Microscopic and environmental controls on the spacing and thickness of segregated ice lenses

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ABSTRACT

The formation of segregated ice is of fundamental importance to a broad range of permafrost and periglacial features and phenomena. Models have been developed to account for the microscopic interactions that drive water migration, and predict key macroscopic characteristics of ice lenses, such as their spacings and thicknesses. For a given set of sediment properties, the temperature difference between the growing and incipient lenses is shown here to depend primarily on the ratio between the effective stress and the temperature deviation from bulk melting at the farthest extent of pore ice. This suggests that observed spacing between ice lenses in frozen soils, or traces of lenses in soils that once contained segregated ice, might be used to constrain the combinations of effective stress and temperature gradient that were present near the time and location at which the lower lens in each pair was initiated. The thickness of each lens has the potential to contain even more information since it depends additionally on the rate of temperature change and the permeability of the sediment at the onset of freezing. However, these complicating factors make it more difficult to interpret thickness data in terms of current or former soil conditions.

Introduction

The landforms we observe today often contain information on the conditions of their genesis. Washburn (1980) used such reasoning to interpret modern and relic occurrences of permafrost features as evidence for climate change in Arctic environments. Many, if not most, of these features contain segregated ice that forms by pushing aside mineral particles as liquid water is drawn into it to fill the vacated space. Much has been learned since early experiments (Taber, 1929, 1930) and field observations (Beskow, 1935) first reported on the formation of sequences of segregated ice lenses during prolonged periods of sub-freezing surface temperatures. Here, I describe how microscopic interactions at the interfaces between mineral particles, water, and ice conspire with the prevailing environmental conditions to produce macroscopic ice lenses and determine their spacing and thickness.

Our modern understanding of ice lens growth and frost heave developed along a number of fronts; a history of the early literature is given by Henry (2000). The first comprehensive and tractable model for ice lens growth was produced by O’Neill and Miller (1985). Since heat flow is normally predominantly vertical, ice lenses tend to form parallel to the ground surface and a one-dimensional treatment captures the essential controlling dynamics. Formulated as a series of differential equations that describe the conservation laws beneath the lowermost growing, or active lens, O’Neill and Miller’s “rigid ice” model postulates the existence of a partially “frozen fringe,” within which the overlying weight is supported by a mixture of ice, liquid water, and mineral particles (see Fig. 1). Water is drawn upwards through the fringe to supply lens growth, and the hydraulic requirements on fluid flow determine the distribution of fluid pressure over the ice surface. This pressure distribution produces an effective fluid force that is balanced at a given depth by the combined effects of gravity, the forces transmitted between the particles at that depth, and the forces transmitted by the ice to the particles at lower depths. Steady lens growth can occur when the water is supplied just quickly enough to enable the rate of lens growth to be matched by the rate at which the isotherms advance relative to the ground surface as heat is conducted upwards. When the flow of heat is too rapid, however, insufficient water can be drawn to the growing lens. This causes the fringe to get thicker with time as the isotherms penetrate deeper beneath the lens. Under one range of controlling parameters, fringe thickening continues indefinitely and water simply freezes within the pore space without significant lens growth. The more interesting “secondary heaving” regime is attained when all the ice beneath a particular level within the fringe is able to transmit a force to the mineral grains at lower levels that is just large enough to balance the sum of the overlying weight and the effective fluid force. Since no net force is left to push the mineral particles together when this happens, this marks the location at which a new lens is initiated in O’Neill and Miller’s (1985) model. Though typically neglected, this lens-initiation condition can be generalized to address cases where soil cohesion is important. (For further discussion of the conditions...
that set the boundaries between these different freezing regimes, see Rempel et al., 2004; Rempel, 2007."

The O'Neill and Miller (1985) model has served as the starting point for subsequent studies that have significantly improved its implementation and facilitated predictions for ice-lensing behavior (e.g., Fowler, 1989; Fowler and Krantz, 1994). However, it is only quite recently that an understanding has been developed for the microphysical controls on how forces are transmitted between the ice and the mineral particles across the thin liquid films that separate them. As discussed further below (see also Rempel et al., 2001), the net ice-particle force within the fringe is proportional to the mass of ice that would otherwise occupy the volume contained by the water and sediment, and the temperature gradient (more accurately, the gradient in chemical potential, but this and ∇T are directly related under typical freezing conditions). In the original O'Neill and Miller (1985) model the transmission of forces by the ice to underlying mineral grains had to be prescribed in an ad hoc manner. By showing that the forces acting over the ice surface can be determined without detailed knowledge of its precise geometry it has now become possible to calculate this force transmission directly (e.g., Rempel et al., 2004; Rempel, 2007). This advance makes only minor differences to predictions for the rate of lens growth (e.g., see Rempel et al., 2007), but it is crucial for enabling predictions of the conditions under which new ice lenses are initiated. This makes it possible to predict the lens spacing and thickness under varying environmental conditions.

The next section begins with a brief description of the microphysical interactions that are ultimately responsible for the ice-particle forces that drive segregated growth. This is followed by a description of the model for ice lens initiation and growth. Particular attention is paid to the environmental controls on lens spacing and thickness—the primary potential indicators for the conditions that prevailed during ice emplacement. Post-emplacement changes can affect the observed ice distribution. These and other potential complications are discussed before the concluding remarks.

**Equilibrium between ice and water at subzero temperatures**

Even without any soluble impurities, two distinct sets of physical processes combine to let liquid water and ice remain in equilibrium at sub-zero temperatures (e.g., Cahn et al., 1992; Dash et al., 2006). Both phenomena have analogues above 0 °C that are described in introductory hydrogeology and geotechnical engineering textbooks. Their influence on freezing dynamics is outlined briefly here.

The surface energy of curved--liquid interfaces plays a role that is similar to that played by the surface tension of liquid--vapor interfaces. Under warmer conditions, surface tension enables liquid to hang above the water table within pendular rings at sub-atmospheric pressures. The curvature of the liquid--vapor interface can attain a value such that the liquid pressure is in equilibrium with the vapor concentration of the air immediately adjacent to it. At colder temperatures with the air replaced by ice, a similar liquid interface geometry is found above the lowest extent of pore ice because the energy required to maintain small liquid volumes at sub-zero temperatures is less than the surface energy that would be required for the ice surface to conform more closely to the geometry of the particles near their contacts. As the temperature cools, the ice penetrates increasingly further into confined regions and causes the liquid volumes in pendular rings to shrink (labeled as “pendular vols.”)

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liquid" in Fig. 1). Interestingly, except for the small displacements
required by the density contrast, this change in liquid fraction can be
accommodated by freezing rather than by water transport (for further
discussion, see Worster and Wettlaufer, 2006). The water present
because of surface energy is nevertheless important for determining the
permeability to fluid flow through the frozen fringe.
Surface energy effects only cause liquid water to be present at sub-
zero temperatures where the ice interface is convex outwards. At sub-
zero temperatures along flat interfaces, and notably along the
predominantly concave interfaces that separate the ice lens from
the particles that lie directly beneath, a different physical mechanism
is required to allow liquid water and ice to coexist. The phenomenon
known as interfacial premelting is crucial for causing thin films to
separate the ice and particle surfaces (see Fig. 1) and enable the liquid
transport that is needed along an ice-lens surface during growth (e.g.,
Dash et al., 2006; Rempel et al., 2004). The long-range intermolecular
forces that act between the ice, the water, and the mineral surfaces are
analogous to those that produce the swelling of some clays and the
rich variety of other colloidal interactions that occur within
groundwater flows. Interfacial premelting occurs when these long-
ranged intermolecular forces (e.g., van der Waals forces, double-layer
forces) are made less energetic by the insertion of a liquid layer to
separate the ice and mineral surfaces. Effectively, ice is “wetted” by its
own melt.

The controls on interfacial premelting are shown schematically in
Figure 2. The interfacial contribution to the total free energy is
represented by a dashed curve that decreases with film thickness d. At
larger separations, the interfacial energy \( I(d) \) trends downwards
and remains positive (as in a monotonically decreasing contribution to
the free energy in an ice-particle system). The total free energy is minimized at the equilibrium film thickness shown by the asterisk.

The total free energy encompasses both interfacial and bulk
contributions. The free energies of the liquid and solid phases are
equal at the normal melting temperature \( T_m \). At any subzero
temperature \( T \), however, the free energy of liquid water is greater
than that of solid ice. Accordingly, the dotted line in Figure 2 shows
the increase in bulk free energy that is associated with increasing the
thickness of liquid. The rate of increase rises as \( T \) falls further below \( T_m \),
so the slope of the dotted line is proportional to \( T_m - T \). The equilibrium
configuration is reached when the total free energy is at its lowest and
a small change in film thickness would cause gains and losses to the bulk
the ice and mineral surfaces. Effectively, ice is “wetted” by its

own melt.

### Ice segregation model

In a fully saturated, incompressible porous medium, the rate of
growth of a segregated ice lens \( V_L \) is proportional to the rate of water
transport. Changes in this growth rate are small enough that inertia is
negligible and the forces acting on the ice lens are balanced. This implies
that the integrated fluid pressure over the ice surface from the fringe
depth is found as $\theta = 1 - \phi$.

The integral on the left represents the non-hydrostatic part of the
equation can be approximated as $\theta = 1 - \phi$.

The conditions for lens initiation are key to predicting the
The second term accounts for gravitational

The buoyancy ratio $\nu \equiv (1 - \phi)/(\rho_f - \rho)g/\rho = (1 - \phi)/(\rho_f - \rho)gT_z/(pCDT/\Delta z)$ measures the relative importance of gravitational

Figure 3 illustrates the behavior of these functions for the case of

Lens spacing

Together, Eqs. (5) and (6) predict the spacing between lenses (or

The thickness of an ice

The thickness of an ice

The small density

The conditions for lens initiation are key to predicting the

The functions $\Gamma_1(\theta)$ and $\Gamma_2(\theta)$ are defined as

$\Gamma_1(\theta) \equiv \int_0^1 (1-\phi) = 1 - \phi$.

$\Gamma_2(\theta) = (1 - \phi) = 1 - \phi$.

$\phi(\theta^{1-\beta} - \beta) + \Delta \phi \theta^{1-\beta} + \phi^2 \theta^{2\beta - 2\beta}$.

$\phi(\theta^{1-\beta} - \beta) + \Delta \phi \theta^{1-\beta} + \phi^2 \theta^{2\beta - 2\beta}$.

$\phi(\theta^{1-\beta} - \beta) + \Delta \phi \theta^{1-\beta} + \phi^2 \theta^{2\beta - 2\beta}$.

$\phi(\theta^{1-\beta} - \beta) + \Delta \phi \theta^{1-\beta} + \phi^2 \theta^{2\beta - 2\beta}$.
equal to the distance over which the temperature changes by the
characteristic amount $T_m - T_i$; from this it follows that $G_l$ marks the
number of times by which the lens spacing exceeds this characteristic
distance. Not surprisingly, the scaled spacing between lenses $G_l$ is found
to increase with $N/p$. The precise form of the dependence shown in
Figure 4 is also influenced by the porosity $\phi$ and the exponents $\alpha$ and $\beta$
that describe the constitutive behavior of the sediments; the role played
by these parameters is illustrated in Figure 6 and will be discussed later.

Interestingly, it turns out that the lens spacing that is predicted from these
calculations has no direct dependence on the ice-free permeability $k_w$
which is typically one of the more uncertain parameters in the natural
physical system.

For a quantitative example, consider the case where the liquid
pressure at the base of the fringe and the weight of overlying material are
both proportional to the depth below the ground surface $H$ so that
$N \approx (\rho_b - \rho_f)gH$, where $\rho_b$ is the average density of material above the
fringe base. For example if the total heave, or thickness of overlying lenses,
is much less than $H$ then $\rho_b \approx (1 - \phi)\rho_f + \phi$, in such circumstances
$N \approx p_f (\rho_b - \rho_f) gH / \phi \approx (8.1 \times 10^{-3}) H / (T_m - T_i) \ C / m$
when $p_f \approx 200 \ p_a$. The scaled fringe thickness is $G_l = |dT/dz|/|T_m - T_i|$, which
marks the same inverse dependence on the temperature scale $T_m - T_i$. Using the freezing parameters of Chena silt (Andersland and
Hallet, personal communication). The inferred temperature gradients
obtained in this way might be used to test scenarios for the environmental
forcing at a particular location; for example, higher temperature gradients at a given depth can be interpreted to imply a
greater heat flux from the ground surface and a more abrupt onset of
freezing, as would be expected to accompany colder temperatures.

**Lens thickness**

The lens thickness $h_l$ depends on the rate of freezing and the
integrated history of lens growth, so $h_l$ is sensitive to $k_w$. For the same
ice saturation and permeability functions as those used above, Eq. (3)
predicts that the lens growth rate satisfies

$$V_l = \frac{V}{\Gamma_1 |\theta'|} \left[ \theta_l |1 - \phi| + \phi \frac{\beta}{\nu - \beta} \theta_l |\nu - \beta| - \frac{N \nu}{p_f} + \nu (\theta_l - 1) \right],$$}

where the characteristic velocity scale is defined as $V \approx k_w p_a G / g$
and $\gamma = k_w p_a |dT/dz|/|T_m - T_i|$. The lens thickness depends on how much
growth can occur during the time taken for its reduced temperature to
where \( \dot{\theta}_0 \) is determined by the transport of latent and sensible heat. For simplicity, consider the case where the duration of lens growth is short in comparison with the time over which \( \dot{\theta}_0 \) undergoes significant change. This is expected to be the case when the heat flux towards the ground surface at depth \( H \) greatly exceeds the latent heat required for the lens and fringe ice to grow. Figure 5 shows the scaled lens thickness that is predicted to result, plotted as a function of \( N/p_l \) for the same parameter choices used to generate the predictions for scaled lens spacing shown in Figure 4. At higher levels of \( N/p_l \), the increased lens spacing shown in Figure 4 indicates that lens growth occurs over a broader temperature range. However, since the temperature needs to be colder at lens initiation in order to support larger gravitational loads, the initial fringe thickness increases with \( N/p_l \) and the rate of water supply is increasingly restricted by the ice-clogged pores. This has the effect of reducing the initial rate of lens growth \( \dot{V}(t_l) \) and the integrated result predicted by Eq. (8) is a decrease in \( L_i \) with \( N/p_l \), as shown in Figure 5.

For a quantitative illustration, using the behavior of Chena silt again and the simple dependence of \( N \) on depth described above, with \( H = 0.1m \) so that \( N/p_l \approx 0.026 \), the asterisk in Figure 5 indicates that \( L_i \dot{\theta}_0 / V \approx 1.1 \), whereas the plus sign marks a value of \( L_i \dot{\theta}_0 / V \approx 0.14 \) when the depth \( H \) and \( N/p_l \) are increased tenfold. The unfrozen permeability of Chena silt is \( k_{0s} = 4.1 \times 10^{-17} \text{m}^2 \) (Andersland and Ladanyi, 2004) so the velocity scale \( v \approx 2.5 \times 10^{-4} \text{m/s} \) can be used to estimate the rate at which the freeze front advances. Estimates for both the temperature gradient and the rate of change of reduced temperature at the lens boundary are needed to predict \( L_i \). Note that \( \dot{\theta}_0 = (T_l - T_i) \dot{d}T_l/\dot{d}t \) so that with \( T_i - T_0 = 0.031 ^\circ \text{C} \) and the lens temperature decreasing at a rate of \( \dot{T_l} = 0.031 \text{ °C day}^{-1} (1.2 \times 10^{-3} \text{ °C s}^{-1}) \), the rate of change of reduced temperature is \( \dot{\theta}_0 \approx 3.7 \times 10^{-4} \text{ °C s}^{-1} \). For a temperature gradient of \( \text{d}T_0/\text{d}z = 10 \text{ °C m}^{-1} \), the predicted lens thickness at \( H = 0.1m \) is \( L_i \approx 7.4 \times 10^{-4} \text{ m} \) and \( L_i \approx 9.5 \times 10^{-5} \text{ m} \) at \( H = 1m \). These calculations suggest that for the lens thickness to increase with depth as is often seen, the ratio of \( \text{d}T_l/\text{d}T_i \) must increase with depth to offset the decreased predicted change in \( L_i \dot{\theta}_0 / V \) with \( N/p_l \) that is shown in Figure 5. For example, if \( \text{d}T_l/\text{d}T_i \) were to stay approximately constant as \( \text{d}T_0/\text{d}z \) decreased in proportion to the freezing depth, reaching \( \text{d}T_0/\text{d}z \approx 1 \text{ °C m}^{-1} \) at \( H = 1m \), these calculations predict that \( L_i \) would increase slightly from 0.74mm at \( H = 0.1m \) to 0.95mm at \( H = 1m \). It should be recognized as well that the assumption used here of a linear increase in \( N \) with \( H \) should be used with caution since the water pressure at the fringe base in a particular field setting is governed by local hydrogeological considerations.

Experiments by Penner (1986) provide a qualitative test of predicted changes in lens thickness with experimental parameters. Using inter-layered samples of Leda clay against a mixture of Fairbanks silts, meant to represent varved sediments, Penner applied a constant imposed stress and ramped the temperatures at both ends of his samples at a controlled rate. The temperature gradient through the fringe can be estimated from the isotherms plotted in his Figure 6 as nearly constant at between 90 and 100 °C/m throughout the experimental duration. Just prior to the formation of his numbered lens 7, the rate of temperature change imposed on both sample boundaries was decreased by a factor of 5. The thickness of lens number 6 inferred from the heavy accumulation reported in his Figure 5 was 0.5 mm, whereas the thickness of lens number 8 was 2.3 mm—representing an increase by a factor of 4.6. This is roughly consistent with the expected five-fold increase predicted by the current model under the assumption that the rate of change of temperature at the lens-fringe interface is comparable to the imposed rate of change of temperature at the sample boundaries.

It should be noted that the thicknesses of the “varves” in these experiments were a controlling factor in determining lens spacing since lens nucleation tended to occur along each silt-to-clay interface. However, consistent with expectations for a cooling lens boundary with a progressively decreasing nearby permeability and increasing fringe thickness, the experimental data reported in Penner’s Figure 7 shows that heave was much less rapid during the later stages of growth for each lens than the average over the lens lifetime. Therefore the thickness data is interpreted to be only weakly influenced by the varved nature of the experimental medium and hence the reported change in lens thickness following immediately upon a change in cooling rate provides qualitative support for the current model.

More accurate predictions for the lens thickness \( L_i \) under field conditions require a proper treatment of the temperature evolution through time. From a practical standpoint, such calculations are much more involved than those entered into here (e.g., Rempel, 2007), and they also require considerable knowledge or assumptions about the environmental forcing. In contrast, \( L_i \) is predicted to primarily depend on only the dimensionless load \( N/p_l \) and the scaled temperature gradient \( G \), but not at all on the unfrozen permeability \( k_0 \) or the rate at which the lens temperature changes. In testing scenarios for past environmental forcing using temperature gradient estimates obtained from measured lens spacings, a set of measured lens thicknesses could provide a valuable additional constraint.

**Discussion**

The calculations shown here suggest that observations of the spacing between lenses \( l \) hold potential for inferring the fringe temperature gradient during lens growth. As a complicating factor, the expected lens spacing depends also on the effective stress \( N \) and certain properties of the sediments. Figure 6 illustrates the sensitivity of \( L_i \) to a) the porosity \( \phi \), b) the empirical permeability exponent \( n \) (i.e., from the power law used to describe the reduction in permeability with reduced temperature \( k = k_0 \theta^{-n} \)), and c) the ice saturation exponent \( \beta \) (i.e., from the power law used to describe the increase in ice saturation with reduced temperature \( S_1 = 1 - \theta^{\beta} \)). For any particular \( N/p_l \) at higher porosities the fringe contains a larger volume of ice and is more effective at transmitting forces to the particles beneath a given level; this facilitates lens initiation and results in decreased lens spacing. Larger values of the permeability exponent \( n \) lead to more rapid changes in \( k \) with reduced temperature so that the liquid pressure gradient becomes steeper close to the lens boundary. Because this tends to increase the average fluid pressure nearer to the lens boundary, there is a corresponding reduction in the total force that must be transmitted by the ice to unload the sediment contacts at \( z_a \); this also results in smaller lens spacing. Larger values of \( \beta \) correspond to more rapid increases in ice saturation with \( \theta \). Just prior to lens initiation, if the fringe is sufficiently thick that the rate of lens growth \( V_l \rightarrow 0 \), Eq. (4) describes how the gradient in \( p_f \) near the fringe base is primarily controlled by the gradient in \( S_1 \), which is higher for larger \( \beta \) and promotes initiation at smaller \( z_a \). Conversely, since larger values of \( \beta \) tend to cause the pore space to become clogged with ice more rapidly, this leads to lower \( V_l \) for any given fringe thickness and promotes initiation at smaller \( h \). Figure 6c indicates that these effects combine to give a predicted lens spacing \( L_i \approx h - z_a \) that decreases with \( \beta \) at low \( N/p_l \) but increases with \( \beta \) at high \( N/p_l \).

The temperature scale \( T_l - T_i \) is needed to translate the scaled axes in Figures 4–6 into dimensional terms. Recall that \( T_l \) represents the temperature to which pore ice can extend beneath the lens and is limited by the curvature \( K \) that is needed to penetrate pores, as described by Eq. (2). Since the required \( K \) depends primarily on the size distribution of mineral particles, it is these geometrical details that ultimately control the value of \( T_l \). Andersland and Ladanyi (2004) compiled data for a broad range of different sediment types, and where the specific surface area \( SSA \) was also known the data suggest a correlation of the form \( T_l - T_i \approx 4.3 \times 10^{-6} \text{SSA/(1m}^2/\text{g}) \times 1.5^\circ \text{C} \) (see...
Further empirical measurements of $T_m - T_f$ for the sediment types of interest in specific field settings would provide increased confidence in the validity of this fit. However, even allowing for uncertainty in the precise value of $T_m - T_f$, it is clear from the discussion above that changes in lens spacing that are observed in a given sediment can be used to infer changes in $N$ and $|dT/dz|$.

The quantitative examples from the previous section illustrate the predicted behavior when $N$ increases linearly with depth $H$. Caution should be exercised in cases where groundwater flow through low permeability, heterogeneous sediments might complicate profiles of $N$ to such an extent that this assumption is not warranted. Even for a well-characterized sediment with known values of $T_m - T_f$, $\phi$, $\alpha$ and $\beta$, a single set of measurements of $l_l$ should not be viewed as sufficient to uniquely determine the values of $N$ and $dT/dz$. However, a suite of such measurements does allow for the discrimination of certain combinations of $N$ and $dT/dz$. Moreover, at lower values of $N/p_f$, the form of the curves in Figures 4 and 6 suggest that the lens spacing responds primarily to changes in the magnitude of the temperature gradient $dT/dz$; this diminishes the degree to which interpretations of past temperature gradients can be affected by uncertainties in the past hydrologic conditions that helped to set the precise value of $N$.

The predictions shown here have been made while treating the temperature gradient through the fringe as constant. In actual fact, during secondary frost heave the temperature at a given location within the fringe progressively cools and this implies that $S_i$ increases locally so that the latent heat of fusion contributes to the heat balance and causes $dT/dz$ to vary spatially. More involved treatments that solve for the changing temperature profile within the fringe suggest that variations in $dT/dz$ do not significantly change the essential patterns of ice growth.
The segregation of ice into lenses that exclude mineral particles is a key aspect of the development of many permafrost features. At its heart, this behavior is caused by the influence of the mineral particles on the equilibrium phase behavior of water and ice. The net thermodynamic buoyancy force that results can be used as an ingredient of larger-scale models of freezing behavior to predict the initiation and growth of ice lenses. Using empirical formulations for the sediment freezing behavior, predictions can be made for how environmental controls determine the spacing and thicknesses of ice lenses. An approximate treatment demonstrates that the main controls on lens spacing are the effective stress at the furthest extent of pore ice, the temperature to which the ice extends, and the temperature gradient between that depth and the base of the overlying, active ice lens. The lens thickness depends additionally on the rate of change of lens temperature and the permeability of the ice-free sediments. This analysis suggests that observations of lens spacing and hold promise for inferring the environmental conditions during ice emplacement. Observations of lens thickness are expected to be more difficult to interpret because of the greater sensitivity to parameters that are more difficult to constrain. These considerations bring to mind Washburn’s observation in the concluding paragraph of his paper summarizing the use of permafrost features as evidence of climatic change (Washburn, 1980), namely that: “…permafrost evidence, despite numerous problems, appears to offer the exciting prospect of some quantitative and rather precisely limiting terrestrial temperature parameters that may not be obtainable in any other way.” Whether this prospect is to be realized in the case of ice lens data has yet to be fully judged.

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Hallet, B., Walder, J.S., Stubbs, C.W., 1991. Weathering by segregation ice growth in unconsolidated porous media. Much of the frost damage that occurs in rocks and other cohesive materials can be traced to the same underlying physical mechanisms (e.g., Hallet et al., 1991; Matsuoka et al., 2001; Matsuoka and Burton, 2008; Burton et al., 2006; Walder and Hallet, 1985). Liquid water is drawn towards freezing centers by the liquid pressure gradients that are required to balance the ice–mineral forces that act across interfacially melted films at colder temperatures. Rather than the growth and initiation of new lenses, however, the extension of pre-existing fractures is in this case a much more important control on the extent of frost damage.

Conclusions

The segregation of ice into lenses that exclude mineral particles is a key aspect of the development of many permafrost features. At its heart, this behavior is caused by the influence of the mineral particles on the equilibrium phase behavior of water and ice. The net thermodynamic buoyancy force that results can be used as an ingredient of larger-scale models of freezing behavior to predict the initiation and growth of ice lenses. Using empirical formulations for the sediment freezing behavior, predictions can be made for how environmental controls determine the spacing and thicknesses of ice lenses. An approximate treatment demonstrates that the main controls on lens spacing are the effective stress at the furthest extent of pore ice, the temperature to which the ice extends, and the temperature gradient between that depth and the base of the overlying, active ice lens. The lens thickness depends additionally on the rate of change of lens temperature and the permeability of the ice-free sediments. This analysis suggests that observations of lens spacing and hold promise for inferring the environmental conditions during ice emplacement. Observations of lens thickness are expected to be more difficult to interpret because of the greater sensitivity to parameters that are more difficult to constrain. These considerations bring to mind Washburn’s observation in the concluding paragraph of his paper summarizing the use of permafrost features as evidence of climatic change (Washburn, 1980), namely that: “…permafrost evidence, despite numerous problems, appears to offer the exciting prospect of some quantitative and rather precisely limiting terrestrial temperature parameters that may not be obtainable in any other way.” Whether this prospect is to be realized in the case of ice lens data has yet to be fully judged.

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