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FREEZING FRONTS AND THEIR POSSIBLE INFLUENCE UPON PROCESSES OF SUBGLACIAL EROSION AND DEPOSITION

by

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ABSTRACT

Recent studies have shown the important influence of pore-water movement and the subglacial thermal regime on processes of erosion and deposition at the subglacial interface. The influence of migrating freezing fronts within subglacial material has been largely ignored. The phenomena of ice-water interface processes will be examined and their relevance to subglacial processes illustrated. Four case studies are presented that deal with the various effects that freezing-front movement may have on pore water, consolidation, shear strength, and likely diagenetic characteristics of subglacial deposits. The influence upon erosional and depositional processes will be outlined, and a mechanism related to potential surge-like conditions within the subglacial zone postulated.

INTRODUCTION

The influence of processes of freezing and thawing upon soils in terms of their permeability, consolidation, and other geotechnical characteristics has been long established (Taber 1930, Anderson and Morgenstern 1973, Andersland and Anderson 1978, Jessberger 1979). However our knowledge of these processes at the subglacial interface and within subglacial materials is deficient.

Recent studies have stressed the importance of pore-water movement and the subglacial thermal regime in the hydrogeological processes that lead to subglacial erosion and deposition (Boulton 1972, Clayton and Moran 1974, Boulton 1975, Menzies 1979[a]). The present author believes that the influence of the migration of freezing fronts within subglacial material, whether in traction or lodged at the base of an ice mass, must be considered further (Mathews and Mackay 1960).

Discussions on subglacial interface temperatures indicate that the subglacial thermal regime can be expected to fluctuate across the freezing point both temporally and spatially over wide areas of a glacier bed (Paterson 1969, Hooke 1977, Sugden 1977). It is therefore likely that conditions do occur beneath ice masses such that freezing-front migrations will take place within subglacial debris.

At present, data on subglacial debris temperatures appear to be limited. However, from computations of subglacial interface temperatures and the likely heat balance within subglacial debris some estimates of the probable rate of freezing-front propagation can be made. It should be borne in mind that these estimates are tentative and must remain so until actual subglacial debris temperatures become known.

From Table I it can be seen that with an assumed surface temperature of -1°C and a linear thermal gradient into a fully saturated soil, penetration rates of the freezing front vary considerably depending on soil porosity, soil thermal conductivity, and the geothermal heat flux. Within Canada and on adopting values for porosity of 0.30 to 0.65, for thermal conductivity 2.1 W m^{-1} deg^{-1} (Penner 1970) and for geothermal heat flux 42 mW m^{-2} (Judge 1973), penetration rates of 1 to 2 m a^{-1} were calculated. It can therefore be suggested that such penetration values might have occurred within subglacial debris beneath the marginal areas of the Laurentide ice sheet. Marked variations of these rates can be expected to occur depending on the state of jointing and fracturing within the debris, the hydraulic conductivity, and the temperature of the percolating melt water as well as deviations from the simplified assumptions used to calculate the penetration rate values.

PHENOMENA ASSOCIATED WITH THE MIGRATION OF FREEZING FRONTS

When a state is reached at which propagation of a freezing front occurs downwards into a saturated material, critical processes occur at the interface between the frozen and unfrozen parts of the material. The result is that either volume expansion occurs, followed by heave, or it does not occur, and no segregation ice forms. At the micro-level, the propagation of a freezing front can be regarded as progressive pore-water freezing. The rate of advancement is, as will be shown below, largely a function of pore-water availability, and debris porosity and permeability. As pore water freezes at the front several phenomena have been observed. Firstly, material which is saturated may freeze *in situ* with no pore-water migration. Secondly, pore water may, due to varying hydraulic potential gradients, migrate toward the freezing front. Finally, it is thought that under saturated conditions pore-water expulsion from the front may occur due to volumetric expansion as water freezes (Khakimov 1957, McRoberts and Morgenstern 1975).

The above phenomenon of pore-water movement at the freezing interface can be analysed using Everett's (1961) approach involving the equilibrium between ice and water phases within the

TABLE I. MAXIMUM DEPTH AND ANNUAL RATE OF PENETRATION OF THE 0°CELSIUS ISOTHERM INTO SOILS OF VARIABLE POROSITY AND THERMAL CONDUCTIVITY UNDER CHANGING GEOTHERMAL HEAT FLUX RATES*

Thermal conductivity ($W\ m^{-1} deg^{-1}$)	Geothermal heat flux ($mW\ m^{-2}$)	Soil porosity (n)	Maximum penetration depth of 0°C isotherm (m)	Penetration rate to 0°C isotherm ($m\ a^{-1}$)
1.46	42	0.20	35.08	3.94
1.46	42	0.45	"	1.75
1.46	42	0.60	"	1.30
2.09	42	0.20	50.00	3.95
2.09	42	0.45	"	1.75
2.09	42	0.60	"	1.32
2.93	42	0.20	70.42	3.93
2.93	42	0.45	"	1.74
2.93	42	0.60	"	1.31
1.46	84	0.20	17.51	7.95
1.46	84	0.45	"	1.75
2.09	84	0.20	25.00	7.91
2.09	84	0.45	"	3.51
2.93	84	0.20	35.00	7.90
2.93	84	0.45	"	3.51

*Calculations were made assuming a surface temperature of -1°C and a linear thermal gradient into saturated soil.

pores of the material. The pressure difference across the ice-water interface is given by

$$p_i - p_w = \frac{2\sigma_{iw}}{r} \qquad (1)$$

where p_i is ice pressure,

p_w is pore-water pressure,

σ_{iw} is surface tension ice-water, and

r is equivalent pore radius of the soil.

Before discussing the conditions that are predicted from Equation (1) it can be stated more precisely that the differences between the ice and pore-water pressures be represented as Δp where $\Delta p = p_i - p_w$. If conditions occur on freezing where Δp is less than $\frac{2\sigma_{iw}}{r}$ pore-water migration occurs toward the front thus creating a pressure gradient with low pressure at the ice-water interface. If, however, $\Delta p > \frac{2\sigma_{iw}}{r}$ then pore-water expulsion away from the front takes place (McRoberts and Morgenstern 1975, Arvidson and Morgenstern 1977).

It is normally accepted that p_i is equivalent to the overburden pressure or total stress, p. From Equation (1), therefore, it can be written that:

$$p - p_w = C \qquad (2)$$

where C is a constant for a given soil and is equivalent to $\frac{2\sigma_{iw}}{r}$. Williams (1968) has shown that C varies from a value of zero for coarse sands to values exceeding 0.2 Pa for clays.

Test data derived experimentally by several workers (Williams 1968, Arvidson 1973, Sutherland and Gaskin 1973, McRoberts and Morgenstern 1975) confirm that pore-water expulsion, as indicated above, does occur in both coarse- and fine-grained materials although in the latter case a subsequent reversal of pore-water flow may sometimes occur. In the former, expulsion occurs under most conditions of stress since C approaches zero. In the latter, however, expulsion is observed only under conditions of higher total stress. Experimental values of higher stresses required to cause expulsion are in the range 80 to 200 kPa, well within the normal stress levels likely to occur at the base of a glacier, where normal stresses may exceed 30 MPa.

Beneath an ice mass conditions as described in Equation (2) can be written as

$$(\rho_i g h_i + \rho_s g h_s) - p_w = C, \qquad (3)$$

where ρ_i is density of ice,

ρ_s is density of soil,

g is acceleration due to gravity,

h_i is height of glacier ice, and

h_s is depth of frozen soil.

Since in most instances $\rho_s g h_s$ greatly exceeds $\rho_i g h_i$ Equation (3) becomes

$$\rho_i g h_i - p_w = C. \qquad (4)$$

From this generalized equation it can be noted that pore-water expulsion from the freezing front will largely become a function of glacier-ice thickness provided that h_s remains relatively small.

OTHER FACTORS ASSOCIATED WITH PORE-WATER MIGRATION

Experimental data derived by Penner (1970) and McRoberts and Morgenstern (1975) indicate that the rate of freezing plays a major role in influencing pore-water pressures close to the ice-water interface. It can be shown that:

$$F = E\,\frac{dy}{dt}, \qquad (5)$$

where F is flux of water expelled and $\frac{dy}{dt}$ is rate of freezing-front advance, and that

$$E = n\,(\rho_w - \rho_i)\,/\,\rho_w \approx 0.009n$$

where n is porosity and ρ_w is density of water.

Using Darcy's law, Equation (5) becomes:

$$ki = E\,\frac{dy}{dt} \qquad (6)$$

where k is hydraulic conductivity and i is hydraulic gradient.

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From Equation (6) it can be noted that the other factors influencing rates of pore-water migration are changing permeability, variations in hydraulic gradient and length of flow paths. In fine-grained material, changes in effective pressure strongly control permeability whereas in coarse material such influences are minimal.

Beneath an ice mass it can be postulated that the rate of freezing-front advance will be a function of ice overburden pressures, subglacial debris permeability, and the thickness of the subglacial debris stratum, as well as the associated thermal factors previously mentioned.

THE INFLUENCE OF FREEZING FRONTS WITHIN SUBGLACIAL DEBRIS

The following set of hypotheses are put forward to illustrate the influence that fluctuating freezing fronts might have on subglacial debris. It has been shown from recent studies that pore-water conditions within subglacial debris allied with changes in the subglacial thermal régime lead to important boundary conditions on processes of erosion and deposition (Boulton 1972, Clayton and Moran 1974, Boulton 1975, Andrews 1980).

The areas within the subglacial zone where such conditions of descending freezing fronts and deformable beds (Fig. 1a) are likely to occur are in the "hinge" zones near the ice margin where wet-based ice gives way to a cold-based snout region (Clayton and Moran 1974, Menzies 1979[a]) or in sub-marginal areas where a "polythermal" set of conditions may exist at the bed as described by Goodman and others (1979) from work at the base of Glacier d'Argentière. In these sub-marginal zones, variations in basal and surface velocity, ice thickness, bed roughness, sediment characteristics, and atmospheric temperatures can be expected to cause oscillations of the freezing isotherm across the ice-glacier bed interface.

The following hypothetical models summarize some of the effects descending freezing fronts may have upon subglacial debris, and on subsequent subglacial debris, and on subsequent subglacial process responses.

Case I. Pore-water movement toward freezing front: permeable substrate

In Case I, under conditions where $\Delta\rho$ is less than C, pore water will move toward an advancing freezing front especially if the sub-front debris is permeable (Fig. 1b). An alternative response, not considered here, might occur due to the segregation at the glacier ice-bed interface resulting in the glacier being "lifted" above the debris. In this latter instance the zone of maximum shear strain would not descend into the debris, as is envisaged in Figure 1b.

If this latter state does not occur then the displacement of the zone of maximum shearing will occur down into the debris from the interface, resulting in increased debris erosion by freeze-on processes. With loss of pore water to the freezing front increased shearing resistance can be expected to occur within the sub-front debris leading to increased consolidation. The sediment and landform, on deglaciation, will be lodgement till, possibly fluted and moulded.

Case II. Pore-water expulsion from freezing front: permeable substrate

Under certain conditions it has been shown, as previously noted, that when $\Delta\rho$ exceeds C there is a tendency for pore water to be expelled from the freezing front (Fig. 1c). If the permeability of the sub-front debris is sufficiently large such that pore-water expulsion is of a high volume, the rate of advance of the freezing front may be considerably reduced. As in Case I a series of zones of maximum shearing will develop descending into the debris as the front progresses. Consequently re-erosion and re-incorporation of debris up into the glacier ice will occur. Permeable material beneath this expulsion zone may exhibit the effects of pore-water throughflow by either being low in clay content or having coatings or cutans of silt and clay. It may also be speculated that narrow, roughly horizontal, lenses or bands of higher strength material may occur due to pore-water expulsion from them as they lie immediately in front of the freezing line. A rough horizontal banding has been reported in several basal tills and may be indicative, in part, of this process (Menzies 1979[b]:320).

Case III. Pore-water movement toward freezing front: impermeable substrate

Similar conditions are developed as in Case I except that the debris is relatively impermeable to pore-water migration toward the freezing front (Fig. 1d). This state could lead to a much slower propagation of the freezing front, since effective pore-water attraction to the front would be restricted. Zones of maximum shearing would tend to persist for longer periods in any one location resulting in more efficient re-erosion of debris.

Case IV. Pore-water expulsion from freezing front: impermeable substrate

In this case it is envisaged that pore-water expulsion will occur from the freezing front into a lower stratum of impermeable material resulting in elevated pore pressures developing at some depth beneath the front (Fig. 1e). As previously noted, with pore-water expulsion the propagation of the freezing front will be slowed . The elevated pore-water pressures may, in certain conditions, lead to either the development of low internal shear strengths or virtual liquefaction of the substrate material. The effect of these pore-water pressures may be two-fold. Firstly, penecontemporaneous deformation of the debris is liable to occur with water-escape structures being developed, such as dish-like folds. Secondly, the influence of the pore-water pressures may lead to a form of hydrodynamic instability with frictional values in the area of high pore water approaching zero. This state may then develop into a "surge-type" condition in which velocities of internally deforming material beneath the ice rapidly increase (Clarke and Jarvis 1976, Jones 1979). So that this surge condition may occur, a tightly sealed system must exist around the area of potential instability in order to decrease considerably the possibility of pore-water escape. Debris beneath this deforming zone may become fluted and surficially moulded by the moving debris above it. Evidence is now accumulating, both in North America and Europe, that indicates that lobes of the Quaternary ice sheets may have surged in their outer marginal areas.

CONCLUSION

Freezing-front migration may have an appreciable influence upon processes active at the basal ice-bed interface and on resultant

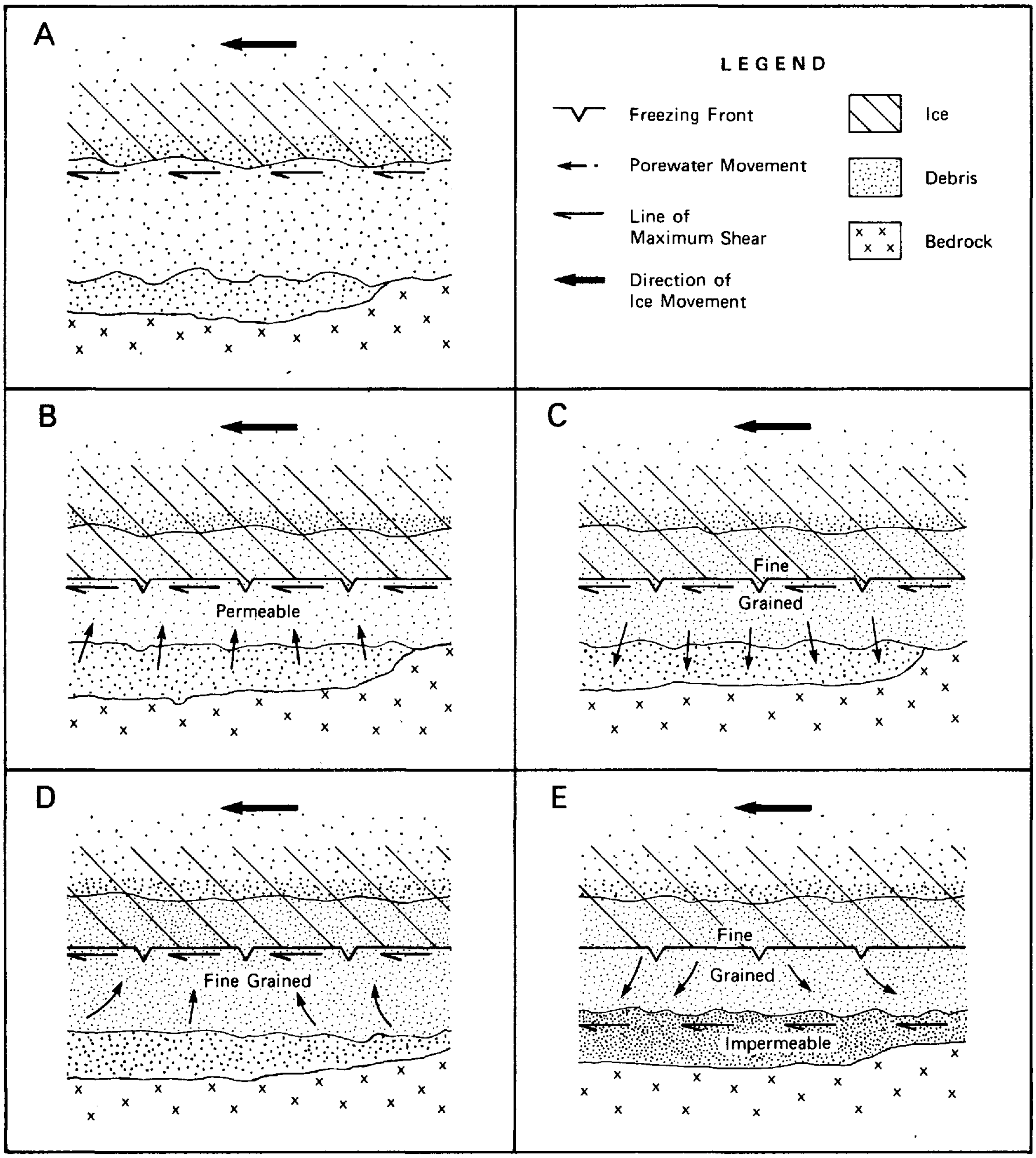

Fig.1. The influence of descending freezing fronts within subglacial debris: (A) hypothetical pre-conditions to freezing, (B) pore-water migration toward front into permeable debris, (C) pore-water expulsion into permeable debris, (D) pore-water migration into impermeable debris near freezing front, and (E) pore-water expulsion into impermeable debris leading to elevated pore-water pressures within unfrozen debris zone.

sediments and landforms. The hypotheses described simplify greatly the possible combinations of sediment type, sediment permeabilities, thermal conductivities, and stress distributions that may exist beneath an ice mass. This simplification illustrates conditions which might arise subglacially with freezing-front propagation into subglacial material, and suggests the processes and responses likely to occur. The likelihood of such freezing processes occurring within Quaternary subglacial sediments appears, on theoretical grounds, to be highly probable; therefore, the hypotheses should be tested in the field before further consideration is given to the implications of this work.

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