MECHANISM OF BEDROCK FROST HEAVE IN PERMAFROST REGIONS

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Abstract

Frost heaving of bedrock is a widespread process in permafrost regions which may generate forces and movements that detract from the otherwise sound foundation performance usually associated with bedrock. Depending on pre-existing fracture fabric, bedrock heave features may take the form of single ejected blocks or dome-shaped accumulations of up to several meters in diameter.

The development of excess pressure by water trapped between the permafrost table and downward freezing has been identified as an origin for the forces producing these types of features. Enclosed in the active layer, the water occupying fracture apertures and spaces vacated by heaved rock gives rise to a pulsating movement. The saturated volume determines the amount of heave possible under freeze back.

Heave occurs when the strength contributed by ice-filled fractures is exceeded by excess water pressure; high water pressure being obtained by an increase in the rate of freezing. Knowing that the main resistance to heave is offered by the weight and the shear resistance of the overlying ice-bonded rock mass, the behaviour of frost-heaved bedrock blocks is determined by the mechanical properties of the ice-filling material. Laboratory experiments indicate that even with a freezing rate 60 times faster than in the field situation, the ice-filling still deforms plastically. The vertical displacement of bedrock blocks is then characterized by a progressive (increase every time) and relatively slow movement (up to months). However, field measurements of heave up to 0.05 m per winter lead us to consider frost heaving as a threat to the stability of any engineering design.

Résumé

Le soulèvement gélival dans la roche en place est un processus très répandu dans les régions pergélisolées. Son action développe de telles pressions qu'elles peuvent détruire la réputation de substrat stable généralement associée à la roche en place. Selon le réseau de diaclases, les formes d'éjection prennent l'allure d'un bloc monolithique ou d'un monticule atteignant parfois plusieurs mètres de diamètre.

L'augmentation de la pression hydrostatique dû au cloisonnement d'eau entre le front d'engel et le plafond du pergélisol fut identifié comme étant à l'origine des forces qui produisent ce type de formes. Emprisonnée dans le mollisol, l'eau contenue dans les fissures et les cavités laissées vacantes par un bloc en voix de soulèvement donne naissance à un mouvement de pulsation. Le volume d'eau à saturation détermine l'ampleur du mouvement lors de l'engel.

Le soulèvement gélival se manifeste lorsque la pression hydrostatique excède la résistance de la glace contenue dans les fissures de la roche. Cette forte pression est engendrée par une augmentation de la vitesse d'engel. Sachant que la résistance au soulèvement provient du poids de la roche et de la résistance au cisaillement de la glace contenue dans les fissures, les soulèvements rocheux périglaciaires se forment selon les propriétés mécaniques de la glace. Des expériences en laboratoire ont clairement démontré que même avec un engel 60 fois plus rapide que les conditions normales de terrain, la déformation de la glace est toujours de type plastique. L'éjection de quartier rocheux est donc caractérisé par un mouvement progressif (augmente à chaque fois) et relativement lent (quelques mois). Cependant, certains mouvements atteignant jusqu'à 0.05 m par année portent à croire que le soulèvement gélival peut menacer la stabilité de certaines constructions.

Introduction

Frost occurence in soils is well known, but it is also widespread in bedrock. Many examples have been reported from permafrost areas of both upward displacement of bedrock blocks (Yardley, 1951; Washburn, 1979; Dionne, 1981, 1983; Dyke, 1984; Michaud, 1985, 1987; St-Onge *et al.*, 1988) and ice-filled fractures (Taber, 1943; Samson and Tordon, 1969; Garg, 1979; French *et al.*, 1986). In general, frost-heaved bedrock features result from vertical and lateral movements caused by the growth of ice in bedrock discontinuities.

In addition to the destruction of the glacially sculptured bedrock surface, frost heaving may generate forces and movements that detract from the otherwise sound foundation performance usually associated with bedrock. If bedrock frost heave is to be accounted for in any engineering design, natural conditions controlling its development must be

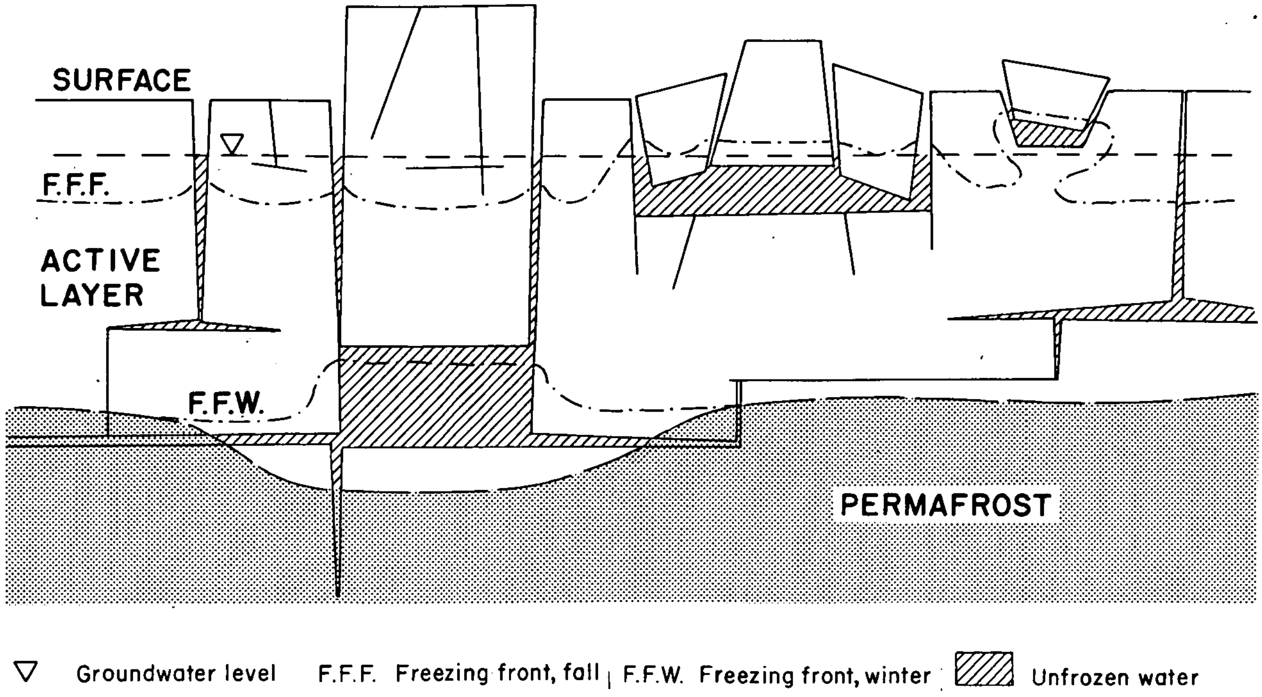

Figure 1. A schematic showing the mechanism of frost heaving in bedrock. This shows the progression of the freezing front (F.F.F. and F.F.W.) through the active layer and the role of permafrost in trapping the unfrozen water in a closed system. The relationship between the fracture fabric and the type of feature is also being demonstrated.

assessed. The purpose of this study is to provide field and laboratory data on the mechanism responsible for the heave of large blocks.

Background

Frost heaving in bedrock can result in spectacular disruption of the bedrock surface. Features evolve as single ejected blocks (monolith) or dome-shaped accumulations of up to several metres in diameter. Unfortunately, the degree of present activity is far less well known. Dyke (1989) reports field and laboratory measurements suggesting annual movements and pressures of up to 0.05 m and 0.4 MPa, respectively (Dyke, 1984).

Both geologic and hydrologic conditions play important roles in the development of frost-heaved bedrock features. Because of their widespread occurrence in many rock types, bedrock structure seems to be the limiting factor rather than the lithology itself. Most frost heave in bedrock appears to take place along pre-existing vertical and horizontal fractures. The fracture fabric and density partly control the shape and the size of the features. Also, saturation of the fracture porosity of the rock mass is essential.

Frost heaving of bedrock can be generated by at least three processes, of which the formation of segregated ice in soil trapped between bedrock blocks is most akin to frost heaving in bulk soils. However, absence of fracture fillings in the rock mass in many locations demands other explanations. A second mechanism involves the force developed by a high hydraulic pressure when movement of water through a confined aquifer is blocked by ice. It is responsible for the formation of frost blisters (Van Everdingen, 1982; Pollard and French, 1984) and open-system pingos (Müller, 1963; Péwé, 1969; Pissart, 1970). This mechanism is least common because of the necessity of considerable elevation differential in the water conduit. Finally, a pore-water expulsion mechanism can be invoked to explain the origin of the forces producing large rock-heave features (Dyke, 1984). The entrapment of groundwater in a closed system creates zones where high hydrostatic pressures can be developed. This process is common in the highly cohesive, crystalline rocks of the Canadian Shield.

Pore-water expulsion mechanism

As a bedrock outcrop near saturation freeze (fig. 1), the freezing front advances through the rock mass from the surface. Once a water-filled void is reached, freezing front migration is retarded because of the need to remove latent heat of fusion. If the water is already confined in an isolated space, the water-filled gap is eventually surrounded by the freezing front and begins to freeze inwards from all directions. Alternatively, if the water is included in an open fracture system, the excess water may be expelled ahead of the freezing front until it becomes trapped due to differential advance of the freezing front. A closed-system then forms between retarded parts of the freezing front and the permafrost table. Hydrostatic pressure starts to develop and the volume increase associated with the water-to-ice phase change pushes the overlying blocks in the direction offering the least resistance. Heave is then determined by the balance between the driving and the resisting forces.

THE DRIVING FORCE

For a block of rock bounded on the sides and base by open fractures, the driving force for heave will be proportional to the area over which pressure is exerted beneath the block. The driving force (F_d) is given by the hydrostatic pressure (P_w) times the area of the block perpendicular to the most probable direction of movement (A):

$$F_d = P_w * A \qquad (1)$$

To measure excess water pressures during freezing, a series of experiments have been carried out in a controlled temperature room. The apparatus consisted of a square concrete box with the opening measuring 0.3 m on a side. A concrete block was placed in the opening such that a gap was maintained on all sides and the bottom. This gap was filled with water and a freezing temperature was applied. Experiments performed at -5, -10 and -20°C have shown that displacement of blocks and water pressures are closely related to the intensity of freezing. The displacement history of the block was measured by mechanically transfering movement of the block to the pen on a drum chart recorder. This enabled an average displacement rate to be determined for each freezing temperature. In all tests the displacement rate was more or less constant during the freezing interval. Average displacement rates of 0-24, 0.43 and 0.90 cm/day were measured for the three freezing temperatures respectively. Correspondingly, duration of the freezing interval was approximately 48, 30, and 24 hours. Therefore total heave increased with intensity of freezing. At the same time, the average maximum water pressures were 0.285, 0.313, and 0.397 MPa.

The increase in heave rate is in direct proportion to the intensity of freezing. This is expected but the corresponding increase in maximum water pressure is more gradual. Up to some threshold pressure, the volume increase may be accommodated by escape of water either into the concrete or along fractures in the ice. If so, heave may begin at an elevated pressure, relative to which further increases with intensity of freezing would be in closer proportion to intensity of freezing.

At slow rates of freezing, signs of water leakage were noticed. This phenomena took the form of an ice extrusion, resulting in a decrease in the level of excess water pressure and a shift in the direction of the block movement. In other words, by allowing the migration of water into a fracture in the ice-seal, the expansion of the ice created an oblique displacement of the block. Horizontal movement is then increased at the expense of vertical movement, resulting in the production of tilted features (fig. 1, heaved block on the right).

This phenomenon of ice extrusion has been well documented by Davidson and Nye (1985), especially along linear and smooth fracture faces. The maximum water pressure of 1.1 MPa measured by Davidson and Nye (1985), was obtained inside rough and wavy wedge-shaped cracks which is not the case here.

Several factors influence the rate of freezing. Besides the geographical location of the site, the size and the depth at which the water-filled gap occurs are very important. A large opening as well as a deep location in the active layer considerably decrease the rate of freezing. It would appear that, since the driving force is generated by freezing, areas or zones affected by a fast rate of freezing are most likely to heave.

THE RESISTING FORCE.

Two forces inhibit block motion : friction along vertical fractures and resistance to bending.

The first type occurs where blocks can easily slide along vertical and inward dipping fractures (fig. 1). Like a simple hydraulic press, excess water pressure applied equally over the base of a block overcomes the resistance given by the weight of the block (W) plus the shear resistance of the ice-filling along the peripheral fractures. In order for heave to occur the following balance must be achieved:

$$P_w * A \geq W + (\tau * A_i) \qquad (2)$$

where τ is the shear resistance and A_i the crossectional area of the ice filling parallel to the fracture surfaces. This is similar to Gilbert's laccolith model (Johnson and Pollard, 1973). Equation 2 would describe the force balance necessary for the initiation of a monolith heave feature. In order to evaluate the resisting force, shear tests have been performed with this model. Using a larger version of the frost heave simulation previously described, shear resistance of the ice-filling was measured by artificially inducing the hydrostatic pressure. When the ice-filling was 0.10 to 0.12 m thick, the hydrostatic pressure was increased by inflating a rubber bladder placed in the gap beneath the block. This experiment showed that at failure the shear stress was in the order of 0.3 MPa, implying that the main resistance against heave is offered by the shear resistance of the ice-filling.

When the fracture density increases, the water-filled gap will be overlain by several blocks. In this situation, sliding is likely to be achieved along multiple fractures. This type of failure is responsible for blocks heaved to different heights (fig. 2).

The second type of resistance invokes the flexural rigidity of the frozen rock mass. Instead of sliding, a layer of rock is bent by the excess water pressure. Since this layer is made up of blocks bonded by ice, all the heave is taken up by deformation in the ice. To measure the resistance, the flexural rigidity has to be calculated with the elastic properties of the ice-filling material. Bending of the frozen layer automatically involves displacement of more than one block. Thus, rock heave features comprised of a bent discontinuous layer occur where the water-filled gap is overlain by several blocks and where the fractures dip outwards (fig. 1). In this case, blocks adjacent to the centre block are involved in the process and create dome-shaped features (fig. 3).

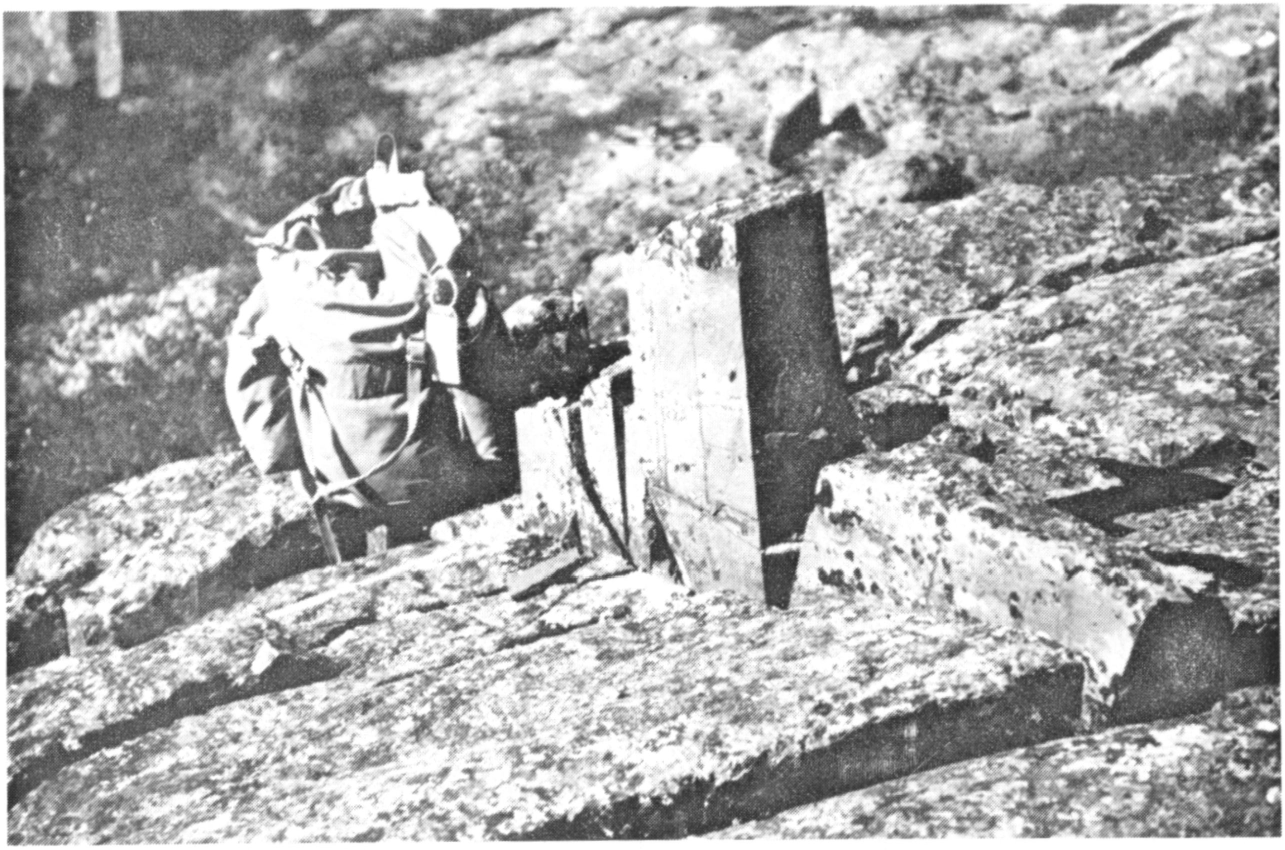

Figure 2. Frost-heaved bedrock feature representing three blocks heaved at different heights. This is an example of multiple shear fractures (Guillaume-Delisle Gulf).

Figure 3. Dome-shaped feature in basalt where blocks adjacent to the center block have been tilted. This shape is typical of a bended rock layer (Guillaume-Delisle Gulf).

The process of heave probably takes place on several time scales. However, when occurring in the active layer, a seasonal or annual contribution undoubtedly is made. If upward movement takes place every year and corresponds to the 9% increase in the volume of water trapped beneath the block, then an exponentially increasing progression of heave should occur. In reality blocks are not actively heaved every year, and during the thaw season they may slide back, partially or fully, into the space vacated earlier, until moved again. A heave recorder installed by Dyke (1984) on Melville Island, N.W.T., showed a maximum vertical heave of 0.05 m upon freezing and a settlement of 0.03 m over the summer. This up and down movement tends to slow down the progressive heaving of bedrock blocks, but net upward movement may still accumulate.

As for the type of deformation, an abrupt movement associated with a brittle failure of the ice was first considered. In the light of laboratory work it became obvious that the vertical displacement of bedrock blocks results from the slow ductile deformation of the ice-filling. The heaving tests were performed at freezing rates up to 60 times faster than those found under natural conditions in the field (Table 1) and gave shear strain rates up to 1×10^{-5} s^{-1}, still in the range of ductile deformation for ice (Andersland and Anderson, 1978, fig. 10.6) (table 1). Therefore, the vertical displacement of bedrock blocks can be characterized as a progressive, relatively slow movement (up to months) and irregular (not every year). Furthermore, the experiments suggest that, in nature, some escape of water during freezing will reduce the amount of heave from that potentially possible. On the other hand, the faster the freezing, the greater will be the heave.

Table I. This table represents data on the behaviour of frost-heaved bedrock features during laboratory experiments. It shows that the shear strain rate of the ice is still in the range of ductile deformation for ice, even at the fastest rate of freezing.

	-5 °C	-10 °C	-20 °C	Field
Cooling rate (°C day^{-1})	6	8	15	0.24
Displacement rate (cm day^{-1})	0.24	0.43	0.9	—
Strain rate (s^{-1})	3×10^{-6}	5×10^{-6}	1×10^{-5}	—

Discussion

Virtually all rock masses exposed to subaerial conditions in a cold environment are prone to heave. Hydrologic and geologic factors control the specific occurrence of heave. Presence of permafrost helps to maintain the groundwater level near the surface, and to trap that water in a closed-system during annual freezing of the active layer. Vertical and horizontal fractures are necessary to define blocks, and to host ice growth. Thus, a relationship exists between the fracture density and the susceptibility of a rock mass to frost heave. Reconnaissance fracture surveys in the Guillaume-Delisle gulf region (subarctic Québec) have shown that heave features composed of single or a few blocks tend to be associated with a fracture spacing in the range of 1 fracture per metre. A fracture ratio lower than 0.3 fracture per metre is rarely associated with heave features. Finally, a fracture ratio higher than 3 fractures per metre is commonly associated with small heave features.

Movement up to 0.01 m per winter, recorded in the laboratory and measurements of heave up to 0.05 m per winter in the field (Dyke, 1984) lead us to consider frost heaving of bedrock as a potential threat to foundations on rock. The longer the block subject to potential movement, the greater the threat because of the increased heaving force. A 15 m length of 1.2 m diameter pipeline with a gas pressure of about 6 MPa, can withstand only 0.1 m movement of one end before tensile yielding occurs. Assuming an accumulating 9% increase in height of a block underlain by a horizontal fracture of 0.01 m initial aperture, damage due to application of the displacement to one end would occur in 27 years. If the initial aperture is wider, the time before yielding will be reduced. Damage to a more rigid structure may commence more quickly.

Conclusion

Frost heaving in bedrock is a weathering process taking place primarily in the active layer of a frozen rock mass. The growth of ice within the fracture porosity of the rock mass generates the forces responsible for movement of bedrock blocks. The pore-water expulsion mechanism associated with the 9% volume increase during the water-to-ice phase change creates pressures able to uplift, after a certain period of time, bedrock blocks up to 3 m above the surface (Michaud, 1985). This movement can be cumulative and occurs by the ductile deformation of the ice filling. Frost heave movement on a year to year basis is small but, cumulatively, it has the potential to threaten foundations.

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References

ANDERSLAND, O.B. and ANDERSON, D.M., 1978. Geotechnical engineering for cold regions, McGraw-Hill Book Co., N.Y.: 566 p.

DAVIDSON, G.P. and NYE, J.F., 1985. A photoelastic study of ice pressure in rock cracks, Cold regions Sci. and Tech., 11: 141-153

DIONNE, J.C., 1981. Formes d'éjection périglaciaires dans le Bouclier Laurentidien, Québec, Revue de géomorpho. dyn., 30: 113-124.

________, 1983. Frost-heaved bedrock features: a valuable permafrost indicator, Géogr. phys. Quat., 37: 241-251.

DYKE L. D., 1984. Frost heaving of bedrock in permafrost regions, Bul. of the Assoc. of Eng. Geol., 21: 389-405.

FRENCH, H., BENNETT, L. and HAYLEY, D. W., 1986. Ground ice conditions near Rea Point and Sabine Peninsula, eastern Melville Island. Can. Jour. of Earth Sci., 23: 1389-1400.

GARG, O. P., 1979. Mining of frozen iron ore in northern Québec and Labrador. Géogr. phys. et Quat., 33: 369-376.

GRAWE, O.R., 1936. Ice as a agent of rock weathering, Jour. of Geol. 44: 173-182.

JOHNSON, A. M. and POLLARD, D. D., 1973. Mechanics of growth of some laccolithic intrusions in the Henry Mountains, Utah 1. Field observations, Gilbert's model, physical properties and flow of the magma. Tectonophysics, 18: 261-309.

MICHAUD, Y., 1985. Evolution de versants rocheux au golfe de Guillaume-Delisle, Hudsonie, Thèse de M.A., Univ. Laval. Québec, 102 p.

________ et DIONNE, J.C., 1987. Altération des substrats rocheux et le rôle du soulèvement gélival dans la formation de champs de blocailles, en Hudsonie, Géogr. phys. et Quat., 41: 7-18.

MÜLLER, F., 1963. Observation on pingos, Technical translation, National Research Council, Canada, 1073, 117 p.

PÉWÉ, T.L., 1969, The periglacial environment, McGill-Queen's University Press, Montréal: 1-9.

PISSART, A., 1970. Les phénomènes physiques essentiels liés au gel, les structures périglaciaires qui en résultent et leur signification climatique, Ann. de la Soc. géol. de Belgique, 93: 7-49.

POLLARD, W.H. and FRENCH, H.M., 1984. The groundwater hydraulics of seasonal frost mounds, North Fork Pass, Yukon Territory, Can. Jour. of Earth Sci., 21: 1073-1081.

SAMSON, L. and TORDON, F., 1969. Experience with engineering site investigations in northern Québec and northern Baffin Island. Permafrost: Third Canadian conference, Proceedings, National Research Council, Division of Building Research Technical Memorandum 97: 21-38.

ST-ONGE, D. A., McMARTIN, I. and AVERY, R., 1989. Rock blisters and other frost-heaved landforms in the Bernard Harbour area, District of Mackenzie, N.W.T., in Current Research, Part D, Geol. Surv. of Can., Paper 89-1D: 95-99.

TABER, S., 1943. Perennial frozen ground in Alaska: Its origin and history. Bul. of the Geol. Soc. of Amer., 54: 1433-1548.

VAN EVERDINGEN, R.O., 1982. Frost blisters of the Bear Rock Spring area near Fort Norman, N.W.T., Arctic, 35: 243-265.

WASHBURN, A.L., 1979. Geocryology: a survey of periglacial processes and environments, Arnold, London, 406 p.

YARDLEY, D.H., 1951. Frost-thrusting in the Northwest Territories Jour. of Geol., 59: 65-69.