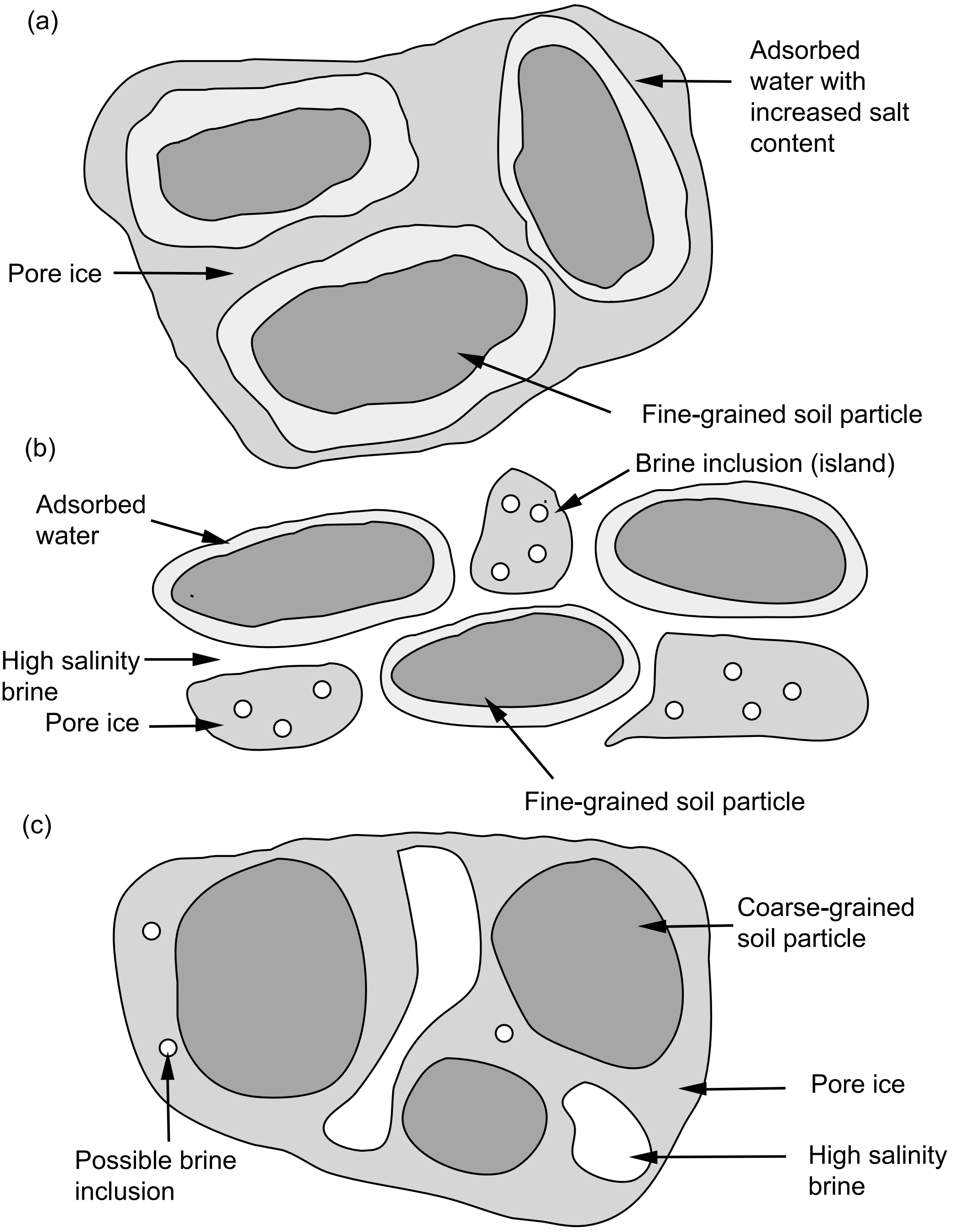

***Figure 2-5**. Schematic diagram showing the distribution of unfrozen water in frozen soils: a) low salt-concentration pore fluid in fine-grained soil, b) high salt-concentration pore fluid in fine-grained soil, and c) high salt-concentration pore fluid in coarse-grained soil /from Hivon and Sego, 1995/.*

3 Effects of permafrost

3.1 Mechanical stability

The formation of ice with the onset of freezing conditions commonly causes frost heave, ice wedging, and displacement of the sediment structure and surface topography. As freezing progresses, massive ice may form either as buried surface ice (e.g. glacier ice) or as intrasedimental ice (e.g. intrusive ice). The latter probably forms in situ by downward permafrost growth in areas of high groundwater levels /Mackay and Dallimore, 1992/.

In non-saline sediments, permafrost provides a very stable and strong substrate which can support the weight of pipelines, buildings, etc over a long period of time. Saline permafrost, however, becomes less stable with time due to the presence of liquid (saline) water between the grains /Nixon, 1988; Biggar and Sego, 1993/. For instance, if the pore water salinity in a soil is 30 g/L, the initial freezing point is –1.8°C. As the temperature falls below this point, relatively pure ice crystals form between the pores leaving salt-enriched fluid (brines) between the ice crystals. These allow a significantly higher creep rate to be sustained by the soil when it is subject to load and this has important implications for foundation design – particularly for pile foundations – and may bring about a large reduction in allowable load for the foundation structure. The differences in liquid water content at temperatures below 0°C for freshwater soils and saline soils are shown in Figure 3-1 /Nixon, 1988/. For instance, at –10°C in saline soils, up to 25% of the soil may be liquid water whereas in freshwater soils the maximum water content is about 5%.

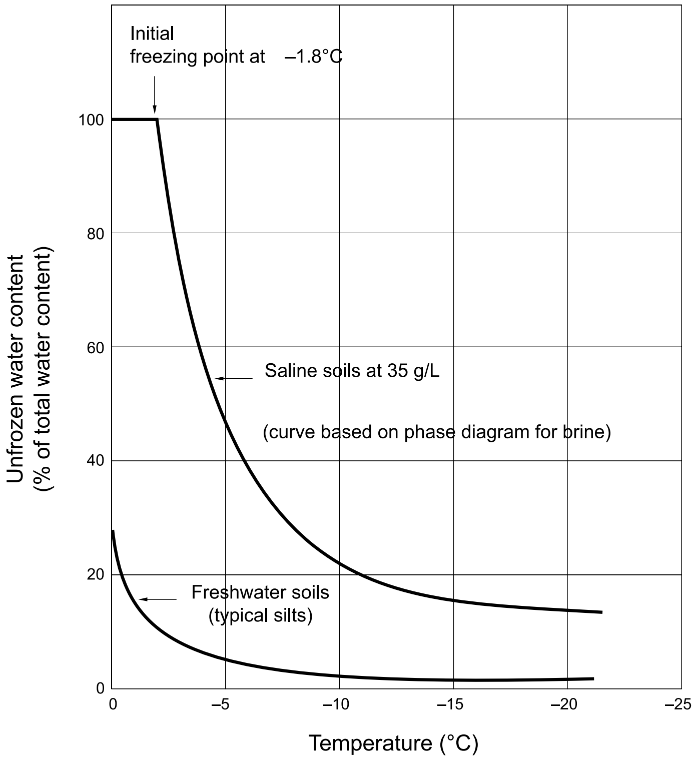

Figure 3-1. *Variation in unfrozen water content with temperature for freshwater and saline soils /from Nixon, 1988/.*

3.2 Groundwater hydrology

The many forms of permafrost tend to have common characteristics of hydrological behaviour /Woo, 1990/: 1) the frozen ground has limited permeability and acts as an aquiclude, 2) most hydrological activity is limited to the active layer that overlies the permafrost, 3) the active layer is largely inactive for the winter months of the year, 4) fluxes of energy and water are closely linked as they are both controlled by freeze-thaw events, and 5) snow and ice storage influence the timing of water release and other hydrological processes.

The hydraulic conductivity of soil or sediment decreases with reduction in temperature to below 0°C because the amount of unfrozen water decreases and so the available contact area of interconnected films of water is reduced /van Everdingen, 1990/. Frozen ground, therefore, can exert a strong retarding influence on groundwater movement. Discontinuities such as fractures and solution channels can provide significant additional hydraulic conductivity to the frozen ground, however.

An important hydrological feature of permafrost is the presence of open, unfrozen groundwater pathways that exist through the frozen ground. These are known as taliks and are usually maintained by upward flow of heated water (hydrothermal taliks) or saline water at subzero temperatures (hydrochemical taliks). Taliks usually occur beneath lakes and rivers. They may be completely open to depth (thereby representing a 'window' through the permafrost), they could be lateral, discontinuous taliks between layers of permafrost, or they could be isolated taliks that are surrounded by permafrost and are usually either transient or maintained by high salinities. Pingos are usually formed above shrinking isolated taliks. Saline waters in taliks are known as basal cryopegs (formed in lateral taliks that are located in inland sedimentary basins) and marine cryopegs (formed in coastal environments).

3.3 Pore-water expulsion

The expulsion of pore-water (containing the salts rejected from ice formation) during the freezing of saturated sands and sediments is a well known phenomenon and results in the ejection of up to the 9% volume expansion of the pore water upon freezing /Mackay and Dallimore, 1992/. Field measurements at northern Canadian locations have been made to compare downward permafrost growth in drained lakes with lake-bottom uplift /Mackay, 1979, 1985/ and they show that up to 80% of the uplift can be accounted for by pore-water expulsion caused by ice formation. Groundwaters expelled by freezing, if confined by overlying sediments in an otherwise flat topography, may develop significant hydrostatic pressures which can result in the formation of pingos and other structures where the surface is disrupted. Evidence of the high pressures can be seen in the artesian nature of the confined water (Figure 3-2) when these structures are penetrated by drilling /Mackay, 1978/.

Figure 3-2. *Photograph of artesian flow from borehole drilled into side of pingo /from Mackay, 1978/.*

3.4 Sub-seabed permafrost

Deep-drilling for oil or gas exploration in offshore environments in northern Canada, Alaska and northern Siberia has resulted in the finding of permafrost existing at considerable depths below unfrozen bottom sediments /Samson and Tordon, 1969; Lewellen, 1973; Iskandar et al, 1978; Harrison and Osterkamp, 1982; Schwartsev et al, 1988/. Permafrost is present to depths of up to 900 m in these areas and is believed to be a result of freezing of the sediments when they were exposed during low sea-stands in Pleistocene time. Inundation of these sediments by seawater is now causing the permafrost to degrade slowly both from the base up and the top down, leaving a residual mound of permafrost in subsurface sediments. These stages are illustrated in Figure 3-3 /Dyke, 1991/.

The mechanisms of aggradation and degradation of permafrost have been considered in detail by /Dyke, 1991/ for the coastal areas of the Beaufort Sea, NWT, Canada. Generally, permafrost is found to be degrading from the Tuktoyaktuk Peninsular in the east to northern Yukon in the west, due to sea-level rise and shoreline erosion and retreat. The process is complicated by the discharge of the warm Mackenzie River water into this area, which causes permafrost melting in the spring and summer seasons in sediments that are covered by 10–20 m of seawater. As sea-level rises, however, thawing stops and the sediments return to a frozen state, controlled by the temperature of the underlying, more-extensive Pleistocene permafrost.

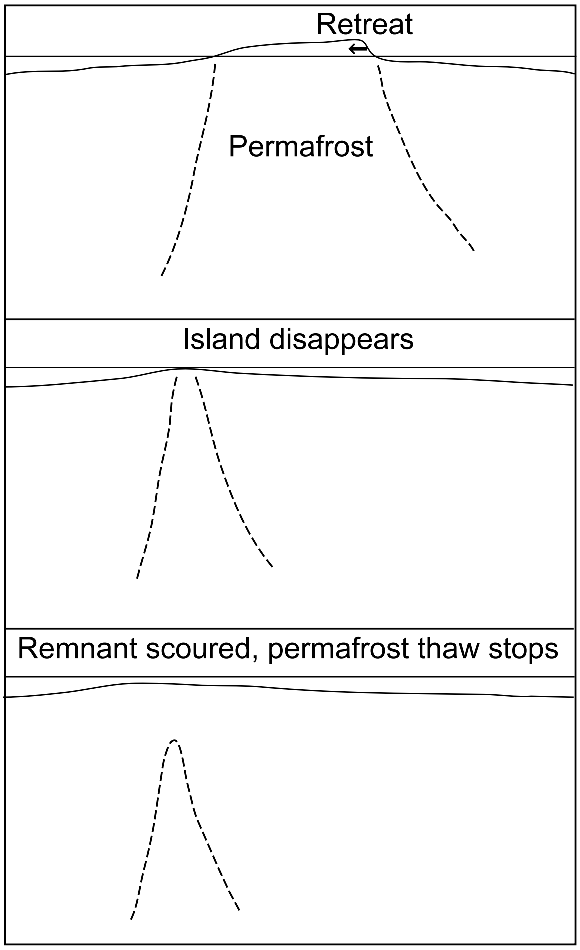

Figure 3-3. *Hypothetical sequence showing the disappearance of an island and the development of a shallow permafrost mound during erosion/deposition sequences associated with sea-level changes /from Dyke, 1991/.*

Not all of the Arctic regions have experienced the same events at the same time. For instance, during the last glaciation in North America, lower sea levels exposed the continental shelf areas of the Beaufort and Chukchi Seas and, as a result, permafrost over 700 m deep formed in these areas /Sproule, 1969; Mackay, 1986/ although it is likely that this thick layer may be the result of more than one glacial event. In contrast, during the glacial periods, the Arctic Islands to the east were largely ice-covered and the land areas depressed and relatively free of permafrost. These areas are now experiencing post-glacial isostatic uplift. Two regions have therefore been developed with different coastal characteristics at the present time: in the western Arctic, coastal recession and erosion is occurring as sea level rises causing degradation of the deep permafrost, whereas in the eastern Arctic and the Arctic Archipelago, isostatic uplift is occurring with permafrost aggradation at emerging shorelines /Hunter, 1988/.

Similar characteristics have been noted by /Are, 1983/ for the northern continental shelf of the former Soviet Union where brines and precipitates of mirabilite ($Na_2SO_4.10H_2O$) have been formed. Are notes that the mean annual temperature of the seabed is dependent on water depth: in shallow water, where ice freezes to the bottom, it is usually negative; in water 2–7 m deep it may be either negative or positive; and below 7 m depth it is again negative. Therefore, the depth of thaw of the seabed in this area depends partly on the length of time the water was 2–7 m deep, and this, in turn, is influenced by the rate of post-glacial sea-level rise.

Because of isostatic movements of the land surface and changes in sea-level associated with glaciations, seawater may have extended inland to a much greater distance than its current position and so saline groundwaters (particularly Na-Cl waters) and soils or sediments could occur some distance inland from the modern coastline.

In a recent evaluation of well-logs from the sub-seabed permafrost on the North Slope of Alaska, /Collett and Bird, 1993/ showed that the ice-bearing permafrost interval was not vertically continuous but was interrupted by numerous intervals in which ice was largely absent. The most prominent zone with these characteristics lay between 50 and 250 m of the surface and was laterally continuous over an area of at least 1000 km^2. The zone mainly lay within a conglomeratic section of sediments with temperatures as low as –8°C. The pore water salinity was calculated to be at least 130 g/L. These brines are believed to have formed at the freezing front as permafrost advanced to greater depths and they migrated downwards, under density-driven flow, to be trapped above a low-permeability, clay-rich rock sequence.

3.5 Geophysical detection

The presence of permafrost in a borehole in soils or marine sediments gives rise to several distinctive changes in physical properties which can be detected by down-borehole surveys using geophysical probes. For instance, the elastic wave (acoustic) velocity and electrical resistivity of sediments both decrease significantly in the transition from ice to water /Pandit and King, 1979/. These measurements, coupled with down-borehole temperature logs, are used to determine the depth of the base of permafrost in sub-seabed boreholes and to identify the presence of saline pore fluids below this interface /Harrison and Osterkamp, 1982; Collet and Bird, 1988/.

The usefulness of various geophysical methods and the influence of pore water salinity is further described by /Hnatiuk and Randall, 1977/ and /Fediukin and Frolov, 1993/. /Collett, 1983/ has also described the application of different down-borehole geophysical tools for their ability to detect the presence of gas hydrates (see section 3.9). The dual induction and mud logs were found to be the most useful, but other methods such as the caliper, sonic and neutron logs held promise.

3.6 Chemical composition

Unfrozen waters in permafrost areas may be relatively dilute if derived principally from 1) the active layer where groundwater residence times are short, 2) degrading permafrost in areas where the influence of modern temperature gradients is causing frozen ice to melt and 3) groundwater flow systems in karst or highly fractured crystalline rocks where flow is rapid and rock-water chemical interaction is slow.

In coastal or marine environments, however, unfrozen waters are usually much more saline and derive their dissolved load primarily from two sources: 1) pore fluids and residual waters that were included with the sediments during the time of deposition from a saline water (e.g. seawater) and 2) higher salinity waters that were formed by salt-rejection processes during aggradation of the permafrost. Examples of locations where the saline water present in sub-surface sediments can be attributed to salt-rejection are given in section 4 below.

If salt concentrations are known, their effect on freezing-point depression can be calculated as follows /Osterkamp and Payne, 1981/:

$$T_c = 0.0137 + 0.05199\ S + 0.00007225\ S^2 \qquad 3\text{-}1$$

where T_c is the depression of temperature (expressed as a positive value) and S is the salinity of the pore water (in g/L) assuming a NaCl composition. This relationship applies to salinities of up to ~42 g/L. /Dubikov et al, 1988/ have determined the freezing point depression caused by other salts in addition to NaCl (Figure 3-4) and find that the depression caused by the salts such $MgSO_4$ or K_2CO_3, is less than that caused by NaCl on an equivalent basis.

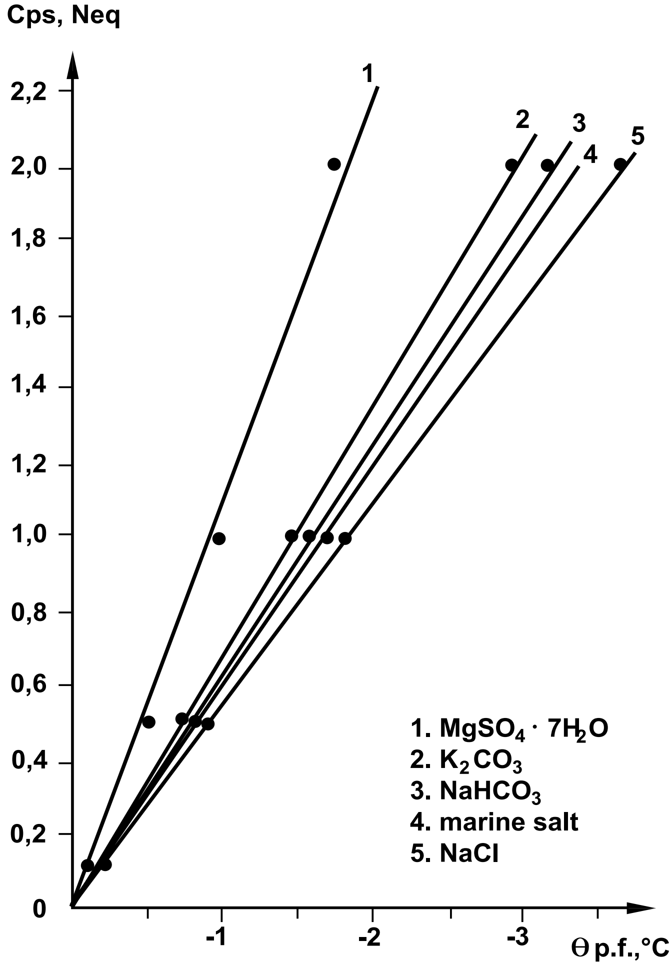

Figure 3-4. Freezing point of salt solutions of different compositions; Cps is the concentration of pore solution in gram equivalents /from Dubikov et al, 1988/.

3.7 Isotopic composition

During freezing, under equilibrium conditions, there is a fractionation of between 2 and 3‰ for ^{18}O and about 20‰ for ^{2}H between ice and water. Various experimentally derived values for the ice-water fractionation factors are given in Table 3-1 (after /Moser and Stichler, 1980/ with additions). Freezing in the subsurface should be an equilibrium process and, therefore, these fractionation factors might be expected to apply producing residual saline waters or brines isotopically lighter than the original groundwaters. Enhanced fractionation in a closed system may take place if depletion of the heavier isotope occurs during progressive freezing of a limited volume of water. This process is known under the general term of the Rayleigh distillation effect and may account for the large isotopic variations that have been observed in ice and waters in permafrost environments /Michel and Fritz, 1978, 1982/.

Alternatively, these large variations may also be due to changing climate over the period of formation of the permafrost. To attempt to answer this question, results have been described by /Michel and Fritz, 1982/ for isotopic analysis of soil and sediment cores up to 8 m deep from the area surrounding Lake Ilisarvik on Richards Island in the delta of the Mackenzie River, NWT, Canada. The profile for the longest core studied is shown in Figure 3-5. The depth of the active layer is determined as about 0.45 m in which there is a steep decrease in $\delta^{18}O$ due to freezing downwards from the surface, followed by a small positive shift indicating freezing upwards from the permafrost interface. A zone of massive ice from ~0.5 to 5.5 m corresponds to an ice wedge which has a uniform composition of –24 to –25 λ. Below this the $\delta^{18}O$ values decrease steeply to –31‰ which is interpreted as indicative of recharge in late-glacial times. Thus, the isotopic record of long-term changes in climate appears to have been preserved in this core with apparently negligible volumetric effects.

A good example of where Rayleigh distillation clearly occurs is in the formation of a frost blister, in which the blister (ice) is formed by continuous downward freezing in a water-filled cavity overlying permafrost /Clark and Fritz, 1999/. A vertical profile of $\delta^{18}O$ through a 1-meter section of ice (Figure 3-6) shows systematic depletion of ^{18}O in the ice, ending at a depletion of about 7‰ when the remaining amount of fluid was ~5% of the original volume.

Table 3-1. Experimental determinations of the isotopic equilibrium fractionation factors (α) for ^{2}H and ^{18}O between ice and water (after /Moser and Stichler, 1980/ with additions).

α (^{2}H)	α (^{18}O)	Reference
1.0171	1.00048	/Kuhn and Thurkauf, 1958/
1.0235	–	/Merlivat and Nief, 1967/
1.0195	1.0031	/O'Neil, 1968/
–	1.00265	/Craig and Hom, 1968/
1.0208	–	/Arnason, 1969/
1.024	1.0022	/Stewart, 1974/*
1.0193, 1.0206	1.0031, 1.0028	/Suzuoki and Kumura, 1973/

* For concentrated seawater, add 0.003 and 0.0003, respectively

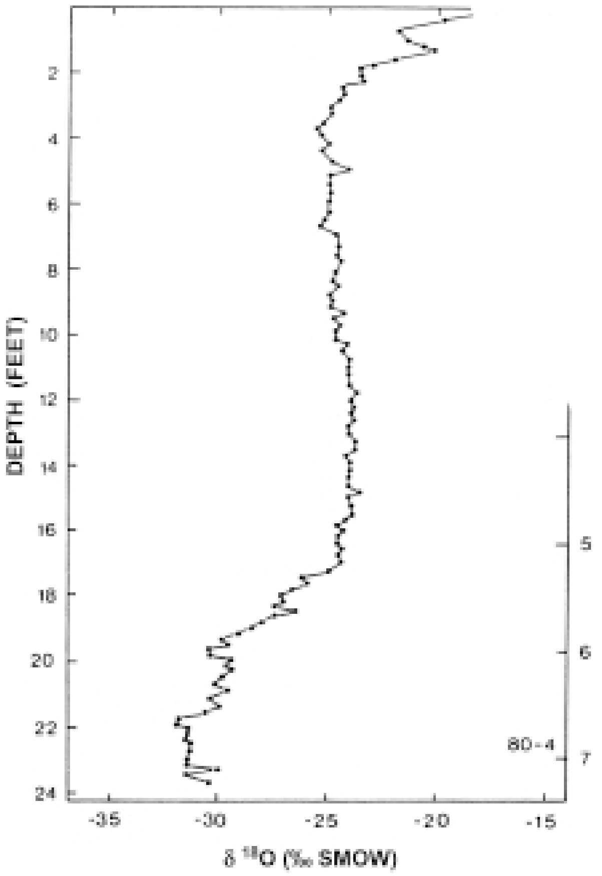

Figure 3-5. *Profile of $\delta^{18}O$ of massive ice in a soil/sediment core from Lake Ilisarvik, NWT, Canada /from Michel and Fritz, 1982/.*

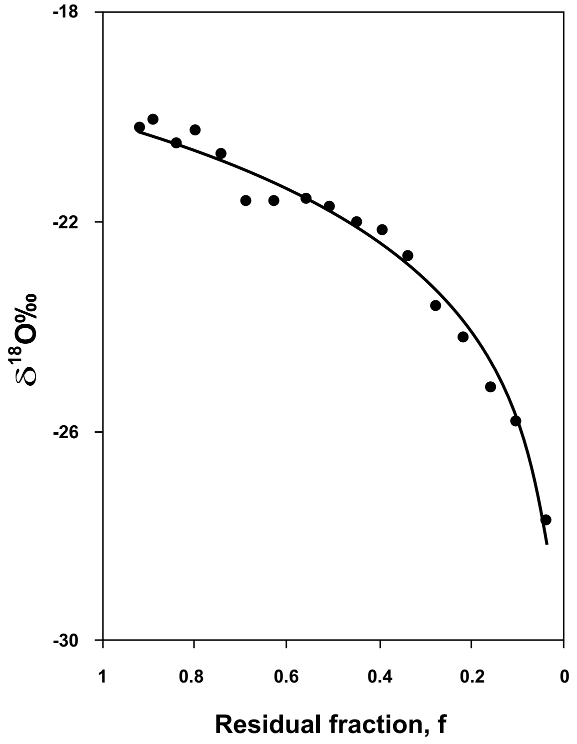

Figure 3-6. *Rayleigh distillation curve and measured $\delta^{18}O$ data for an ice profile through a frost blister in permafrost in the Yukon Territory /after Clark and Fritz, 1999/.*

3.8 Chemical precipitates

Several researchers have observed that chemical precipitates appear to have formed in periglacial environments due to salt rejection during freezing /Cailleux, 1965; Hallet, 1976; Hillaire-Marcel et al, 1979/. These precipitates are formed largely because of solubility constraints at lower temperatures, in which CO_2 release or uptake may be involved as water freezes. For instance, /Vogt, 1991/ has reported that Fe, SiO_2 (as opal) and $CaCO_3$ precipitates have been formed at the microscopic scale on sediment grains during frost and ice formation at several locations in France and Argentina. Cryogenic calcite silt has been identified in river icings, karst springs and limestone caves due to the freezing of groundwater followed by sublimation of the ice, to leave a white (calcite) powder /Hall, 1980; Lauriol et al, 1988; van Vliet-Lanoë et al, 1990/. These calcites have been found to have unusual isotopic compositions (e.g. $\delta^{13}C$ up to +17‰) due to non-equilibrium conditions during their formation /Clark and Lauriol, 1992/. This characteristic may be useful in identifying a cryogenic origin for calcite infillings in crystalline rock that has experienced periglacial conditions.

A more soluble salt that is often found associated with glacial or periglacial conditions is mirabilite which has been observed in large quantities in coastal locations in Antarctica /Burton, 1981/. Formation of mirabilite causes a decrease in the SO_4 concentration in water, which may account for the low SO_4 concentrations of some groundwaters in crystalline rock. Conversely, groundwater found to be enriched in SO_4 in non-glacial times, may have derived some of the SO_4 from re-solution of mirabilite precipitates once deglaciation begins.

3.9 Natural gas hydrates

Gas hydrates are methane (CH_4) molecules enclosed in a solid water (ice) cage structure (also known as a clathrate). They are widespread in permafrost regions, particularly in the sub-seabed, and are found in northern Canada, Alaska, and sedimentary basins in northern Russia, as well non-frozen areas such as the Caribbean and low-latitude, coastal areas of the Atlantic Ocean. While gas hydrates have only a limited bearing on the association of permafrost and saline groundwater, they are important in understanding possible sources of CH_4 in deep groundwaters and whether permafrost formation in crystalline bedrock might influence the dissolved gas content.

The distribution and abundance of gas hydrates has been reviewed by /Judge, 1982/. Extensive data on the varying compositions of gas hydrates and temperature-pressure relationships have been obtained by the oil and gas industry /Collett, 1983/. Gas hydrates typically occur in sediments that are below 200 m of water depth and, from theoretical considerations, are expected to occur down to a maximum sediment depth of 1800 m /Judge, 1982/. The quantity of gas hydrates in sediments, globally, may be as much as 10^{18} m^3 /Dallimore and Collett, 1998/.

The phase diagram of CH_4 hydrates and water is shown in Figure 3-7. It can be seen that gas hydrates can occur at temperatures greater than 0°C provided that the pressure exceeds a water depth of ~300 m (3 MPa). The growth of gas hydrates in sediments has been shown to exclude salts from the clathrate structure, resulting in a concentrated residual pore fluid /Ussler III and Paull, 1995/. Also, the formation of gas hydrates results in isotopic enrichment in the solid phase, of about the same amount as in

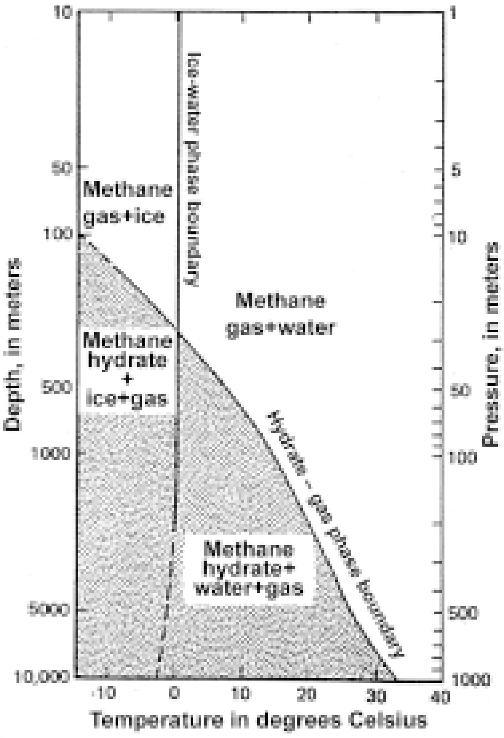

Figure 3-7. Phase-boundary diagram for methane gas and methane hydrate for a freshwater system /from Collett, 1983/.

the ice-water fractionation. This information has been used by /Clark et al, 1999/ to understand the origin of pore waters and their salinities in permafrost-containing gas hydrates from a deep research borehole recently drilled in the Mackenzie River delta, NWT, Canada. The isotopic and geochemical evidence indicate a history of gas hydrate formation and decomposition together with fluid migration. It is believed that the original pore fluids are a result of mixing between seawater and meteoric (fresh) water.

4 Examples of permafrost and salt rejection

In addition to the studies cited above, there are several examples in the literature that describe locations where the processes of permafrost aggradation and accompanying salt rejection have been identified.

4.1 Antarctica

Antarctica has relatively few areas of accessible permafrost because it is largely covered by glaciers and extensive ice sheets. However, some areas are unglaciated and contain lakes that are frozen for most of the year. The occurrence of saline lakes in Antarctica has been reviewed by /Burton, 1981/. Several of these lakes lie to the west of McMurdo Sound and are formed in unglaciated valleys, recharged only by direct precipitation and occasional meltwater from adjacent highlands. Two of these lakes, Lake Vanda and Lake Bonney, have been intensively studied because of their clarity, salinity and unusual biology /Goldman et al, 1967/. The east lobe of Lake Bonney contains a brine at depth which has a salinity of almost 300 g/L /Burton, 1981/. These lakes were originally believed to have obtained their salinity by evaporative loss and capture of airborne aerosols and seaspray but predominance of Ca-Cl waters in some lakes suggested that rock weathering and ion exchange was also important, combined with the loss of Na-Cl by precipitation at temperatures below –36°C.

4.2 Northwest Territories, Canada

The western Arctic coast (Figure 4-1) is an area of continuous permafrost to depths often greater than 400 m /Mackay, 1997/. Construction and development activities in permafrost areas requires knowledge of the characteristics of the soils, underlying sediments and, in some cases bedrock. As described in section 3.1, the presence of saline permafrost may cause frozen soils to creep under load and thus reduce the strength of surface structures. This problem has been particularly of concern in the Northwest Territories and has resulted in a comprehensive gathering of publically available salinity measurements for a database covering the entire Canadian Arctic within the NWT /Hivon and Sego, 1993/. The sites providing data are shown in Figure 4-1. All soils were analysed for salinity by a variety of methods. The results for all regions are plotted in Figure 4-2. Clays and fine-grained soils were found to be the most saline, particularly in coastal areas. Cryogenic effects are clearly occurring in some samples as the maximum salinity observed was greater than the salinity of seawater.

One specific site in the NWT has been studied in considerable detail for almost 20 years in a multidisciplinary experiment on the growth of permafrost on the unfrozen bottom of a drained lake. In 1978, permission was obtained to simulate the natural draining of a shallow lake, Lake Ilisarvik, on Richards Island in the delta of the Mackenzie River /Mackay, 1997/. A bowl-shaped talik of depth 32 m underlay the lake prior to drainage. The site was surveyed in detail, drained and the aggradation of permafrost in the instrumented lake was monitored over the following years. Both downward and upward freezing of the lake bottom was observed (due to sub-zero average annual surface

Figure 4-1. Map of the coastal areas and Arctic islands in the Northwest Territories, Canada, showing locations of salinity measurement sites /from Hivon and Sego, 1993/.

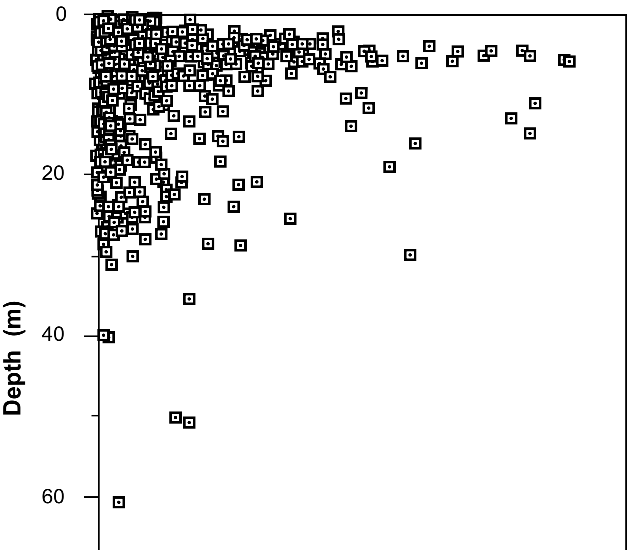

Figure 4-2. Variation of salinity with depth in soils and sediments for all sites sampled at locations shown in Figure 4-1 /from Hivon and Sego, 1993/.

temperatures and the presence of permafrost beneath the talik). This has resulted in thinning of the active layer, ground uplift, growth of aggradational ice, solute rejection and pore-water expulsion from the lake-bottom sediments. The remaining water in the deeper part of the lake, known as South Pond, had a salinity of about 10 g/L, a $\delta^{18}O$ value that was about 6λ lighter than surface ice, and contained no ^{3}H. These data were interpreted by /Mackay, 1997/ as evidence for the expulsion of groundwater derived from deep below the lake bottom together with some of the salt content originating from the salt rejection process.

4.3 High Arctic Islands, Canada

A number of hypersaline lakes have been found in the Canadian Arctic in which there is strong stratification of salinity with depth. The lakes are termed meromictic, indicating that water mixing, or 'turnover' does not occur because of the high density of the deep waters. Therefore, the bottom waters are isolated from the surface environment and have become anoxic, and enriched in P and H_2S. Garrow Lake, on Little Cornwallis Island, is an example of this type of lake /Ouellet and Pagé, 1988/. Its salinity is a constant ~90 g/L in the lower section and it is believed that the salinity arises from the freezing out of salts in the sediment by permafrost aggradation as the land slowly rises. The origin and evolution of these types of lakes is shown in Figure 4-3. However, these

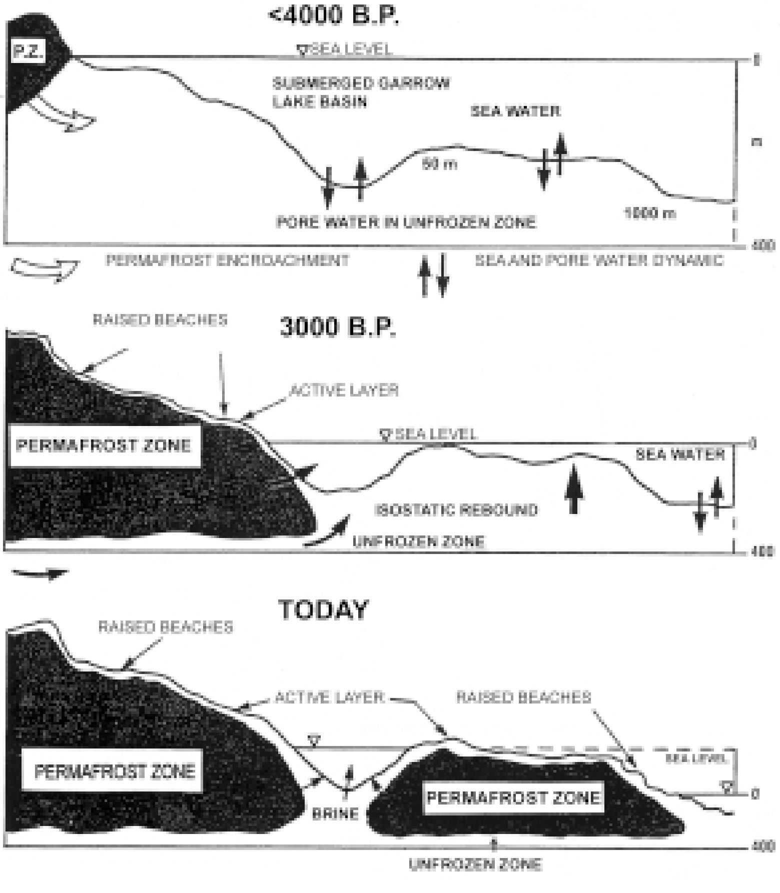

Figure 4-3. *Proposed origin of hypersaline water in Garrow Lake, Little Cornwallis Island, in the Canadian Arctic /from Ouellet and Pagé, 1988/. Shaded areas are continuous permafrost. The advance of permafrost in surrounding ground since lake formation (~4000 years ago) causes residual brines to migrate into the lake bottom.*

lakes may be similar to those in Antarctica (section 4.1) which appear to have formed partly by evaporative loss under relatively dry climatic conditions. Other occurences of saline waters in the Canadian High Arctic are described in section 5.

4.4 Northern Russia

Of all the countries in the world that have studied permafrost, Russia (or formerly, the Soviet Union) has undoubtedly done the most work on the topic. Unfortunately, much of this work is reported only in the Russian language and in Russian publications, and so has not been seen by the western world. However, some North American authors have summarized and cited Russian work in their publications and Russian scientists have presented their work at international meetings, notably the International Conferences on Permafrost, of which, so far, there have been seven. The review of Russian work described here is restricted to papers given in English or subsequent translations of papers from Russian.

/Mel'nikov, 1983/ has given a broad summary of the developments and findings in the Soviet and Russian programs over the preceding ~50 years. Fully half of the territories of the former Soviet Union are perenially frozen and thus, the study (known as geocryology in Russia) of these regions (cryolithozones), began as early as the 1920's. Areas of high and low geothermal heat flux have been identified and mapped and the heat and moisture flux requirements to establish the climatic conditions necessary for permafrost growth, have been quantitatively assessed.

Using permafrost facies analyses and dated paleontological deposits, it has been shown that permafrost in some basins in Yakutia (eastern Siberia) may be as old as two million years. In addition, several interesting findings have been made: 1) intense physico-chemical processes occur not only in the active zone, but at greater depths; 2) in many areas, permafrost is maintained not by climate but by surficial cover (removal of the cover during resource development causes the permafrost to degrade giving detrimental consequences); and 3) in the inland mountainous areas of Central Asia and Kazakstan, permafrost occurs no deeper than 200 m in unconsolidated sediments but in bedrock, occurs at depths of up to 360 m.

Shvetsov (1941, in /Chizhov, 1980/) was one of the first to draw attention to the association of saline groundwaters and brines with permafrost aggradation in polar regions. Since then, the abundance of saline waters in association with permafrost has been noted by several Russian scientists as described below.

1) A major emphasis of permafrost studies in the former Soviet Union has been sub-seabed permafrost in the Arctic coastlands and islands to establish methods for predicting sub-seabed permafrost distribution for resource development. During the Quaternary, part of the Soviet shelf was continually submerged and existing permafrost degraded /Are, 1983/. During periods of emergence, due to sea-level lowering, sediments froze and brines and precipitates of mirabilite were formed when the temperature of the permafrost fell below –8°C /Fotiev, 1980; Are, 1983/. Because of the periods of aggradation and degradation during cycles of emergence and submergence, respectively, permafrost is now often found at depths well below the seabed.

2) /Dubikov et al, 1988/ described the occurrence of permafrost in the USSR and identified permafrost in two types of saline ground: marine and continental. Marine salinity (mainly found in the northern lowlands adjacent to the Arctic coastline, Figure 4-4) is caused by Pleistocene marine transgressions and sediment deposition on to permafrost ground, followed by local freeze-thawing and desalinization of the top layer of marine sediments, giving rise to salt-rejection and migration of brines to lower strata. Marine salinity is characterized by ionic concentrations as follows: $Na>>Mg>Ca$ and $Cl>>SO_4>HCO_3$. Continental salinity in permafrost (Figure 4-4) is generated in areas where high summer temperatures and a negative balance of soil moisture promotes salt accumulation in the soils and underlying strata. The salinity is typically more variable and enriched in SO_4 and HCO_3.

3) Other instances of saline waters in permafrost areas of northern Russia include the existence of Mg-Ca-Cl brines, up to 100 g/L, in northeastern Siberia /Fotiev, 1983/ where the depth of cryogenic beds (i.e. the depth of permafrost) is up to 1500 m. In addition, /Chizhov, 1980/ has described the existence and location of cryopegs in the Arctic and northern Siberia, discovered during exploration for minerals, oil and gas. He argues that a thick cryopeg zone can impede the upward movement of subsurface brines that originate at much deeper, warmer levels and uses the depth to the zone as an indicator of the underlying presence or absence of these potential discharges (i.e. shallow cryopegs indicate brine upwelling). Thus he claims that large negative temperature anomalies in the earth's crust are associated with cryopegs.

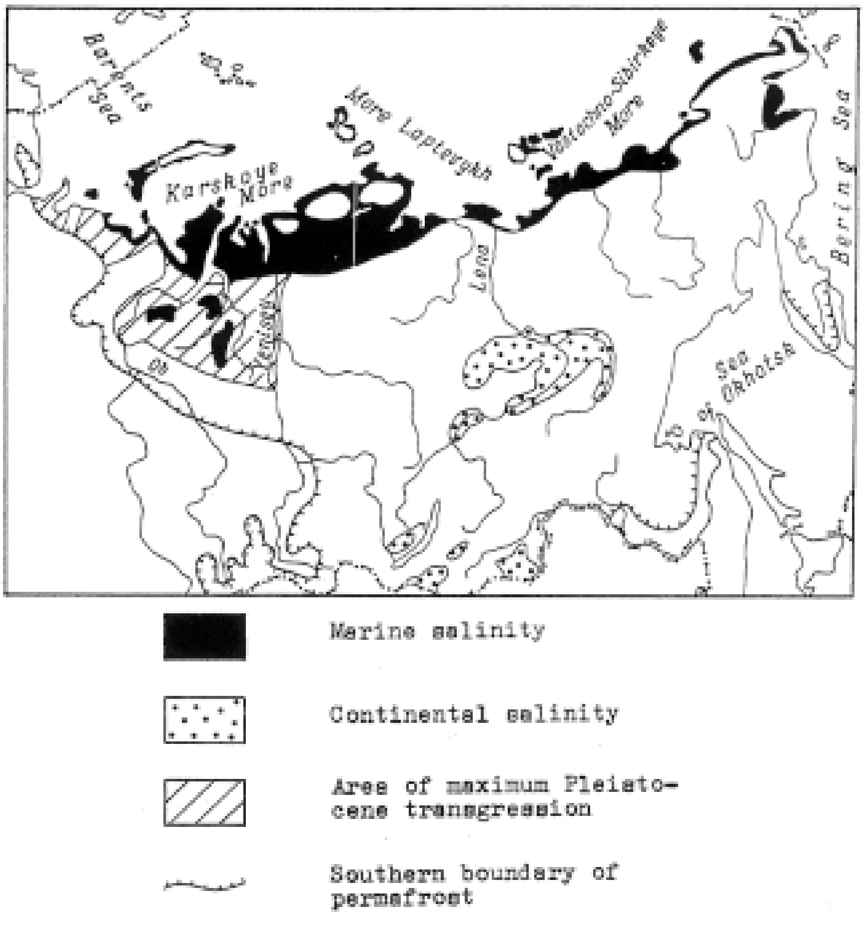

Figure 4-4. Location of saline permafrost (marine and continental) and the area of maximum transgression of seawater during Pleistocene time in northern Russia /from Dubikov et al, 1988/.

4) In a study in western Siberia, /Kritsuk and Polyakov, 1993/ have observed two types of groundwater associated with permafrost: Na-Cl and Mg-SO_4, with concentrations up to 7 g/L. Lenses of ancient, low salinity (~5 g/L) Na-Cl groundwaters have been found in southwestern Siberia. Radiocarbon dating suggests that these waters have been isolated from the surface for over 10,000 years. Cryopegs are most common in the north, towards the coast, and salinities range as high as 80 g/L (as Na-Cl and, occasionally, Na-Mg-Cl-HCO_3). The $^2H/^{18}O$ composition of these waters lies slightly above the meteoric water line leading the authors to conclude that the cryopegs are relicts of cold climates when surface water and most taliks were frozen (however, this in itself should not cause waters to trend above the line).

5) /Anisimova, 1980/ has provided an interesting and readable description of hydrogeochemical investigations in permafrost in the former Soviet Union. She describes the formation of brackish water lenses in non-marine environments (in central Yakutia) which attain similar salinities as marine cryopegs. Some of these are formed by freezing of domestic and industrial waste waters. In the uncontaminated areas, numerous taliks have formed in sand deposits and have been found to have high Mg-Na-HCO_3 contents. These are believed to be products of the first stage of cryopeg formation. Anisimova points out that groundwater from thawed ground differs considerably from the water which first saturated it prior to freezing because, as the ground freezes, the low-solubility salts are precipitated. On thawing, these waters are less mineralised because they are likely to have been separated from the precipitates and the unfrozen, salt-rich residual fluids. The chemical composition of numerous types of ice in frozen ground (e.g. wedge ice, fissure ice, injection ice, icings) are interpreted on this basis.

/Anisimova, 1980/ goes on to describe examples of how residual saline fluids can migrate through permeable sediments in response to diffusion, seasonal temperature changes and gravitational density effects. One example is the development of cryopegs in the town of Yakutsk. Deep underground excavations (for cellars, trenches, etc) have resulted in saline waters of 25–55 g/L (Mg-Na-Cl) forming taliks underneath the building foundations.

6) /Streletskaya, 1998/ has recently described the characteristics of cryopegs in the Yamal region of northern Russia. Most cryopegs are found in the flood-plain areas, from +20 to –200 m elevation of mean sea-level, and all have Na-Cl compositions with salinities ranging from 7 to 150 g/L. Streletskaya classifies cryopegs according to their formation, composition and conditions of formation (i.e. whether they are associated with permafrost that is currently aggrading/degrading, or passive).

Further Russian studies are described in the following section.

5 Permafrost in bedrock

Relatively few of the publications in the open literature on permafrost and salinity development describe the occurrence of saline waters in bedrock permafrost. They largely deal with soils or unconsolidated sediments, either on land or in the seabed. Most reports of permafrost in bedrock are of work done in conjunction with mining activities. Some examples are described below.

1) Ice in bedrock was observed at the Asbestos Hill mine, northern Quebec /Samson and Tordon, 1969/ in a chlorite sericite schist. Fractures in the rock were observed to be ice-filled and thicknesses of ice ranged from a few millimeters at depth up to 50 mm near the surface.

2) Permafrost occurs in bedrock above the ~70 m level at the Giant gold mine, Yellowknife, Canada. Most of the permafrost lies below a surface valley in which a clay and gravel cover appears to provide an insulating layer /Espley, 1969/. The permafrost here, therefore, is likely to be old and is presently degrading. The presence of permafrost in the upper levels has provided a convenient method of storing enormous amounts of arsenic trioxide dust, without containers, in rooms excavated above the 70 m level. Similar conditions exist in the Miramar Con mine, also near Yellowknife. Considerable work has been done in determining the hydrogeochemistry of groundwaters entering this mine /Frape et al, 1984; Frape and Fritz, 1987/ and, recently, the possibility of a cryogenic origin for the saline waters has been proposed by /Bottomley et al, 1999/.

3) /Williams and Waller, 1963/ and /Williams and van Everdingen, 1973/ have reviewed permafrost occurrences in bedrock and the availability of unfrozen groundwater in permafrost terrain. They find widespread brackish/saline groundwater in bedrock beneath continuous permafrost in the northern part of Alaska. Some compositions of these waters are given in Table 5-1. The authors cite reports showing that continuous permafrost extends nearly everywhere into bedrock and can attain depths of up to 610 m.

4) /Ginsburg and Neizvestnov, 1973/ have reported saline groundwaters in basalts on Franz-Josef Land in the Russian Arctic islands (Table 5-1). No depth data were given. These waters have a cationic composition that is characteristic of concentrated seawater.

5) /Pinneker, 1973/ has reported the presence of brines of at least 200–300 g/L in Permian sandstones at 300–500 m depth in the Tungusskiy artesian basin of the Siberia platform. These brines discharge to the surface through taliks in the form of springs that are located above permeable fault zones. The taliks represent flowpaths that penetrate through the frozen, overlying Triassic tuffs.

6) /Wang, 1990/ has reported the occurrence of permafrost in granitic bedrock in the Huola River basin in northeast China. The permafrost was observed in boreholes that were drilled during the siting studies for a coal-burning power plant and occurred at depths ranging from 30 to 100 m deep. In the active layer near the surface, groundwaters were Ca-Mg-HCO_3 (0.1–0.2 g/L) in composition, tending to higher salinity (0.2–0.3 g/L) and Na-HCO_3 at depth. Wang believes that water-rock interactions are more likely to control this change than salt-rejection processes associated with permafrost formation.

Table 5-1. Examples of groundwater salinity (in g/L) associated with permafrost in bedrock in Alaska, northern Canada and Russia.

Location	Na + K	Ca	Mg	Cl	SO_4	HCO_3	TDS	Reference
N. Canada (maximum values)	8.5		15.8				18.4	/Williams and Everdingen, 1973/
N. Canada (maximum values)	25			18.3	8	8	300	/Williams and Everdingen, 1973/
N. Canada (springs)	5.7			5.2	2.8		12.7	/Williams and Everdingen, 1973/
N.Canada (Gypsum Hill, AH Is.)				42.9	4		75	/Williams and Everdingen, 1973/
Alaska (Copper R. lowland)			no	data	(Na-Ca-Cl type)			/Williams and Everdingen, 1973/
Russia (Franz Josef Is.)	65	18	17	98	2		200	/Ginsburg and Neizvestnov, 1973/
Barents Sea	14.9	0.6	3.2	16.9	1.8		37.4	/Neizvestnov and Semenov, 1973/
Barents Sea	36.6	1.9	8.3	42.5	4.1	0.1	93.6	/Neizvestnov and Semenov, 1973/
Siberian platform			no	data	(Ca-Cl type)		200–300	/Pinneker, 1973/

7) /Zhukovskiy et al, 1973/ have examined the ice in permafrost formed in granite at the site of construction of the Kolyma hydroelectric power dam in eastern Siberia. Boreholes were drilled to over 100 m depth in the rock and permafrost conditions were observed to depths as great as 300 m below the overlying hill surface (Figure 5-1). The river beds forms an open talik. As a result of drilling and excavation of adits in the granite, ice was observed in a number of forms in the fractures. Zhukovskiy et al describes these observations as follows [sic]:

> "The formation of the ice in the granite massif during its freezing, took place along the cracks primarily as a result of filling of them and in the surface part also as a result of expansion of the cracks during the process of freezing and thawing of the rock. With respect to the peculiarities of its formation in the granite, the ice belongs to the vein and injection-cementation types, although sublimation is noted and it is represented in the fissures both by pure ice and ice in combination with various types of minerals and loose fillers. The fissures of different genesis are characterized by different ice content and different ratio of it to the filler. The joints usually contain pure ice of a turbid white colour in the form of thin interlayers several millimeters thick. In the thin cracks, the crusts, films and various layers of sublimation ice are observed. In the tectonic cracks, the ice is in the form of streaks between the surfaces of the fissures, frequently covered with calcite or tourmaline, or it is in contact with a layer of mylonite. The form of the streaks is usually complex, and their thickness varies from 1–5 mm to the first centimeters; then cementation of the mylonite with ice is noted. The cataclastic broken granite is impregnated with ice or is dissected in the complex part by a network of ice veins, and it is the iciest rock."

Details of the ice infilling in a fracture zone in this study are shown in Figure 5-2.

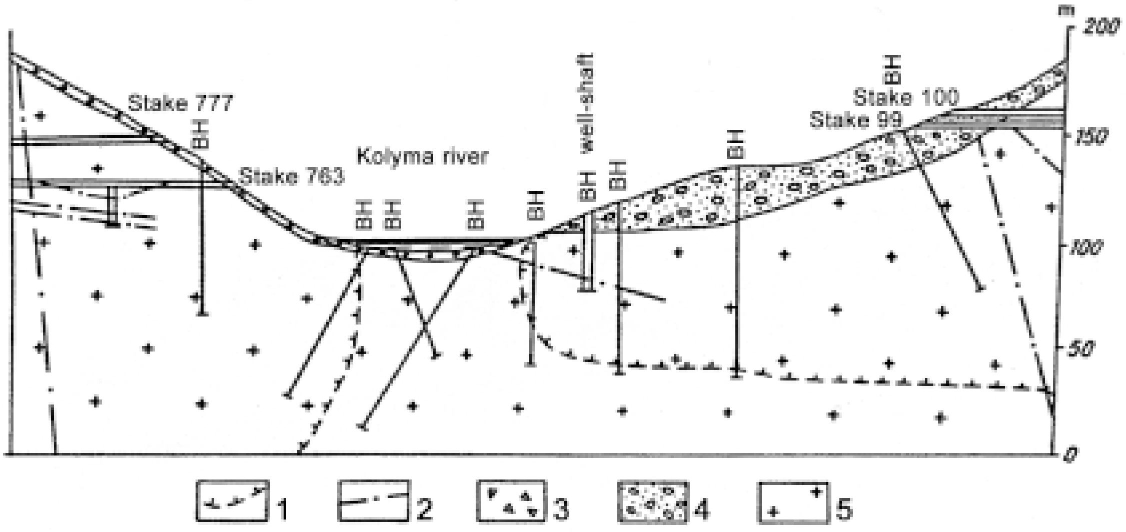

Figure 5-1. *Geological section of the Kolyma valley, northeastern Siberia, showing the permafrost boundary (1), major faults (2), colluvial (3) and alluvial (4) deposits, and granitic basement (5), /from Zhukovskiy et al, 1973/.*

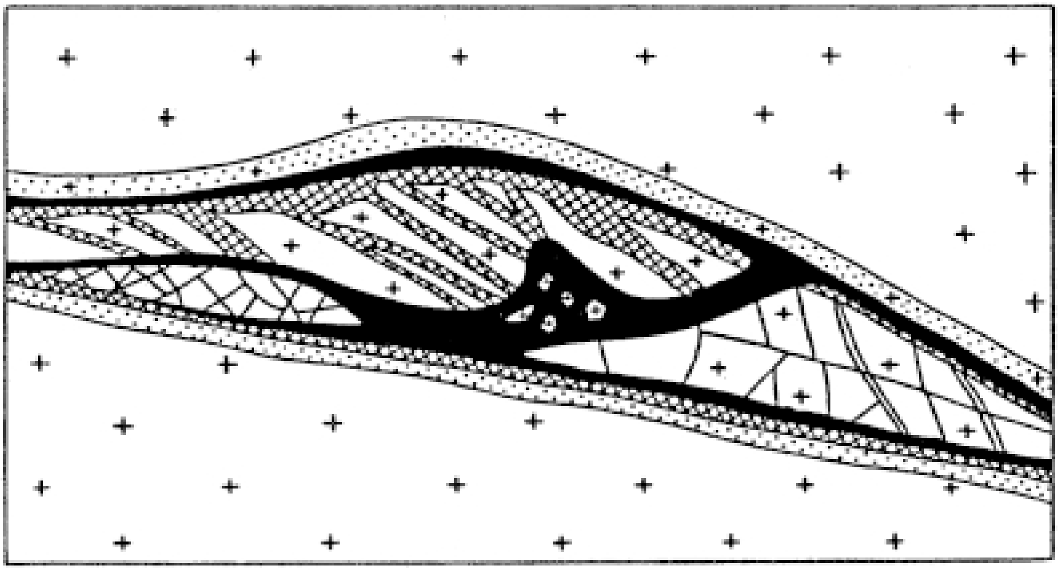

Figure 5-2. *Schematic diagram of the nature of the ice content in the low-dip fault zone in moderately fractured granite (1) showing iron oxide-rich granite (2), mylonite zones (3) and ice (4) /from Zhukovskiy et al, 1973/.*

8) The cryogenesis of groundwater in the Daldyn-Alakit region of western Yakutia has been studied as part of a deep-drilling program for diamond exploration /Alexeev and Alexeeva, 1998/. Permafrost-related saline waters and brines up to ~200 g/L have been found at depths of about 200 m and are believed to have concentrated to these levels from predecessor waters over long periods of permafrost aggradation and salt rejection. This work is one of the few recent studies that is concerned with the development of permafrost in fractured bedrock. Over 400 groundwater samples have been obtained and analysed in this ongoing work (S V Alexeev, pers. comm.).

9) Numerous groups of springs discharging from faulted and folded sedimentary rocks have been studied over an extensive period on Axel Heiberg Island, NWT, Canada. The latest results are summarized by /Pollard et al, 1999/. These springs are marked by abundant mineral precipitates of halite, gypsum and calcite, and groundwaters with salinities up to 130 g/L. The source of salts for these springs has not been studied in any detail.

6 Modelling of permafrost growth

A number of efforts have been made to model the growth, thickness and degradation of permafrost. Models have been developed ranging from simple one-dimensional thermal diffusion calculations, assuming steady state, to complex analytical and numerical models to describe heat transfer in permafrost in response to varying paleoclimatic conditions. It has been shown that the extent and depth of permafrost varies with temperature, geothermal heat flow, thermal conductivity of the host medium and its water content, and duration of exposure of the ground surface to freezing conditions /Lebret et al, 1994/.

These parameters have been used to determine the growth and thickness of permafrost in the sediments of Prudhoe Bay, Alaska, over Pleistocene time /Osterkamp and Gosink, 1991; Lunardini, 1993/. In this work, /Osterkamp and Gosink, 1991/ initially describe simple models to determine the change in permafrost thickness in response to change in climate. For instance, the time (t_c) for adjustment of subsurface temperature to a change in surface temperature can be simply expressed as

$$t_c = X^2 / 4D \qquad 6\text{-}1$$

where X is permafrost depth and D is the thermal diffusivity of the permafrost. In most cases, t_c ranges from a few years to about 3000 years. The time required for permafrost thickness to respond to change in surface temperature (e.g. due to a warming event) is longer than t_c because of the additional freezing or thawing that will occur once the temperature has stabilized. It has been shown to be several tens of thousands of years. /Osterkamp and Gosink, 1991/ developed detailed finite difference and finite element models to determine the thickness of deep permafrost in Prudhoe Bay and the relative influences of brine-containing permafrost and pure-ice permafrost. They compare thickness predictions with those of other models (e.g. the step model of /Brigham and Miller, 1983/, the SPECMAP model of /Matteucci, 1989/ and a model developed for East Siberia by /Maximova and Romanovsky, 1988/, and with the currently observed permafrost thickness (~600 m).

Other examples of permafrost models include a model of permafrost development over the last 50,000 years in the East Siberian Arctic shelf /Danilov et al, 1998/ and a model to determine permafrost depth in France during the last glaciation /LeBret et al, 1994/. /Harada and Yoshikawa, 1998/ recently reported a simple diffusion model which they used to determine the age and growth rate of permafrost at a site on the island of Spitsbergen, Norway, that was only 2 m above sea-level. Together with data from electrical soundings, they were able to define permafrost to be ~32 m in depth and to have taken ~530 years to form (since exposure by sea-level regression).

7 Summary and conclusions

The formation of permafrost in wet soils or sediments, or in water-saturated bedrock, proceeds with the production of essentially solute-free ice and the rejection of dissolved salts into an unfrozen aqueous phase. The concentration of salts in the aqueous phase will inevitably be greater than that of the original water and will increase as temperatures decrease below 0°C. Thus the formation of saline groundwaters is inevitable at a site where climate is deteriorating and where the groundwaters initially contain some salts.

There are abundant examples in the northern hemisphere of where saline groundwaters underlie or are otherwise associated with permafrost. However, it is not at all clear in most of these examples, how much of the salinity is due to concentration of salts by salt-rejection during freezing and how much is simply because saline groundwaters existed at these locations before the onset of freezing conditions. Distinguishing between these two origins is difficult but there may be certain characteristics that indicate that permafrost has been important in changing groundwater composition. These include: 1) greater salinity than adjacent seawater, 2) presence of mirabilite deposits, 3) depleted or enhanced SO_4 concentrations and 4) a lighter isotopic signature caused by the ice-water fractionation during freezing.

It is worthwhile, therefore, to assemble a database of occurrences of saline groundwater in sediments and bedrock that are subject to permafrost conditions at the present, and to search them for indicators of permafrost influence on groundwater salinity.

More precise information can only come, however, from the detailed study of a permafrost site, preferably in bedrock, in which the existence of permafrost and detailed hydrogeochemistry of groundwaters can be determined accurately. Such locations are rare but possible sites that are currently under investigation for their permafrost characteristics include the Miramar Con gold mine, near Yellowknife, NWT, Canada /Bottomley et al, 1999/, Lake Ilisarvik, NWT, Canada /Mackay, 1997/, the high salinity springs in bedrock on Axel Heiberg Island, NWT, Canada /Pollard et al, 1999/ and the diamond mines of the Daldyn-Alakit region, western Yakutia, Russia /Alexeev and Alexeeva 1998; S Alexeev pers. comm./.

The alternative hypothesis for the origin of saline groundwater in crystalline rock (the freezing of seawater and infiltration of residual brines, /Bein and Arad, 1992/, must be examined carefully as it presents a simple mechanism for the production of brines. However, the hydrogeological aspects of this hypothesis are less acceptable because the brines must somehow infiltrate sea floor sediments, enter the bedrock, and then migrate a considerable distance (because of the regressed shoreline) in order to be found at their present locations on the Fennoscandian Shield.

The hypothesis presented here, of formation of saline waters and brines by permafrost aggradation and salt-rejection, while relying on the freezing of seawater-like groundwaters in bedrock fractures, is more acceptable from a hydrogeological standpoint because the saline waters are formed in situ and need not migrate (except by the fact that they are physically displaced downwards by the advancing permafrost interface). This situation is particularly relevant to locations on the present Baltic Sea coastline, such as Olkiluoto and Äspö, where brackish and saline groundwaters now exist at depths below ~100 m. Paleogroundwaters at these locations will have experienced freezing during the onset of cooling conditions prior to glaciation and dissolved salts will have been rejected from the ice and displaced downwards and possibly laterally to form fluids of a saline or brine composition. Because the depth of permafrost penetration is likely to have been large (~300 m, /King-Clayton et al, 1995/), the quantity of saline fluids produced would also be quite large and so it could be expected that these fluids might be intersected by widely dispersed boreholes and be identified as a distinctive groundwater type. If temperatures are low enough, loss of SO_4 by mirabilite precipitation would be expected but, on warming and degradation of the permafrost, lower-salinity meltwaters would re-dissolve the mirabilite, giving rise to a SO_4-rich groundwater. This may be the origin of what is currently identified as the SO_4-rich Litorina Sea water at the Äspö and Olkiluoto sites. The lighter isotopic signature of these waters is consistent with a melt-water composition.

Using the models described above for permafrost formation and thickness, it should be possible to determine the extent of permafrost formation at the Olkiluoto and Äspö sites for specific climatic conditions at the surface. With suitable modification, these models could be used to assess the volume and concentration of saline groundwater formed as a result of downward advancement of permafrost in the crystalline bedrock. It may then be possible to determine whether the saline groundwaters at these sites have been formed or, at least, modified, by permafrost formation during glacial cycles. However, because of the sensitivity of permafrost depth to small changes in paleoclimatic conditions (e.g. surface temperature), the results of such calculations would be mainly governed by assumptions made regarding the prevailing paleoclimatic conditions.

8 References

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