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Modeling relative frost weathering rates at geomorphic scales

Alan W. Rempel [a,*], Jill A. Marshall [b,c], Joshua J. Roering [a]

[a] Department of Geological Sciences, University of Oregon, Eugene, USA
[b] Department of Earth and Planetary Science, University of California, Berkeley, USA
[c] Institute of Arctic and Alpine Research, University of Colorado, Boulder, USA

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ABSTRACT

Frost damage is a powerful agent of geomorphic change. Cracks can grow when the ice pressure in pores reaches a threshold that depends on matrix properties and crack geometry. Mineral surfaces that are preferentially wetted by liquid water rather than ice are coated by premelted liquid at a pressure that is lower than the ice pressure. Because this pressure difference increases as the temperature cools, when the ice pressure is effectively pinned at the cracking threshold, temperature gradients induce gradients in liquid pressure that draw water towards colder temperatures. Porosity increases and frost damage accumulates in regions where water supplies crack growth. To apply this understanding over the large spatial and temporal scales that are relevant to evolving landscapes, we develop a simple model that tracks porosity changes. Our central assumption is that frost damage is correlated with porosity increases under conditions where frost cracking takes place. Accordingly, we account for the permeability reductions with decreased temperature that accompany ice growth along porous pathways and derive general expressions for the porosity change through time at particular depths, as well as the total porosity increase through all depths beneath a point at the ground surface over the time during which cracking occurs each year. To illustrate the resulting patterns of frost weathering, we consider a general case in which the permeability has a power law dependence on temperature and the annual surface-temperature variation is sinusoidal. We find that the degree of frost damage generally decreases with depth, except at localized depths where damage is elevated because the rock spends longer times near the threshold for cracking, leading to enhanced water supply in comparison with neighboring regions. The magnitude of the net expansion that results from porosity changes at all depths beneath the ground surface is increased for seasonal thermal cycles with larger amplitudes, with a broad maximum centered on a mean annual temperature near the threshold required for crack growth. Warmer mean annual temperatures lead to less damage because of the reduction in time during which it is cold enough for cracking, whereas colder mean annual temperatures are accompanied by reduced water supply due to the temperature dependence of permeability. All of the controlling parameters in our model are tied explicitly to physical properties that can in principle be measured independently, which suggests promise for informing geomorphic interpretations of the role of frost weathering in evolving landforms and determining erosion rates.

1. Introduction

Ice formation is widely recognized as a leading agent of physical weathering in nature (e.g. French, 2013; Hall, 2004; McGreevy and Whalley, 1982; Ollier et al., 1984) and costly deterioration to the built environment (e.g. Coussy, 2005; Ho and Gough, 2006; Scherer, 1999). Such frost damage takes place when the pressure exerted against pore walls exceeds the cohesive strength of moist porous media and causes cracks to extend. The density change upon solidifying liquid water (density ρ_l) into ice (density $\rho_i \approx 0.9\rho_l$) can cause significant pressure increases (e.g. Davidson and Nye, 1985). However, the effectiveness of this particular mechanism in isolation is limited because the density change drives water flow away from the solidification front into unfrozen or unsaturated pore space, which precludes the generation of stress concentrations sufficient to propagate cracks (Hallet et al., 1991). Instead, the efficacy of frost damage stems from the common tendency for liquid to flow in the opposite direction and supply crystal growth so that the mass of ice in the frozen pore space exceeds the mass of water that was present initially at warmer tempera-

* Corresponding author.
E-mail address: rempel@uoregon.edu (A.W. Rempel).

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tures (e.g. Akagawa and Fukuda, 1991; Taber, 1930). (A particularly convincing demonstration of this physical mechanism was first revealed by Taber (1930) through experiments that demonstrated "frost" expansion during the freezing of two liquids, benzene and nitro-benzene, that have higher densities in their solid states.) This flow is a consequence of the phase behavior, referred to as *interfacial premelting*, that induces liquid water to wet interfaces between the pore walls and ice at temperatures T that are colder than the normal bulk melting temperature T_m (e.g. Dash et al., 2006; Wettlaufer and Worster, 2006). Changes in the strength of the interfacial forces that cause this wetting behavior produce liquid pressure gradients that commonly are aligned with gradients in temperature. These liquid pressure gradients drive the redistribution of water mass that is a defining characteristic of the range of phenomena that result from *segregation ice growth*, which has enjoyed a particularly long history of study in the context of frost heave (e.g., Rempel, 2010). More recently, this mechanism has been invoked to explain spatial and temporal variations in erosion rate (e.g. Delunel et al., 2010; Hales and Roering, 2005; Marshall et al., 2015), yet the basis for relating the physics of this process to geomorphic work requires justification. Here, we consider segregation ice growth in cohesive porous media and present a mechanistic description that is amenable for application over the large spatial and temporal scales relevant for understanding the role of frost weathering in landscape evolution.

While the detailed thermo-mechanical interactions that produce frost damage can be influenced by the density change upon freezing and ubiquitous dissolved salts, the essential behavior can be understood without these complicating factors. The equilibrium presence of liquid water below T_m (i.e. 273 K) is accompanied by a difference between the ice and liquid pressures (Dash et al., 2006). As T drops so that the *undercooling* $\Delta T \equiv T_m - T$ increases, there is a proportional increase in the strength of the intermolecular forces that both give rise to this pressure difference and enable ice to exert pressure against the pore walls across the intervening premelted liquid (Dash, 1989; Rempel et al., 2001). The total force exerted on the solid matrix must be balanced and the resistance to deformation is inevitably characterized by stress concentrations near the tips of crack-like regions where the pore surface curvature is high. Frost damage occurs when conditions are not only sufficiently cold that the net pressure exerted against the pore walls pushes the stress concentrations to levels where the matrix material fails and fractures, but also warm enough to enable the liquid flow that supplies ice growth into the newly opened space (Hallet, 2006; Walder and Hallet, 1985). The range of temperatures that meet these criteria has been used to define a "frost-cracking window" within which most damage takes place (Anderson, 1998).

The mechanics that control frost damage in idealized systems have been examined in considerable detail using both theoretical and experimental approaches (e.g. Murton et al., 2006; Vlahou and Worster, 2015; Walder and Hallet, 1985). Some of the resulting insights have been incorporated within several parameterized measures that are designed to gauge differences between the relative intensity of frost damage expected at the much larger scales relevant to geomorphic change. The simplest of these formulations associates relative frost damage with the total time spent within a frost-cracking temperature window (e.g. $-8\,^\circ\mathrm{C} < T < -3\,^\circ\mathrm{C}$, see Anderson, 1998). Noting the direct relationship between temperature gradients and the pressure gradients that drive the liquid flow needed to supply ice growth in cracks, a second measure of the tendency for damage weights the time within the frost-cracking window by the temperature gradient, while also requiring the presence of a flow path along which the temperature cools monotonically from positive values (Delunel et al., 2010; Hales and Roering, 2007, 2009; Marshall et al., 2015; Savi et al., 2015). A variant on this approach prioritizes hydraulic resistance by deploying the distance between an unfrozen liquid source and the potential frost-cracking location within an exponential penalty function that modifies the gradient-weighted time integral (Anderson et al., 2013; Scherler, 2014); the weighting function has also been augmented to include a dependence upon the volume of liquid present along connected flow paths (Andersen et al., 2015). The patterns of frost damage predicted by these methods share common features, but there are also significant differences. Moreover, it is not obvious how changes to some of the basic physical parameters that are known to control frost damage in idealized systems can best be represented. Although it is not practical to detail the evolution of each crack-like pore that is subject to freezing conditions within a given landscape, improved confidence in predictions for the patterns of frost damage through space and time can be gained by revisiting and building upon the mechanical understanding achieved in studies of the incremental damage that accumulates in simple systems. The study of crack growth in bergschrunds by Sanders et al. (2012) is notable for taking the direct approach of tracking crack extension at a discrete series of depths and developing a frost damage index based upon an ensemble average of outcomes from calculations that sample a distribution of controlling parameters. Here, we take a continuum approach and retain the computational simplicity of earlier qualitative damage indices that do not explicitly track the evolution of discrete cracks; instead, we associate the propensity for damage with the accumulation of ice that increases porosity in locations were cracks can grow.

In discussing the implications of earlier field and laboratory work, McGreevy and Whalley (1982) suggested that "it would seem reasonable to assume that for most rocks the degree of frost damage can be equated with the amount of ice (that) forms in them during freezing". The mechanical interactions that determine the degree to which ice-filled pores can expand and produce frost damage are now understood well enough to make quantitative predictions for ice accumulation through space and time. Because the permeability to liquid flow decreases sharply with temperature in frozen porous media, the total water flux along a flow path largely driven by the temperature gradient must drop as the temperature decreases; mass conservation ensures that porosity increases as a result and frost damage accumulates provided that the ice exerts sufficient stress in the porous medium to propagate cracks. In essence, rather than explicitly tracking crack growth, the generation of porosity is treated here as a measure of frost damage induced by segregation ice. We show how the measurable parameters that characterize a given setting (including rock properties) and thermal history combine to determine the spatial and temporal patterns of damage that are implied by this connection. To forecast the degree of frost damage at larger scales, we show how the annual temperature variation at the ground surface can be combined with considerations of heat and mass transport to quantify the ice-induced expansion of porous materials during the portion of the year in which frost-cracking is active beneath a particular location. This enables an estimate of the potential for frost damage that is tied explicitly to the increase in water mass that accompanies ice formation.

2. Porosity changes during freezing

The basic premise underlying our treatment is that the frost damage caused by crack growth correlates with increases in porosity that are made possible through water supply to growing ice. Any valid description of these processes must account for the controlling thermo-mechanical properties and phase behavior, as well as the evolving environmental conditions. In this section, we begin by outlining the simplest set of assumptions that is needed to develop such a model. We then explore the model predictions that follow, before moving on to discuss some of their implications for