THE GROUNDWATER HYDRAULICS OF OPEN SYSTEM PINGOS

Kenji Yoshikawa

Water and Environmental Research Center, Institute of Northern Engineering, University of Alaska, Fairbanks
PO Box 755860 Fairbanks, AK 99775-5860
e-mail: kenji @ polarnet.com

Abstract

The characteristics of spring water from open-system pingos in interior Alaska and Svalbard were examined to elucidate the relationship between groundwater and open system pingos. Water from springs under pingos creates a variety of icing blister formations in the winter. It was concluded that pingo formation pressure varied from pingo to pingo, with artesian pressures sometimes less than 20 kPa. The pressure from ice crystallization is one of the important factors for pingo growth when artesian pressure was low. Springs warmer than 3°C or with discharge rates greater than 3 liters per second did not have pingos associated with them. Experimental evidence indicates that in order for pingo growth to occur, heat transferred to the pingo through groundwater discharge must be less than 37 kW.

Introduction

There are two general types of pingos: open-system and closed-system pingos. An open system pingo is "open" to groundwater (the source of water is not immediately adjacent to the pingo, but moves to the pingo through a regional groundwater aquifer), whereas a closed system pingo is "closed" with respect to groundwater (the souce of water is limited to supply adjacent to the pingo)(Müller, 1959). Mackay (1979) described the Tuktoyaktuk Peninsula area as "closed." However, the terms open and closed are ambiguous when applied to the Tuktoyaktuk Peninsula pingos, and probably to those of many other areas. If water comes from a distant elevated source then the pingo is a hydraulic system pingo. If water moves under hydrostatic pressure from local permafrost aggradation, then the pingo is a hydrostatic system pingo. Therefore, the terms "hydraulic" and "hydrostatic" are probably more accurate than "open" or "closed." However, "open system" and "closed system" are commonly used terms, and thus, this paper uses them too.

Müller (1959) attempted to calculate the total updoming pressure and explain an open-system pingo developed by groundwater supply. It is generally accepted that pingos need between 600 and 2200 kPa of pressure to develop in East Greenland. However, Müller calculated the approximate heaving pressure of Trout Lake pingo in East Greenland to be 500 -600 kPa. Müller's (1959) work serves as a basis of theory for the formation of open-system pingos.

Berezantsev (1947) measured the maximum tensile strength of overlying permafrost to be 250 - 1800 kPa. Pingo development was affected by gravity and the strength of the overlying material. The ice crystallization pressure was 4000 kPa at an ice temperature of -0.3°C. However, growth mechanisms are still poorly understood. Spring discharge is sometimes associated with the occurrence of open-system pingos. Thus one approach that has been utilized in some previous studies of open-system pingos is the analysis of spring geochemistry to characterize ground water origin (e.g. O'Brien, 1971). However, the physical characteristics of open-system pingos with springs require further investigation.

In the winter, groundwater discharge increases hydraulic potential in the active layer as the soils freeze-back. Icing blisters are seasonal frost feature, which develop in response to natural discharge of ground water throughout the winter. Pollard and French (1984) measured pressure potentials in a number of icing blisters in North Fork Pass, Yukon Territory Canada. The pressures varied between 30 and 81 kPa. In East Greenland, Washburn (1969) reported a continuous discharge of sub-permafrost water at 170 kPa.

The purpose of this paper is to clarify the mechanism of open system pingo formation by considering water pressure, water source and icing blisters associated with adjacent springs.

Study Area

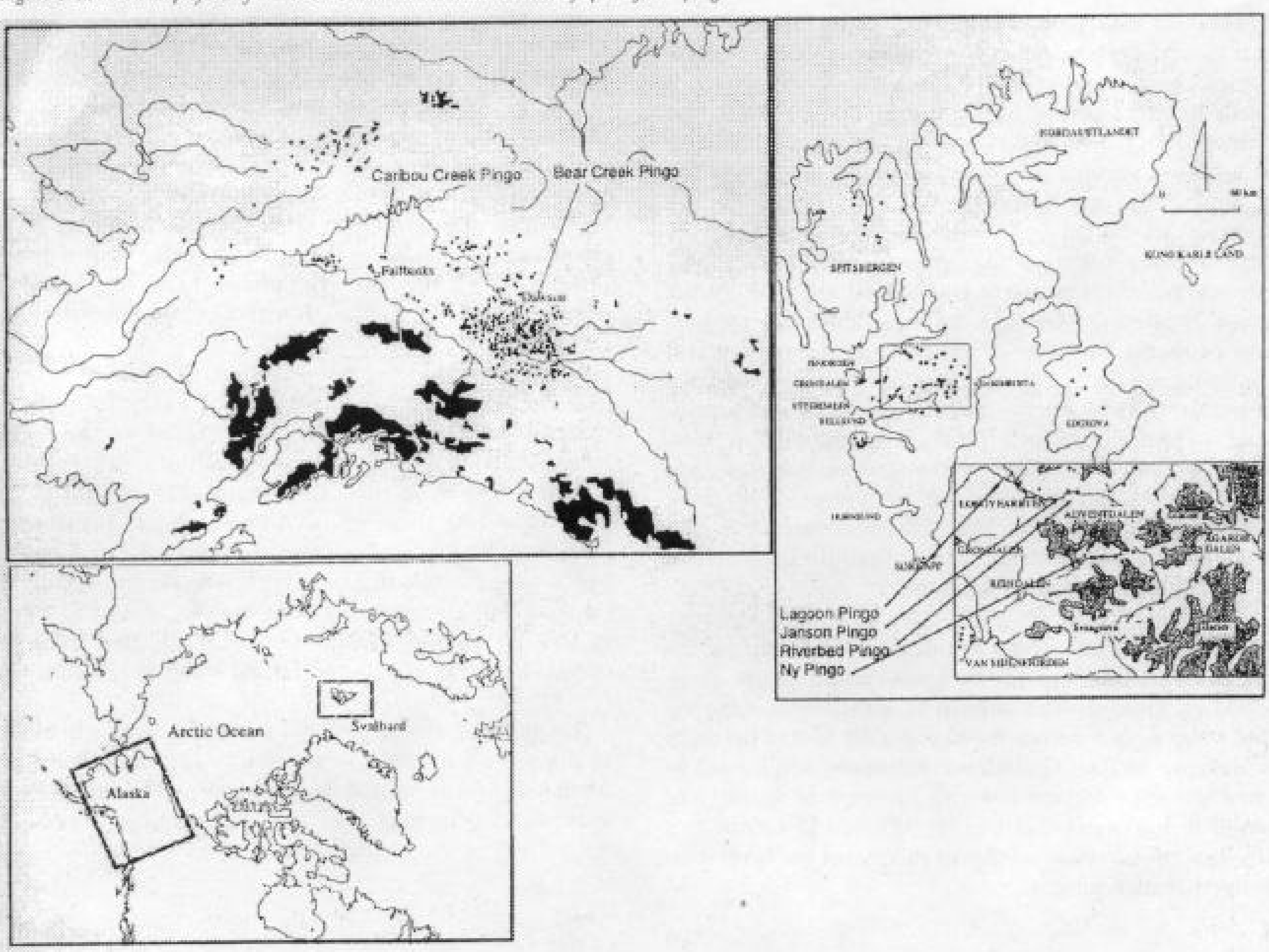
Four pingos were examined in Adventdalen and Reindalen in Svalbard (Figure 1). Field observations at Svalbard were carried out during the summer and winter from 1988 to 1994. The Adventdalen area has continuous permafrost. The snow depth around the pingo was 50-100 cm in April 1993. Mean annual ground temperature was -5.2°C (1993-1994). In the Adventdalen delta area, the permafrost thickness ranged between 3 and 100 m.

Ny pingo is located out of Kokbreen (local glacier) at Reindalen. This pingo is rounded, approximately 750 m in diameter with no crater. The pingo consists of a single dome 50 m long (east-west) with a big dilation crack across the top. Tritium analysis of ice and spring water shows that the water is of recent origin. The upper part of the ice (5 cm depth), however, was 0.5 ±0.7 TU implying this ice formed earliest. The lower part of the ice (110 cm depth) was 9.5 ±1.3 TU; this value is very close to the spring water value of 8.2±1.1 TU (Figure 2). Therefore, the bottom of the ice was formed recently by spring water.

Riverbed, Janson, and Lagoon Pingos are located at Adventdalen. Small springs are observed near these pingos. During the winter, icing blisters are developed at these spring sites. Ground water temperature is considered critical for pingo formation. The measured bubble pressure in the pingo ice was 48 - 52 kPa in Riverbed Pingo implying very low upheaving pressure of pingo grouth.

Two pingos were also examined at Caribou Creek, Interior Alaska, and near Bear Creek, Dawson, Yukon Territory (Figure 1). Field observations were carried out on these pingos between 1994 -1996 in winter and summer. Bear Creek Pingo is situated 12 km upstream of Dawson, on the Klondike River. The pingo is quite large in diameter (approximately 500 m wide) and 14 m high. The pingo is vegetated with black spruce. Caribou Creek is located in the Yukon - Tanana Uplands of central Alaska, 48 km north of Fairbanks. Mean annual air temperature is -4.9 °C (Haugen et al., 1982) with a freezing index of 3278°C-days, and a thawing index of 1814°C-days (Slaughter and Hartzmann, 1992). In Caribou - Poker Creeks, permafrost is generally found on north-facing slopes and in valley bottoms beneath

Figure 1. Location map of study areas. Dots indication known location of open system pingos.



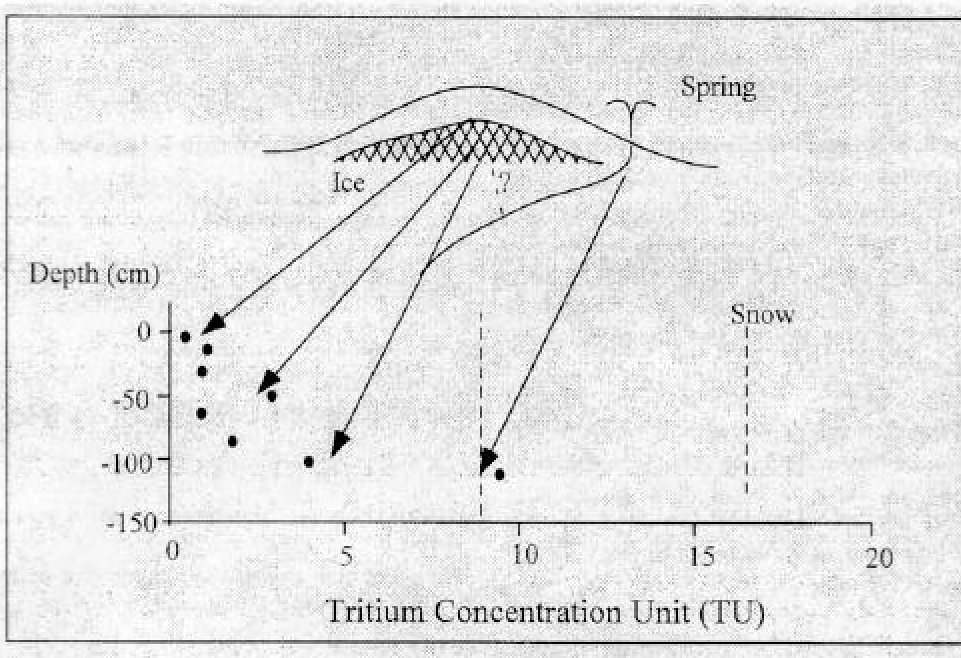


Figure 2. Tritium analyses of ice-core from Ny Pingo.

black spruce. South-facing slopes are generally free of permafrost. Permafrost is thin or absent around hill tops. In April, 1995, drilling was carried out on the pingo. The pond ice thickness at the top of the pingo was 60 cm; below the ice was water to a depth of 51 cm and then continuous loess and sand with weathered schist down to 5.33 m. The pingo ice started at 5.38 m below the pond water level. Temperatures at the bottom of the pond never dropped below 0°C. A spring was observed at the edge of the pond.

On November 8, 1995, an icing blister was formed at the spring. The mound was 1.7 m in diameter, and 60 cm high, formed by overflow ice. Spring water was still running under the ice to the pond. On January 14, 1996 the icing mound had grown to 3.8 m in height, and 5 m in diameter. Continuous overflow contributed to icing development in February 1996, although the height of the icing mound remained the same. The volume of the spring water fluctuated cyclically during the snow meltwater season. Annual variations of the oxygen isotope values are confirmed in the Caribou Creek Pingo (Figure 3).

Methodology

Ground and water temperatures at pingos and nearby springs were measured by thermistors and in some cases recorded on a data logger. Pressure transducers were installed under the icing blisters. Electrical resistivity profiles of pingos were collected using a electrical

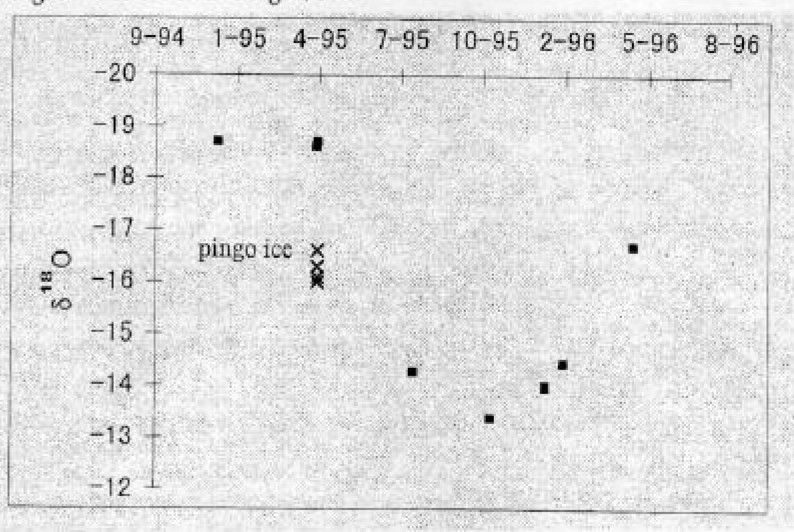


Figure 3. Annual $\delta^{18}O$ variation from the Caribou Creek Pingo.

resistivity meter (OYO McOHM) in a Wenner electrode configuration (Harada and Yoshikawa, 1996). A 48 mm single core sampler was used for drilling.

Water samples were taken from pingo ponds and springs and were transported to Japan and analyzed in the laboratory. ^{18}O analyses were carried out by the National Institute of Polar Research in Tokyo. Tritium(3H) analyses were carried out by Dr. H. Satake (Toyamo University). Chemical analyses were performed by the Institute of Low Temperature Science, Hokkaido University.

The air bubble pressure in ice samples taken from the Riverbed Pingo were measured. After two ice samples were collected (about 150 g each), they were cut into cubic shapes by a band saw in the laboratory. Calculations were then made to determine the volume of air in the samples.

Initially, the density of dry air was calculated:

$$\rho_a = \frac{1.293 \bullet 10^{-3}}{1 + 0.00367T_a} \frac{P_a}{1013.25} \qquad [1]$$

where ρ_a is the density of dry air in g/cm^3, T_a is air temperature in °C, and P_a is atmospheric pressure in hPa (Nakawo,1980).

Then the ice samples were weighed in air (W_a) and in ice saturated kerosene (W_l). The densities of ice samples (ρ_i) were then calculated by using the following formula:

$$\rho_i = \frac{\rho_l W_a - \rho_a W_l}{W_a - W_l} \qquad [2]$$

Where ρ_l is the density of kerosene. The final calculation for the volume of air bubbles (V_b) was determined by the formula below:

$$V_b = W_a\left(\frac{1}{\rho_i} - \frac{1}{\rho_{ice}}\right) \qquad [3]$$

Where ρ_{ice} is the ice density. After the calculations were made, the true volume for the air bubbles (V_a) was measured by melting the ice samples in air-saturated kerosene under a closed burette. The volume of air trapped above the melted solution was then measured.

Air bubble pressure (P) was determined by the ratio of the volumes:

$$P = \frac{V_a}{V_b} \qquad [4]$$

Results

Water Temperature and Discharge Pattern

Figure 4 shows water temperature and rate of outflow for springs with and without pingos. Water temperature and flow rate are important for ice formation in the permafrost layer. At the pingos investigated, the minimum permafrost thickness was 10.8 m. It appears that this is thick enough to allow the temperature of water migrating through the permafrost under artesian pressure to drop to near freezing. During ice crystallization,

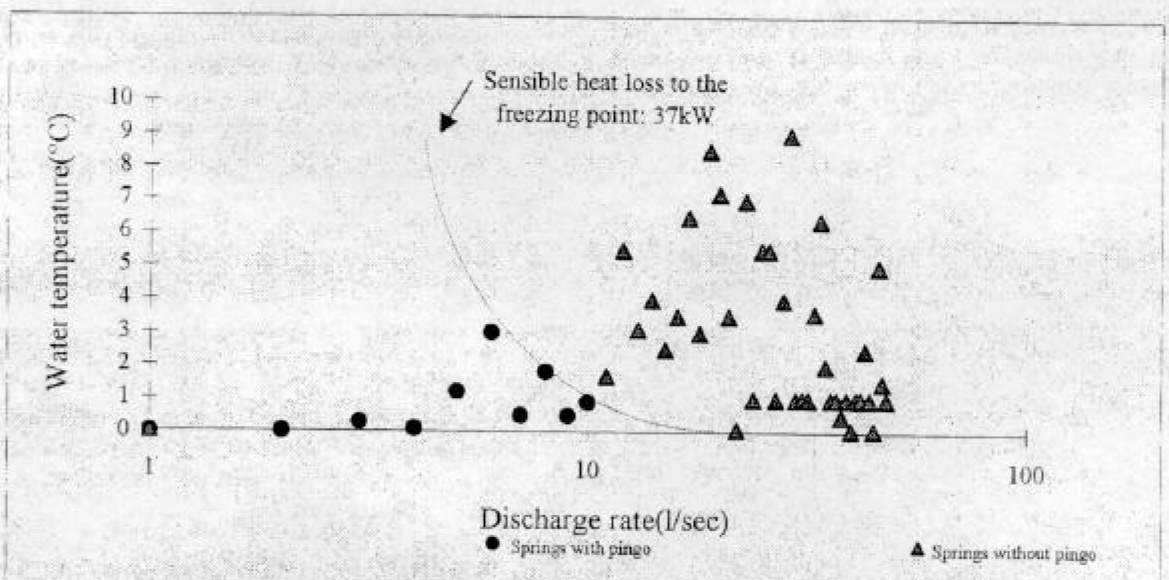


Figure 4. The spring water temperature versus rate of discharge, for springs with and without pingos. Data from springs associated with pingos located in the Alaskan, Canadian and Svalbard study areas (dot symbol) and from springs not associated with pingos, broadly distributed across permafrost regions of Alaska and Svalbard (triangle symbol).

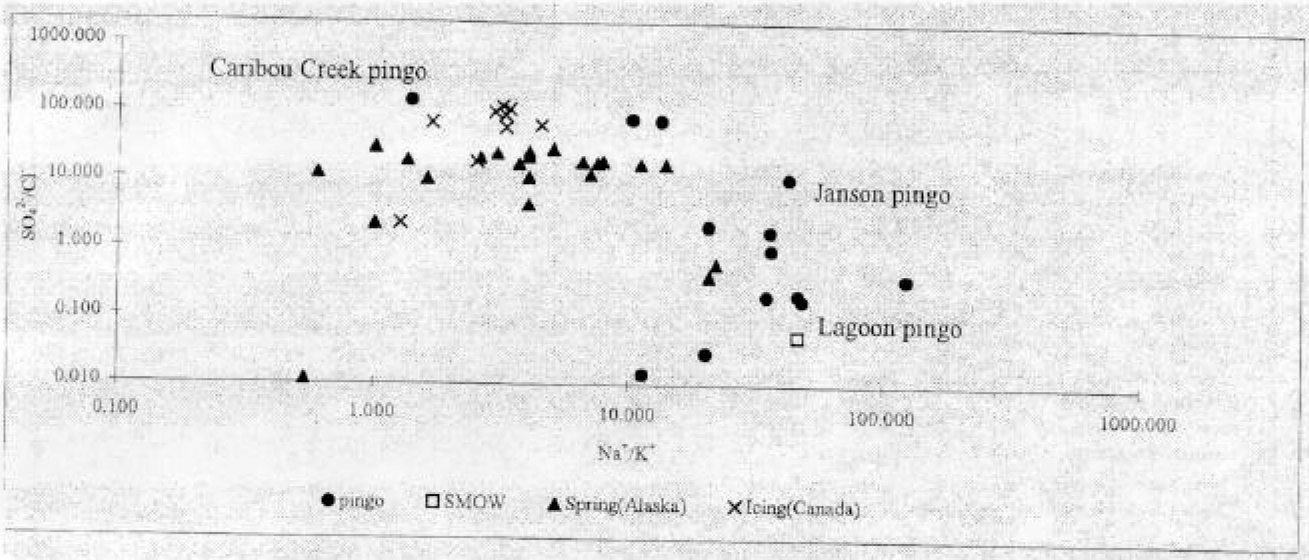


Figure 5. Ion ratios (SO_4^{2-}/Cl^- versus Na^+/K^+) at Caribou Creek, Janson and Lagoon Pingos.

about 330 J of heat are liberated per gram of newly formed ice (latent heat of freezing). Artesian water must be cooled by the permafrost to near freezing. Cooling depends on the inner surface area of the aquifer in the permafrost and on the geothermal gradient in the permafrost. As the water flows through the aquifer, heat is lost by conduction, and the water cools. The rate of discharge also affects cooling. The smaller the discharge rate, the more easily the water is cooled. There are a number of high discharge springs (>3 l sec^{-1}) in Spitsbergen without pingos. High discharge or springs with warm temperature (> 3°C) were not associated with pingos in Spitsbergen or Alaska.

The equation for the rate of sensible heat loss and latent heat loss to the freezing point is:

$$q = C_p \bullet Q\,(t - t_o) + L_f Q \qquad [5]$$

q = total heat loss rate (W)
C_p = specific heat of water (4.186 J/g °C)
L_f = latent heat of freezing (334 J/g)
Q = spring discharge rate (g/s)
t = water temperature (°C)
t_o = freezing temperature of water (°C)

If the water flowing from a spring has greater than 37 kW sensible heat, a pingo will not form in the areas

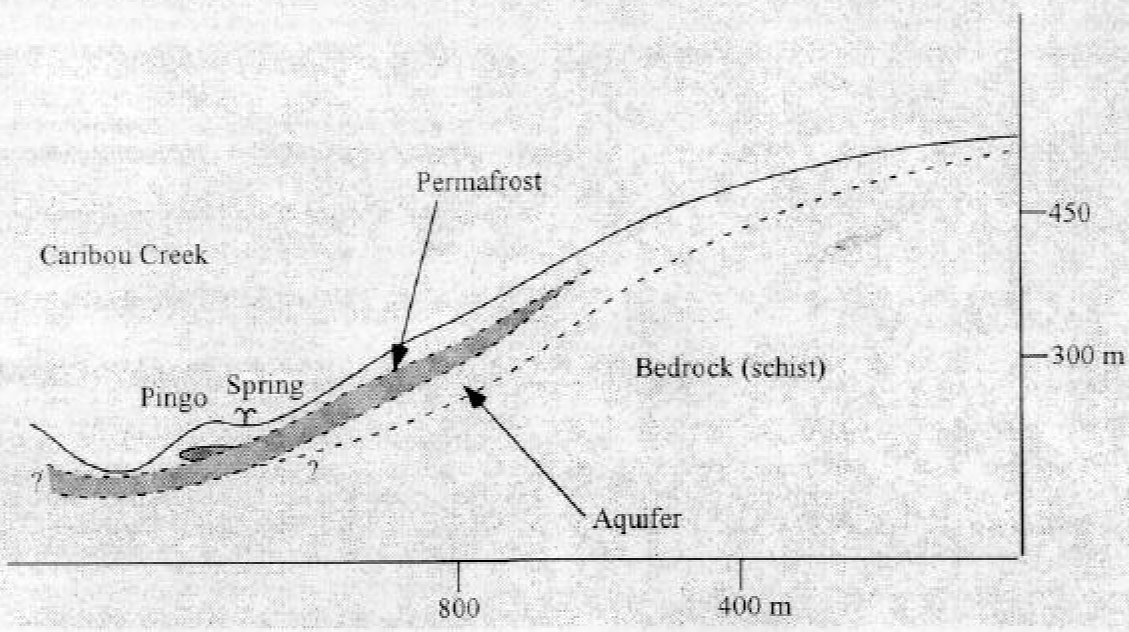


Figure 6. Topographic diagram of the Caribou Creek Pingo.

Table 1. List of the study pingos

pingo	*Ny*	*Riverbed*	*Janson*	*Lagoon*	*Bear Creek*	*Caribou Creek*
dimension (or diameter)(m)	750	200×140	410×200	500×140	500	60
height(m)	36	11.9	28	4.5	14	8.4
overburden material	gravel and pebble (alluvial and moraine sediments)	sandy pebble (river sediment), Cretaceous	Cretaceous shale	clay, silt (delta sediment)	gravel, silt	silt, gravel
morphology	single mound (no crater)	single mound (no crater)	crater ϕ20m	several generation (craters ϕ 16m,5m)	black spruce, Crater30×45m	black spruce, Crater ϕ15m
permafrost thickness(m)	?	15.8	?	22.8	20?	8
location	out of local glacier	riverbed	toe of alluvial fan	delta	north facing slope	north facing slope
elevation(m a.s.l.)	75	80	55	<2	450	240
water discharge (l/sec)	<2-3	>0.016	0.06-0.5	0.013-0.016	0.75	0.5-2
water temp.(°C)	0.5-1.2(Summer)	n/a	-0.3	-1.1	0.9-0.6	0.0-1.8
icing dimension(m)	600×500	10	15	5	500×200	5
icing height(m)	>2	2.5	5	0.5	<2	3.8
pressure(KPa)		0.46-0.55 (pingo ice bubble)		20-22		
$\delta^{18}O$(‰)		pingo ice -10.5±0.5		pond -13.0 spring -14.1	pond -18.9 spring-22.1—15.9	ice -16± spring -12-19 ±
Tritium conc.(TU)	*fig.2. ice 0.5±0.7 spring 9.5±1.3	<5				
pH		ice 6.98	spring 8.87 ice 7.61	spring 9.08		spring 7.83
Salinity(g/l)		<1	3.9	7.8(1993) 4.2 (1972)	spring 0.577 pond 0.089	

studied. The upper limit of the total heat (sensible + latent heat) content in water in the observed springs associated with pingos, was calculated to be 1,040 kW (Figure 4). No pingos were observed in springs which would have required a greater total heat loss than this.

The spring water temperature is close to freezing all year round, but there is seasonal variation due to variations in active-layer temperature. In the Caribou Creek Pingo, daily spring water flow is similar to the pattern of river run off in the thawing season. When the discharge rate is the highest, water temperatures tend to be lower in Bear, Caribou and Janson pingos.

Chemical and Isotope Patterns

Ice and discharge samples were collected from each pingo for chemical analyses. The water quality reflects a systematic change with time, which is difficult to explain. Chemical analyses made in 1924 (Orvin 1944) and in 1972 and 1976 (Liestøl, 1977) from the same place of Janson Pingo confirm this inconsistency. Lagoon Pingo water had a high Na^+/K^+ ratio versus a low SO_4^{2-}/Cl^- ratio, like SMOW (Standard Mean Ocean Water). Lagoon Pingo has experienced post glacial uplift from the sub sea surface. The residual ions are trapped in this originally marine environment. Caribou Creek Pingo, by contrast, has water with a low Na^+/K^+ ratio and high SO_4^{2-}/Cl^- ratio, suggesting that the water is probably from a shallow and more recent origin (Figure 5).

Tritium analyses of spring water and ice in Svalbard showed a mixed trend of water from before the 1950's and recent precipitation by tritium concentration values (2-10TU). The values of tritium concentration in icing ice imply "older age" in the upper layers. However, Riverbed Pingo ice has older values (<3±1 TU) in all samples. Values of the stable isotope $\delta^{18}O$ show a different trend from that of ice geochemistry. The Ny and Riverbed pingos, which have springs, were thought to have stopped growing, but tritium values from the bottom of the ice in Ny Pingo were consistent with those of recent spring water. Therefore, the pingos with outlet springs are still growing.

Hydraulic Potential

The direct measurement of pressure potentials in icing blisters at Caribou Creek Pingo, Bear Creek Pingo and Lagoon Pingo, gave values ranging from 20 to 65 kPa.

For the overburden of Caribou Creek Pingo calculated cohesion, and hence the maximum tensile strength occurring under applied load is 2633 kPa (-1°C) (Sayles and Haines, 1974). However, these values are much too high to be overcome by spring water pressure. The maximum possible artesian pressure is 2735 kPa when hill height is 270m (Figure 6). In the field, many invisible cracks and weak points usually exist in the permafrost. This is the reason for big differences between field and the calculated values.

Several methods were used to estimate the pressure necessary for pingo formation: by measuring icing blister height, by calculating pressure from water discharge and velocity, and by calculating overburden material weight. Each of these methods yielded different values. As a result of the six pingos studied, the pressure necessary for pingo development was found to be a minimum of 25±10 kPa at the Lagoon Pingo, and a maximum of 300±100 kPa at the Ny Pingo. Artesian pressure does not seem to be the major determinant for pingo development; instead, the main controlling factor for pingo formation is the latent heat value of ground water, which help ice segregation at the freezing table under the pingo ice. As a result, the frost heave pressure is an important force for pingo development.

Conclusion

Pingo formation pressure varied from site to site. The artesian pressure was sometimes less than 20 kPa. The pressure from ice crystallization is an important factor for pingo growth when artesian pressure is low, as in closed system pingos (Mackay, 1979).

Spring water discharge rate and temperature in the subpermafrost layer were found to be very important factors for pingo growth. Ground water latent heat loss depends on water temperature and discharge rate. Pingos were not associated with water warmer than 3°C or with discharge rates greater than 3 liters per second. In this study for pingos to occur, the maximum discharge rate was 2 to 3 liters per second and the maximum water temperature was 1.2°C. The sensible heat loss of spring water therefore is important for pingo growth, and had a maximum value of 37 kW , and the maximum latent heat loss was 1,000 kW. As water traveled from beneath the permafrost through permafrost layers, heat was lost, resulting in cooling of the migrating groundwater, which was then able to freeze.

Caribou and Bear Creek Pingos had seasonal variations of $\delta^{18}O$ suggesting a local source of water. In addition, collapsed pingos which were once thought to have stopped growing, had spring water tritium values which showed continued pingo growth with outlet springs. Spring water from Svalbard, however, was found to be more complex and consisted of old water mixed with recent water. Therefore, the origin of this water is probably from the glacier sole.

Acknowledgments

The author is very grateful to Dr. L. A. Viereck and Mr. R. J. Hartzmann for field work and help with logistics, and Drs T. E. Osterkamp (University of Alaska, Fairbanks), O. Watanabe, T. Fujii (National Institute of Polar Research), and H. Satake (Toyamo University) for analyses and for their valuable suggestions. Thanks is also extended to Drs. Y. Ono, N. Matsuoka, T. Shiraiwa and T. Kameda, Messieurs, K. Harada, K. Koizumi and N. Matsumoto for advice and assistance with the fieldwork and Dr. L.D.Hinzman (University of Alaska, Fairbanks) for help editing this manuscript. I thank Omron Corporation for financial support.

References

Berezantsev, V. Z. (1947). The strength of permafrost under building foundation (in Russian). *SIPRE report* 817.

Harada, K. and Yoshikawa, K. (1996). Permafrost age and thickness near Adventfjorden, Spitsbergen. *Polar Geography*, 20, **4**, 267-281.

Haugen, R.K., Slaughter, W. C., Howe, E. K., and Dingman, L. S. (1982). Hydrology and Climatology of the Caribou-Poker Creeks Research Watershed, Alaska. *CRREL report* 82-26, 42p.

Hjelle, A. (1993). *Geology of Svalbard*. Norsk Polarinstitutt, Oslo.

Liestøl, O. (1977). Pingos, springs, and permafrost in Spitsbergen. Norsk Polarinstitut bok 1977, 7-29.

Mackay, J. R. (1979). Pingos of the Tuktoyaktuk Peninsula, Northwest Territories. *Geographie physique et Quaternaire*, **33**, 3-61.

Müller, F. (1959). Beobachtungen uber Pingos. *Meddelser om Grønland*, **153**, 3, 1-127.

Nakawo, M. (1980). Density of columnar-grained ice made in a laboratory. *Building Research Note, National Research Council of Canada*, **168**. 1-8.

O'Brien, R. (1971). Observations on pingos and permafrost hydrology in Schuchert Dal, N.E.Greenland. *Meddelelser om Gronland*. **195**,1,1-20.

Orvin, A. K. (1944). Outline of the Geological History of Spitsbergen. Skr. Svalbard og Ishavet, Nr.78. Oslo.

Pollard, W. H. and French, H.M. (1984). The groundwater hydraulics of seasonal frost mounds, North Fork Pass, Yukon Territory. *Canadian Journal of Earth Sciences*, **21**, 1073-1081.

Sayles, F. H., and Haines, D. (1974). Creep of Frozen Silt and Clay. *CRREL Technical report*. 252, 51p.

Slaughter, W. C. and Hartzmann, J. R. (1992). Hydrologic and water quality characteristics of a degrading open-system pingo. *Permafrost 6th International Conference. Peking, China*. National Academy of Sciences. 574-579.

Washburn, A. L. (1969). Weathering, Frost action, and Patterned ground in the Mesters Vig district, Northeast Greenland. *Meddelelser om Grønland* **176, 4,** 1-303.

Yoshikawa, K. and Harada, K. (1995). Observations on Nearshore Pingo Growth, Adventdalen, Spitsbergen. *Permafrost and Periglacial Processes*, **6**. 361-372.