Earth Surf. Dynam. Discuss., 3, C239–C244, 2015
www.earth-surf-dynam-discuss.net/3/C239/2015/

Interactive comment on "The periglacial engine of mountain erosion – Part 1: Rates of frost cracking and frost creep" *by* J. L. Andersen et al.

J. L. Andersen et al.

jane.lund@geo.au.dk

Received and published: 12 August 2015

We thank the reviewer for the many constructive and supportive comments. We find that the insightfull remarks have helped us to strengthen the manuscript.

In this reply we comment on all remarks given by the reviewer and present the associated changes to the manuscript. The comments have been copied into this document in grey and are marked with C for comment and a sequential number. The corresponding response is marked with R.

Reviewer 2: J. Roering

This well-written manuscript is a straightforward and well-structured analysis of how mean annual temperature and sediment (or soil) thickness may influence the vigor of

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper

frost cracking and frost creep. The quantification of such periglacial processes has become very important for interpreting modern erosion rates as well as deciphering the inheritance of past climate regimes in landforms. I read this manuscript with great interest because my PhD student Jill Marshall and I (with the guidance of our collaborator Alan Rempel) have been digging into the theory of frost weathering processes given our hypothesis that these processes may be responsible for increased erosion rates during the Last Glacial Maximum (LGM) at our western Oregon study site. As detailed in a manuscript submitted last fall and in her 2014 AGU abstract, Jill used cosmogenic nuclides to quantify paleo-erosion rates (>2.5x faster than modern) during the LGM from a 60-m deep sediment core of 50ky-old lake deposits. To be frank, the possibility of frost-driven erosion at our site surprised us and this encouraged us to delve into relevant paleoecology and paleoclimate data with the help of paleoclimate colleagues. Those datasets indicate that LGM conditions at our study site were cold/dry and likely cold enough for frost processes to be prevalent. That said, different interpretations of frost cracking and frost creep theory and experiments predict that different conditions (such as mean annual temp, temperature amplitude, and sediment thickness) are required for these periglacial processes to become relevant. In other words, it's important to properly translate the physics of frost cracking and frost creep when interpreting modern erosion rates or using climate reconstructions to track geomorphic processes back in time. The notion that unglaciated landscapes may be polygenetic (borne of multiple climate/forcing regimes) is the central motivation of Jill's manuscript and dissertation and she discovered that geomorphologists have been vexed by this notion since L. Agassiz documented the diagnostic signature of previously glaciated landscapes. That is a rather long-winded means to say that the type of work contained in this paper is compelling and timely! In fact, Jill became aware of this manuscript from an EGU abstract by the authors and initiated fruitful interactions with the authors via email and a discussion at AGU/Gilbert Club. The authors revisit the conditions that promote frost cracking and frost creep processes and use a parameter-rich numerical model to condense the output with respect to mean annual temperature and

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper

sediment thickness. Again, this framework is well motivated and the authors conducted an impressive number of calculations. Mean annual temp and sediment thickness are among the dominant variables that govern the vigor of frost processes and the results presented here show that to be the case given the theoretical framework adopted here. The manuscript does a very nice job of synthesizing rather complicated models into digestible plots. The authors also lay out the evolution of frost cracking models, including those by Bob Anderson and TC Hales. The central contribution of this study is their revision to the frost cracking model which incorporates a water availability function that accounts for the distribution of free water relative to the zone of predicted frost cracking. In doing this, the authors have advanced a very elegant modeling study by Bob Anderson that uses a penalty function to incorporate the influence of water availability on frost cracking potential. In the present contribution, frost cracking intensity is modeled as the product of the thermal gradient when rock is in the frost cracking window (which is the only term in the TC Hales formulation) and a term that accounts for water availability along the path of a positive thermal gradient. In detail, this additional term is an integral of porosity, water fraction, and an exponentially weighted length scale, which reduces to the same implementation of Bob Anderson given particular parameter choices. When compared with previous studies (particularly Hales and Roering, 2007), the effect of including this additional term is to greatly reduce the predicted intensity of frost cracking for mean annual temperatures above zero because on cold, winter nights water is not proximal to the cracking zone (pg 298, line3:16). This has the effect of restricting substantial frost cracking for MAT>0 to areas with very thin soils (<20cm) where the effect of latent heat doesn't stall the freezing front as it does for thicker soils. The approach taken here is very well executed and the results have important implications for interpreting our LGM erosion rates, which are associated with LGM MAT values of 0 to 1 deg C.

C-2.1: The strong climate dependence invites an examination of the pre-melted film and frost cracking literature, particularly with regard to how one accounts for water availability. First, the notion that ice segregation can only cause water to flow from warm

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper

to cold areas (pg. 290, line 1-2) is not strictly true. Instead, ice segregation occurs due to a pressure gradient that becomes established due to differential disjoining forces, which do depend on temperature but also vary with crack or pore size and geometry (e.g., Rempel et al, JFM, 2004; Dash et al, Rev Modern Phys, 2006). Thus, all else equal a temperature gradient does imply a pressure gradient but this is not required.

R-2.1: We thank the reviewer for providing the links to the literature listed. We agree that the temperature gradient is not alone in establishing the pressure gradient driving ice segregation. We have emphasised that this is, however, the basic assumption of our frost-cracking model, and based on the reviewer's comment and the papers cited, we have improved the discussion of this limiting assumption.

C-2.2: With regard to the water availability function (equation 15), this formulation implies that the temperature gradient is applied across a particular length scale (here defined as an integrated water migration distance). This choice has the effect of penalizing very cold temperatures because of clogged pores that block water flow. This treatment may have utility but the pre-melted film literature does not imply that water becomes limited in these cases but rather that films can continue to become available from ice in pores as water gets cannibalized at the freezing front. In this sense, the extent to which water migration distances influence cracking doesn't emerge from pre-melted film theory. Instead, hydraulic conductivity is highly sensitive to temperature when temps are cold (temps < 1 deg C) and thin films dominate flow. Thus in this regime, small changes in temp (and pore geometry as indicated earlier) dominate the flow of water to the freezing front rather than the store of available water. It may be that the formulation proposed here can account for these effects in some circumstances, but that connection is not clearly established here. Jill communicated some of this thinking to the authors through emails in fall 2014 and some of that exchange appears to emerge in the discussion section 5.4 (p 308, line 13-25). Importantly, the Matsuoka paper cited in that section shows that water is important to frost cracking but does not imply that a penalty function is relevant for regulating the intensity of frost cracking.

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper

R-2.2: We agree that the penalty function used for scaling the water availability represents a weakness in the model as it is not well founded in physics. The water transport penalty function was introduced by Anderson as a simple and intuitive way to reduce a clearly unphysical behaviour of previous models, where very subtle temperature changes around 0 C deep in the subsurface essentially switches cracking off and on at the surface. Based on its weak link to physics, we included a sensitivity analysis of the penalty function and discussed its implications. In order to explore the effects of the penalty functions, we thus compared a model with four different penalty length scales, to a model with only one length scale, and to a model without any water transport penalty. Based on the reviewer's comments we have been able to extend and strengthen the discussion of the water availability function in the new version of the manuscript, and we hope that readers can clearly see that this aspect of the model needs further consideration in the future.

C-2.3: The frost creep component of the model follows the theoretical underpinnings of Davison and Bob Anderson more recently. My main comment is that the integral in equations 19 and 20 is a bit challenging to decipher and could perhaps be simplified. This term essentially constitutes a switch for frost heave, but it's not clear that it accounts for the rate limitation: lenses don't grow if freezing is fast (e.g., diurnal cycles) and infinite lenses can grow given very slow cooling. Perhaps a simpler function accounting for the frost heave switch would help clarify the vigor of this term. Overall, this manuscript is a timely and important contribution to our understanding of a fascinating suite of processes whose physics are challenging to purely and unambiguously link with climate parameters. On one hand, it might be advisable to opt for simplicity in these situations, but on other hand exploring a range of possibilities can be fruitful and informative and this manuscript does that.

R-2.3: We agree that this aspect of the frost creep model was presented in too dense a form. We have now expanded the deviation of equation 19 into several simpler steps. We have also explained the rate limitation better and added a reference to section 3.1

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper

(eq. 13). Essentially, frost creep is limited by the change in water fraction, which in turn is governed by the transient heat equation. The change in water fraction, and thus frost creep, is therefore rate limited by thermal diffusion and exchange of latent heat, which is in agreement with the reviewer's comment.

Interactive comment on Earth Surf. Dynam. Discuss., 3, 285, 2015.

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper