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IMPLICATIONS OF SALT FINGERING PROCESSES FOR SALT MOVEMENT IN THAWED COARSE-GRAINED SUBSEA PERMAFROST

G.C. Baker and T.E. Osterkamp
Geophysical Institute, University of Alaska–Fairbanks, Fairbanks, Alaska 99775–0800

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ABSTRACT

Pore fluid velocities of vertical salt fingers, moving downward, in laboratory experiments with sands and thawed coarse-grained subsea permafrost sediments are on the order of 1 to 3 cm/hr with a maximum velocity of 5.6 cm/hr over distances of 0.1 to 0.4 m. It was demonstrated that fresh meltwater fingers move upward through a saline solution in thawed sand overlying a thawing phase boundary with frozen sand containing freshwater ice. Laboratory measurements of the hydraulic conductivity of thawed coarse-grained subsea permafrost sediments (silty sand) yield values about 10^3 *times larger than values obtained in previous field measurements. The results of these laboratory experiments show that gravity-driven convection, in the form of salt fingering, can produce rapid salt movement in sands and in thawed subsea permafrost sediments. Field observations of coarse-grained subsea permafrost, including the relatively uniform salinity profiles in the thawed layer, the small change in salinity across the phase boundary, the boundary layer thickness, and the topography of the phase boundary, argue in favor of the larger values for hydraulic conductivity and pore fluid velocities suggested by these experiments. If these laboratory results are indicative of in situ conditions in subsea permafrost, then new interpretations of field observations and of previous modeling studies of coarse-grained subsea permafrost are required.*

INTRODUCTION

Subsea permafrost is a product of past cold climates and sea level variations (Mackay, 1972). Permafrost forms in the continental shelves of the polar oceans during periods of low sea level. Submergence during periods of high sea level causes the permafrost to thaw slowly from the top and bottom at rates on the order of a few centimetres per year. As a result, a thawed layer or talik, which generally increases in thickness with distance offshore, is generated in the sediments near the seabed. This talik is permafrost, by definition, since its mean temperatures are negative except for a thin "active" layer at the seabed. Thawing of the talik occurs even though seabed temperatures are negative because of the infiltration of seawater salts into the sediments (Osterkamp and Harrison, 1977). The seawater salts decrease the phase equilibrium temperature at the bottom of the talik (phase boundary) where the soil solution is in contact with the underlying ice-bearing subsea permafrost. If the soil solution is sufficiently concentrated, then the phase boundary temperature will be less than the seabed temperature, heat will flow to the phase boundary and thawing will proceed.

An offshore drilling and sampling program conducted in 1975 in the area of the West Dock at Prudhoe Bay, Alaska showed that the soil solution profiles of electrical conductivity through the talik of this coarse-grained subsea permafrost were nearly constant with depth and that the temperature profiles were nearly linear but with significant gradients (Osterkamp and Harrison, 1977). Subsequent work has confirmed these results (e.g., Lachenbruch and Marshall, 1977; Page and Iskandar, 1978). These results have been interpreted to mean that the movement of the salty pore water was by convection while the heat flow was primarily by

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conduction (Harrison and Osterkamp, 1978). That is, the velocity of the soil solution was thought to be sufficiently "fast" to erase salt concentration gradients but slow enough that heat flow would still be primarily conductive. Soil solution velocities on the border of a few tenths to a metre per year seemed to be consistent with observations and this interpretation (Harrison and Osterkamp, 1978).

Salt movement in the thawed coarse-grained subsea permafrost near Prudhoe Bay, Alaska was thought to be a result of this density-driven convection on a scale of metres to tens of metres. Several possibilities exist for creating settings with concentrated brine over a less concentrated or lower density brine to drive this convection (Osterkamp, 1975). For example, where sea ice freezes into the sediments annually, brine rejected from the pore ice in the sediments during freezing and subsequent brine drainage in the partially frozen zone can increase the salt concentration in the underlying sediments. Where sea ice does not freeze to the seabed, but where circulation is restricted under the ice, salt rejection and brine drainage from the sea ice can create a cold, concentrated brine layer at the seabed which can infiltrate and cause partial freezing in the sediments near the seabed. In some nearshore areas, freshwater run-off from rivers and streams can cause local seawater salinities to be lower during the summer months which leads to lower salinities in the sediments near the seabed. After freeze-up, the water salinity is higher and the water temperature lower (at or near the phase equilibrium temperature) which causes the fresher sediments near the seabed to freeze and increases the salt concentration of the underlying sediments by brine rejection and drainage. The above processes occur in proximity to the seabed. At the phase boundary, thawing of the ice would release fresh, buoyant water which would be expected to mix with the overlying saline pore water (Harrison and Osterkamp, 1978). However, recent theoretical work involving modeling results and energy considerations suggests that this convection produced by thawing at the phase boundary may not be a viable mechanism for salt transport through the full thickness of the talik (Swift et al., 1983; Swift and Harrison, 1984).

Salt fingering on a small scale, as described by Saffman and Taylor (1958), is a gravity-driven salt transport process that has not been explored as a mechanism for salt movement in thawed coarse-grained subsea permafrost. This paper reports the results of laboratory measurements on salt fingering and on the hydraulic conductivity of sand and thawed subsea permafrost samples consisting of silty sand, and explores their implications for salt movement in thawed coarse-grained subsea permafrost.

EXPERIMENTAL DETAILS

Salt fingering experiments

The experiments on salt fingering were conducted in boxes and columns. For the experiments reported here, a plexiglass box was used which was 17 cm wide, 28 cm high, and 5 cm in thickness (inside dimensions). A plexiglass column (6.4 cm I.D., 7.0 cm O.D., and 56 cm in length) was also used; it was constructed from 14 segments, each 4 cm in length, fitted with collars for alignment and clamped together with 3 long threaded rods.

A silica sand with a 250 to 600 micron size range was used in the experiments. It would have been preferable to use samples of subsea permafrost sediments, but preliminary experiments showed that the dye used to define the fingers was not easily visible in the darker sediments of these samples.

The results of two experiments with the box will be presented. In the first test, the box was filled to the 0.1 m level with sand, saturated with 35 ppt (parts per thousand) sodium chloride solution colored with Indigo Rhodamine dye, and packed by mechanically vibrating the box. Dry sand was used to fill the remaining space in the box which was then saturated with distilled water. The box was sealed and allowed to equilibrate overnight. This procedure produced a relatively flat and well-defined interface between the distilled water and the saline soil solution. To start the experiment, the box was rotated 180° to place the saline soil solution over the distilled water. The development and movement of the salt fingers were recorded by measurements with a ruler, watch, and photographs. In the second test, the box was filled to the 0.1 m level with sand, saturated with distilled water containing dye, and then placed in a freezer overnight. The next day, the bottom 4 cm of the box was submerged in a controlled temperature bath at −2.0°C with the top of the box exposed to room temperature. Dry sand was poured into the box, saturated with a 35 ppt sodium chloride solution, and the fingers of fresh meltwater rising from the thawing ice in the frozen sand were measured as described above.

The segmented column was filled to the 0.15 m level with sand which was saturated with a dyed solution containing 35 ppt sodium chloride. The column was then filled to the top with dry sand, saturated with distilled water, sealed, and suspended in a refrigerator for 12 hours at +1°C. At the start of the test, the column was rotated to place the saline solution over the distilled water. Details of the salt fingering were recorded as described above. When the salt fingers extended the full length of the column, the test was stopped and the column broken into segments. Individual segments were analyzed for salinity by measuring the electrical conductivity of the soil solution and using an algorithm to convert to salinity (Baker, 1987a, b).

Hydraulic conductivity

The hydraulic conductivity, K, of the sand used in the above experiments and of reconstituted thawed coarse-grained subsea permafrost samples, obtained from a field site near the ARCO West Dock, Prudhoe Bay, Alaska, were measured using a constant head permeameter. Silt content was varied by extracting the silt fraction by sieving and then reconstituting the samples with known amounts of silt. Additional details of the above experiments are provided by Baker (1987a).

RESULTS

Table 1 shows the results of the hydraulic conductivity measurements on the reconstituted thawed coarse-grained subsea permafrost sediments. For comparison, the sand used in the salt fingering experiments had $K \sim 3.2 \times 10^4$ m/y. Table 1 shows that the addition of silt to the subsea permafrost samples produced a substantial decrease in the values for K. An analysis of the top 2 m of seabed sediments showed that the natural silt content was about 3%.

TABLE 1

Hydraulic conductivity measurements

Silt content (% by weight)	Hydraulic conductivity (m/y)
0	6.3×10^3
3	3.2×10^3
10	3.2×10^2
15	2.2×10^2

Figure 1 is a photograph of salt fingers, taken 3 hours and 56 minutes after the start of the test, in sand with a 35 ppt dyed soil solution over distilled water at room temperature. Figure 2 is a graph of the mean finger amplitude (length), A, versus a parameter, $V_c t$, which is the product of a characteristic velocity, V_c, as defined by Wooding (1969), and time, t. For the experiment with a 35 ppt dyed soil solution over distilled water, A increased initially with $t^{2.94}$ until $A \sim 3.4$ cm and then increased as $t^{0.98}$ to $A \sim 15$ cm at the end of the test. For the experiment with saline solution over a thawing fresh ice phase boundary (Figs. 2 and 3), A increased initially with $t^{1.76}$ until $A \sim 3.4$ cm and then increased as $t^{0.36}$ to the end of the test. While the results for these two experiments are similar for $A < 3.4$ cm, they are quite different for $A > 3.4$ cm. It is thought that the fingering behavior for $A > 3.4$ cm, for the second experiment, was influenced by the rate at which the ice thawed since this would limit the availability of fresh water. The vertical velocities of the tips of the fingers ranged from 0.24 to 5.6 cm/hr for both experiments. Average velocities were 2.8 cm/hr for $A < 3.4$ cm and 1.4 cm/hr for $A > 3.4$ cm. In general, the results are similar to those obtained by Wooding (1969) in a Hele-Shaw cell with potassium permanganate solutions.

Figure 4 shows the mean finger wavelength (width) versus time for the two experiments. The slope of the curves (0.99 and 0.95) are nearly identical suggesting that, while the amplitude of the fingers may have been limited by the availability of thawed water, the wavelength was not.

Figure 5 shows the salinity profiles for the experiment with the segmented column at the beginning

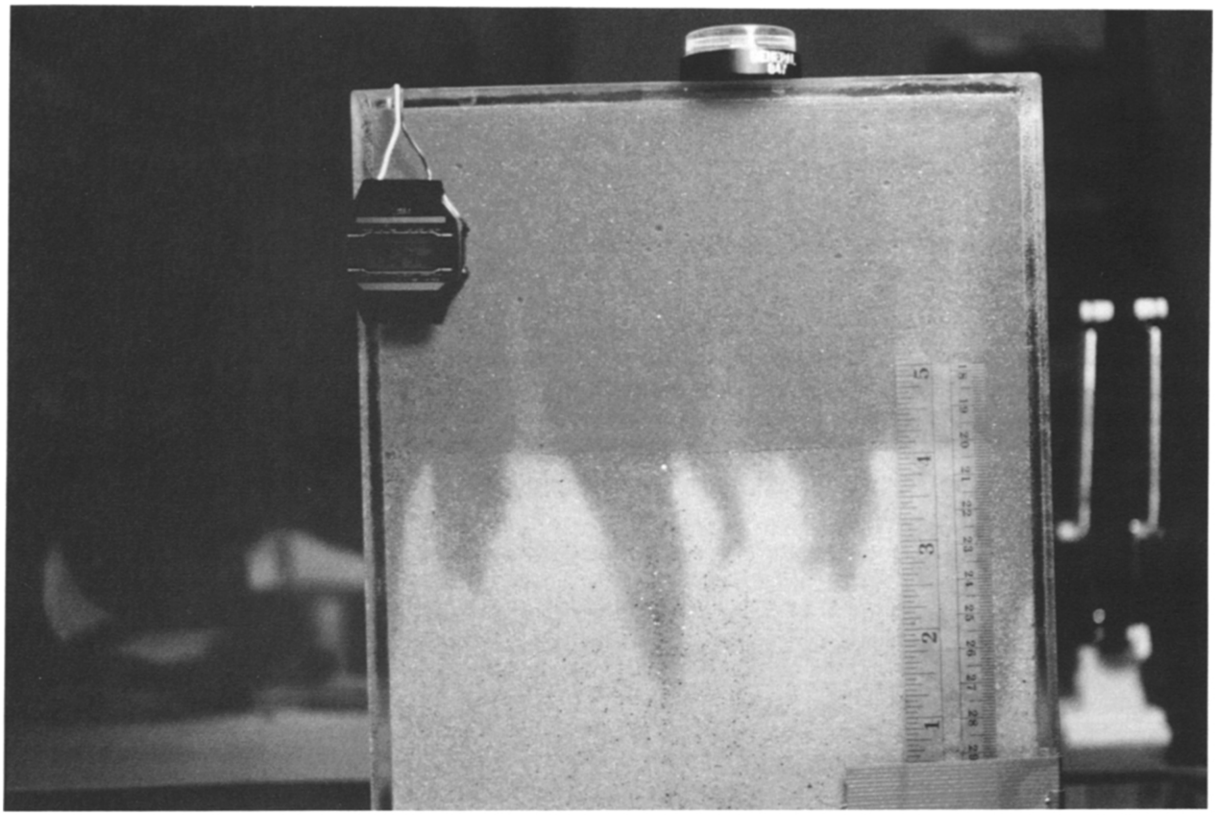

Fig. 1. Photograph of salt fingers taken 3 hours and 56 minutes after the start of an experiment using a dyed soil solution of 35 parts per thousand salinity over distilled water in sand at room temperature.

and end of the test. With a dyed solution of 35 ppt salinity over distilled water, a density-stable salinity profile was produced in about one day. The average velocity for the salt movement was about 2 cm/hr and was maintained over a distance of 0.4 m, about three times that of the box experiments. A subsequent experiment with a continuous (not segmented) column filled with thawed subsea permafrost sediments (no silt) and with a dyed solution of 35 ppt salinity overlying distilled water gave an average velocity of about 1 cm/hr which is reduced from that in clean sand but still large.

The results of these laboratory experiments show that gravity-driven convection, in the form of salt fingering, can produce rapid salt movement in sands and in thawed coarse-grained subsea permafrost sediments whenever sufficient salinity (density) gradients exist. This movement was observed to occur over vertical distances of 0.1 to 0.4 m with average vertical velocities on the order of a cm/hr.

IMPLICATIONS FOR SALT MOVEMENT IN THAWED COARSE-GRAINED SUBSEA PERMAFROST

Previous measurements of the hydraulic conductivity of the thawed subsea permafrost sediments near the ARCO West Dock, Prudhoe Bay, Alaska are open to question. Osterkamp and Harrison (1976) reported laboratory measurements on a drive sample from the 6.7 m depth at a site 3.37 km offshore. The sediments were relatively fine-grained (20% sand, 22% gravel, 49% silt with < 10% clay) and two measurements yielded an average value of 13 m/y. This value is thought to have been affected

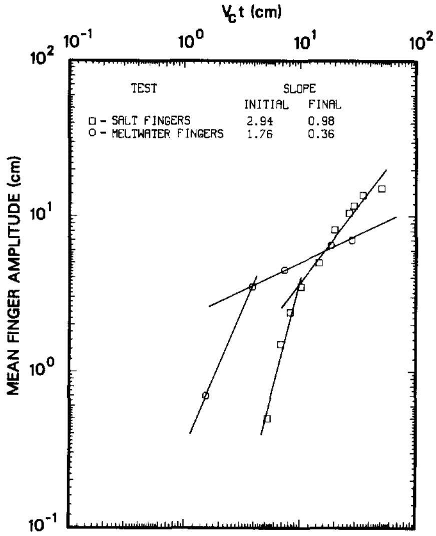

Fig. 2. Mean finger amplitude (length), A, versus a parameter, $V_c t$, which is the product of a characteristic velocity, V_c, as defined by Wooding (1969), and time, t, for the experiments performed in a box.

by compression of the sample while driving the sampling tube into the sediments and is probably lower than the true value. Harrison and Osterkamp (1982) reported values obtained in field measurements to be about 1 to 10 m/y. However, these values have been questioned previously by Swift et al. (1983). A problem with the method of the field measurements is that a shielded probe containing a filter must be driven through a few metres of fine-grained marine sediments to reach the underlying sands and gravels which are thought to be relatively clean. As a result, plugs of fine-grained sediments were often observed to be packed into the holes in the shield through which the pore water was admitted to the filter. These plugs would impede the flow of pore water to the filter, thus affecting the hydraulic conductivity measurement to an unknown degree. In addition, the filters were sometimes observed to be partially clogged with very fine sediment particles after an experiment and the head used was too large, resulting in turbulent flow. Matava (1986) has estimated the hydraulic conductivity of the subsea permafrost sediments in the talik from calculations on the decay of excess pressures generated during driving of a probe to be about 1 to 20 m/y. However, because a similar probe was used, these estimated values may also be too low.

The hydraulic conductivity values reported above for the laboratory measurements are much larger than those obtained in the field measurements. However, these laboratory values are in better agreement with the range of values reported for sands and gravels while the field measurements are more typical of silt (e.g., Bear, 1972). For computational purposes involving thawed coarse-grained subsea permafrost, a value of $K \sim 3$ to 6×10^3 m/y is indicated, which is about 10^3 times greater than the values obtained from field measurements and used in previous calculations (Harrison and Osterrkamp, 1978, 1982; Swift et al., 1983; Swift and Harrison, 1984).

This is a key point and, assuming these higher values of hydraulic conductivity are characteristic of in situ conditions for thawed coarse-grained subsea permafrost, indicates that modifications in current theories of salt movement in this subsea permafrost are required. Such a conclusion is already supported by the modeling studies. For example, the modeling results of Swift and Harrison (1984) were obtained using a typical value for $K \sim 4$ m/y (consistent with field measurements) and what was thought to be an atypical value of $K \sim 40$ m/y for comparison. The results obtained with the larger value for K, which were rejected, were more consistent with field observations. It is suggested herein that even larger values for K are more appropriate for use in modeling studies of coarse-grained subsea permafrost.

The salt fingering experiments reported above showed that the velocity of salt movement in sand and thawed coarse-grained subsea permafrost sediments, for the noted experimental conditions, was on the order of a cm/hr or about 10^2 m/y. Pore fluid velocities in subsea permafrost have never been measured, but they have been inferred to be on the order of a few tenths to a metre per year (Harrison and Osterkamp, 1982). If the larger velocities for salt movement in thawed coarse-grained subsea permafrost are appropriate, then it is possible to interpret some of the field observations that have been previously difficult to understand. For example, the change in salinity across the phase boundary and the thickness of any boundary layer there have been

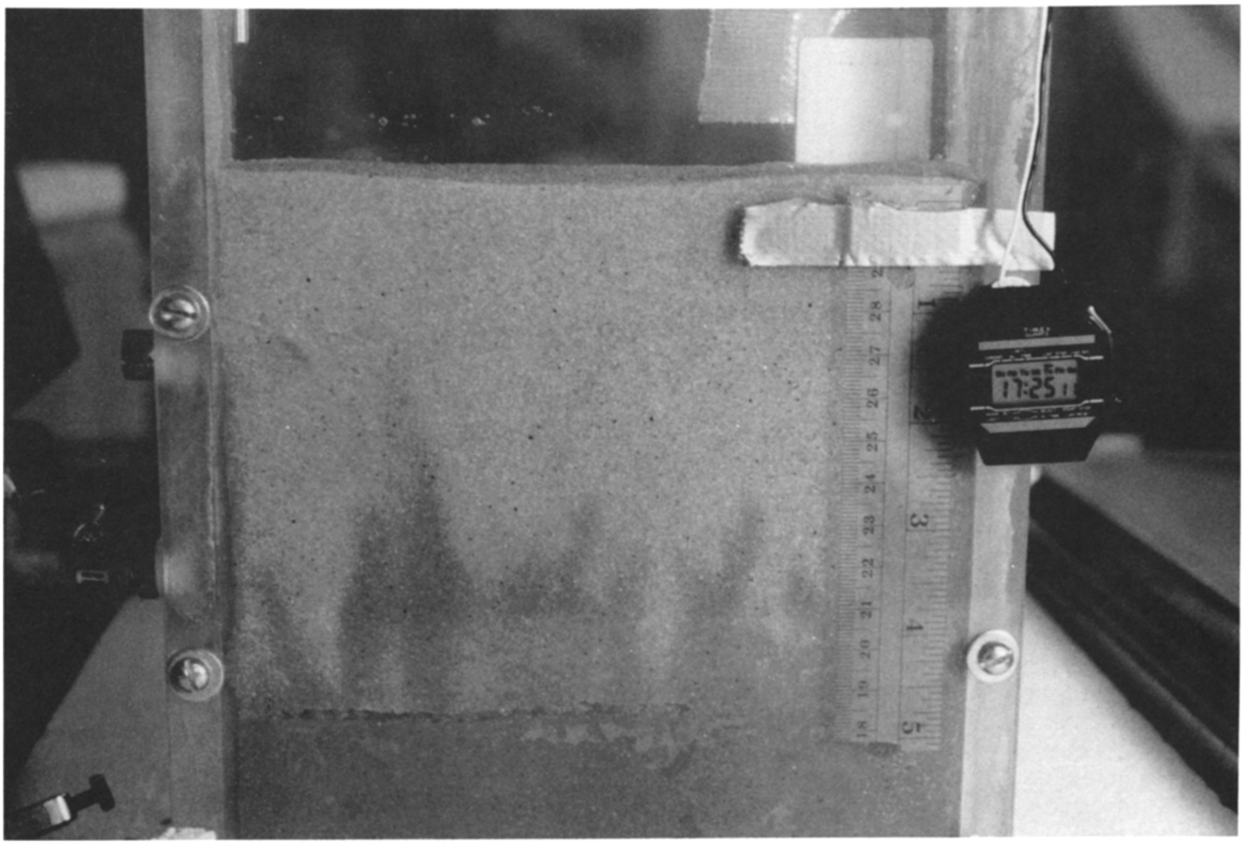

Fig. 3. Photograph of fresh meltwater fingers, taken 2 hours and 15 minutes after the start of the experiment, rising from a thawing phase boundary between thawed saline (35 ppt) sand over frozen sand with dyed freshwater ice.

shown to be small (Harrison and Osterkamp, 1982) which is difficult to understand if pore fluid velocities are low. However, these results are expected when pore fluid velocities are high. Another example involves the phase boundary topography. Swift and Harrison (1984) have proposed that stable ice-bonded ridges should form on the phase boundary beneath upward moving plumes while the regions below downward moving plumes (which carry salt to the phase boundary) should be depressed (i.e., thawed). The scale of these ridges and depressed regions should be the same as that of the plumes (several metres) but this type of phase boundary topography has never been observed. However, if salt fingering is the process by which salt moves, then the scale of the fingers (on the order of centimetres) would be appropriate for variations in phase boundary topography. Such small variations could not have been detected in the probing experiments of Osterkamp and Harrison (1982). A fourth example involves the observed uniform salinities in the thawed layer. This requires that the pore fluid velocities be relatively large in comparison to the phase boundary velocity (on the order of 1 to 20 cm/y), which argues in favor of the larger values of hydraulic conductivity and pore fluid velocities reported here. The observed nearly constant phase boundary temperature of about −2.4°C (Osterkamp and Harrison, 1982) near the ARCO West Dock, Prudhoe Bay, Alaska, beyond about 400 to 450 m offshore, follows directly from the combination of nearly uniform salinities and relatively constant lateral coarse-grained sediment conditions which have little or no effect on the freezing-point-depression at the phase boundary.

A final point, the linearity of the temperature

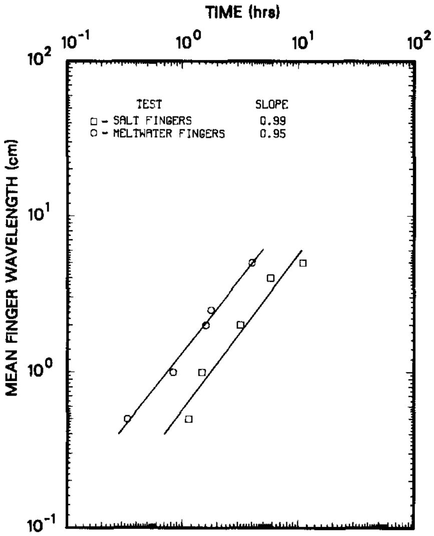

Fig. 4. Mean finger wavelength (width) versus time, *t*, for the experiments performed in a box.

profiles, needs clarification. It has been pointed out that pore fluid motion exceeding a few tenths of a metre per year should be identifiable by curvature in the temperature profiles (Osterkamp and Harrison, 1982; Osterkamp and Gosink, 1984). However, the temperature profiles in subsea permafrost are relatively linear, indicating little or no pore fluid motion, in seeming contradiction to the high pore fluid velocities suggested by the laboratory experiments. This contradiction can be explained by noting that beyond about 0.5 km offshore, where most of the temperature profiles in subsea permafrost have been obtained, the data of Baker (1987a) suggests that very little salt infiltrates the seabed during the annual freezing cycle. As a result, very little pore fluid motion can be expected in the thawed subsea permafrost sediments beyond about 0.5 km offshore. Therefore, the temperature profiles remain linear, or nearly so, salinity profiles remain relatively uniform, and the phase boundary temperature remains nearly constant.

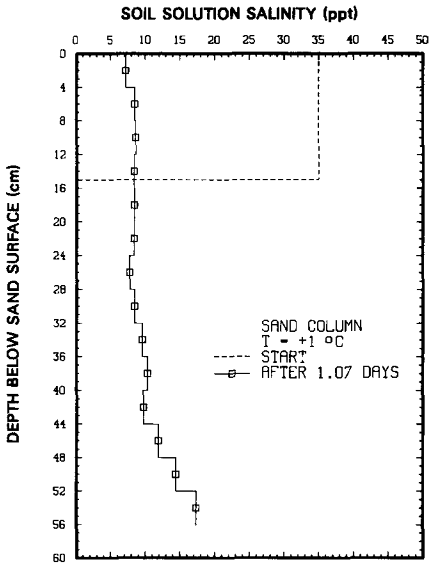

Fig. 5. Soil solution salinity profiles in a column showing the salinity at the beginning of an experiment (dashed line) and after 1.07 days (solid line and data points) using a dyed soil solution of 35 ppt salinity over distilled water in sand at room temperature.

The above laboratory measurements of hydraulic conductivity, pore fluid velocities and salt and fresh meltwater fingers are difficult to apply directly to field studies of subsea permafrost. In situ conditions, including sediment type, pore fluid salinity, temperature, water content, ice content, freezing and thawing of the sediments, and suchlike, can be highly variable on local scales. Nonetheless, the high pore fluid velocities suggested by these laboratory experiments offer satisfactory explanations for a number of field observations that have been difficult to understand using low pore fluid velocities. If the above laboratory results are indicative of in situ conditions in thawed coarse-grained subsea permafrost, they indicate that new interpretations of field observations and modeling studies are required at this time.

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