Solifluction patterns arising from competition between gravity and cohesion

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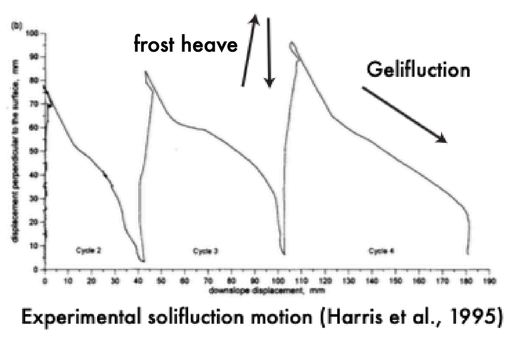
Arctic soil movement, accumulation and stability exert a first order control on the fate of permafrost carbon in the shallow subsurface and landscape response to climate change. A major component of periglacial soil motion is solifluction, in which soil moves as a result of frost heave and flow-like "gelifluction". Because solifluting soil is a complex granular-fluid-ice mixture, its rheology and other material properties are largely unknown. However, solifluction commonly produces distinctive spatial patterns of terraces and lobes that have yet to be explained, but may help constrain solifluction processes. Here we take a closer look at these patterns in an effort to better understand material and climatic controls on solifluction. We find that the patterns are analogous to classic instabilities found at the interface between fluids and air—for example, paint dripping down a wall or icing flowing down a cake. Inspired by classic fluid mechanics theory, we hypothesize that solifluction patterns develop due to competition between gravitational and cohesive forces, where grain-scale soil cohesion and vegetation result in a bulk effective surface tension of the soil. We show that, to first order, calculations of lobe wavelengths based on these assumptions accurately predict solifluction wavelengths in the field. We also present high resolution DEM-derived data of solifluction wavelengths and morphology from dozens of highly patterned hillslopes in Norway to explore similarities and differences between solifluction lobes and their simpler fluid counterparts. This work leads us toward quantitative predictions of the presence or absence of solifluction patterns and their response to variation in material properties (e.g., vegetation, rock type, grain size) and climatic conditions (e.g., water content, active layer depth, variability in snow cover).

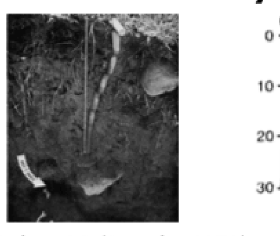
Solifluction deformation style (rheology)

We know that soil moves as a result of frost heave and flow-like "gelifluction"

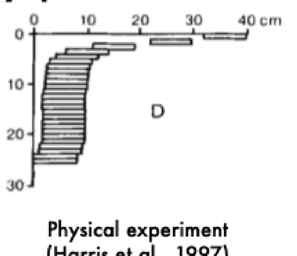


Experimental solifluction motion (Harris et al., 1995)

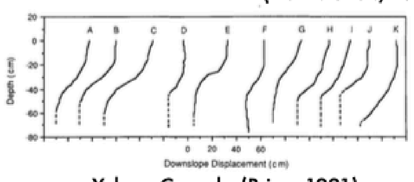
Vertical velocity profiles



Niwot Ridge, CO (Benedict 1970)



Physical experiment (Harris et al., 1997)



Yukon, Canada (Price, 1991)

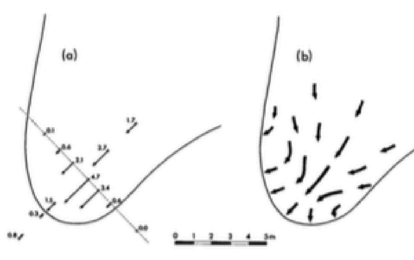
However, solifluting soil is a complex cohesive granular-fluid-ice mixture, and its rheology is largely unknown. It may behave similarly to a yield-stress fluid, especially over long timescales (e.g., Harris et al., 2003; Roy et al., 2017; Jerolmack and Daniels, 2019). But it's complicated given the wide range of observed vertical velocity profiles, the variable presence of ice and liquid water, and soil cohesion...

$$\tau = \tau_0 + k\dot{\gamma}^n$$

Shear stress (τ); Yield stress (τ_0); consistency index (like viscosity) (k); Shear rate (du/dz) ($\dot{\gamma}$); Flow index (n) =1 (newtonian), <1 (shear thinning), >1 (shear thickening)

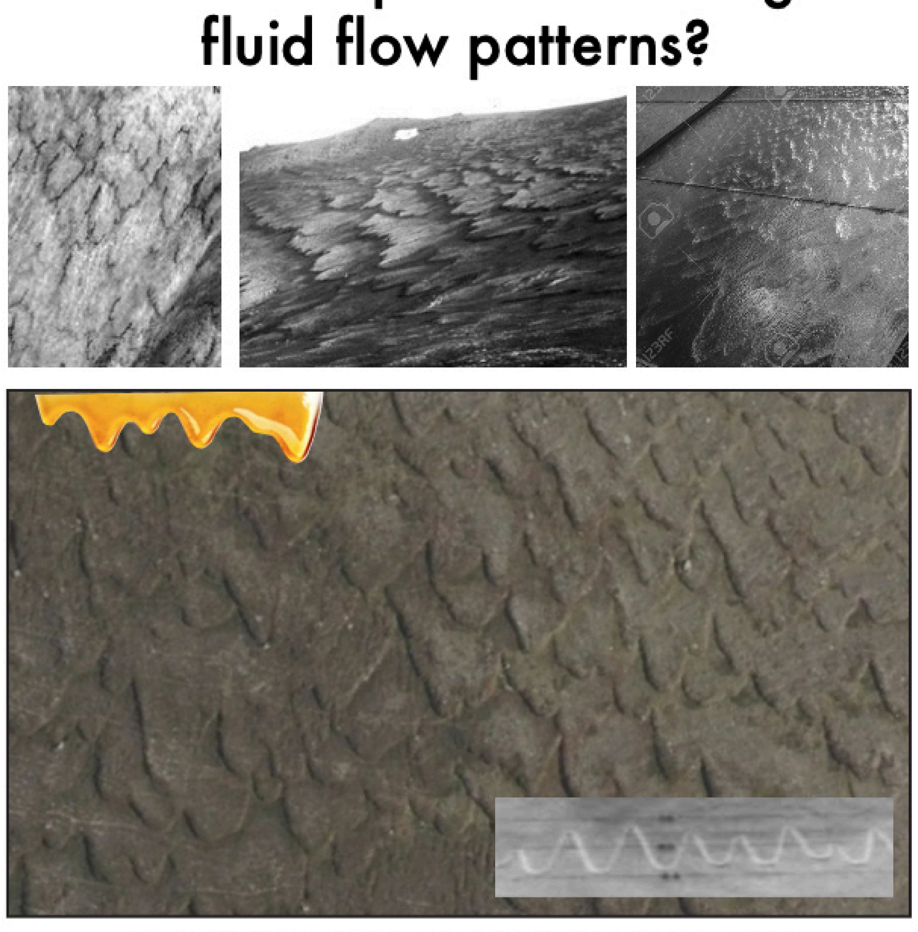
Downslope motion

Solifluction lobes generally move much faster than surrounding soil



Displacement in cm/yr at Niwot Ridge, CO (Benedict, 1970)

Are solifluction patterns analogous to fluid flow patterns?



Top left: Possible solifluction lobes on Mars (Johnsson et al., 2012)
Top middle: Solifluction lobes near Chicken Creek, Alaska
Top right: Water flowing down a window
Bottom: Solifluction lobes in Norway with overlay of honey drips (shutterstock) and oil flowing down a plane (Huppert 1982).

What sets the wavelength of classic fluid instabilities?

1. At a fluid front, cohesion/surface tension holds back flow, causing it to thicken
2. Thicker flow moves faster
3. Small variations in thickness lead to growth of "fingers" with wavelength (λ). This is called a "contact line instability."

$$\lambda \sim H\left(\frac{3\mu U}{\sigma}\right)^{-1/3} \quad \text{(Eqn. 2)}$$

Wavelength (λ); Thickness (H); Viscosity (μ); Velocity (U); Surface tension (σ)

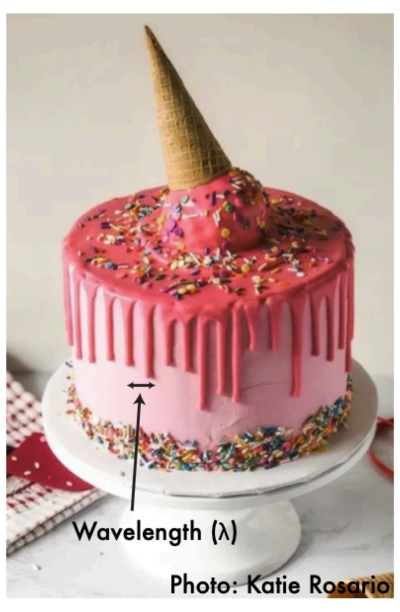
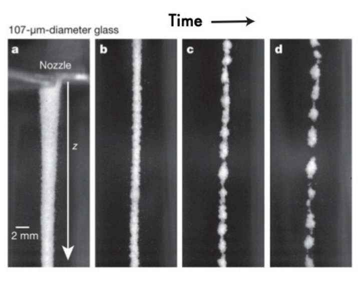


Photo: Katie Rosario

Where the right hand side is multiplied by a constant (~14 for newtonian fluids (e.g., Huppert 1982; Troian et al., 1989), ~35 for shear thinning (de Bruyn et al., 2002).

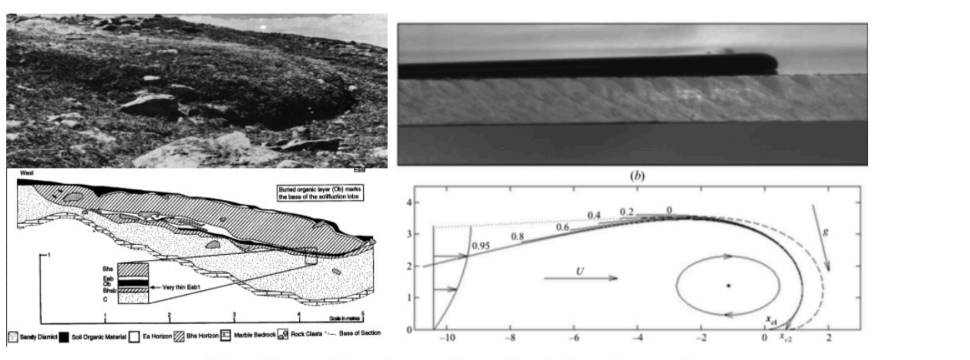
Effective surface tension in soils?

If fluid flow patterns result from surface tension, could an "effective" surface tension due to soil cohesion explain solifluction patterns? Recent work has found evidence of effective surface tension, even in dry granular materials (Shen et al., 1999; Brewster et al., 2009; Royer et al., 2009) due to small cohesive forces between grains and in soft solids (Style et al., 2017).



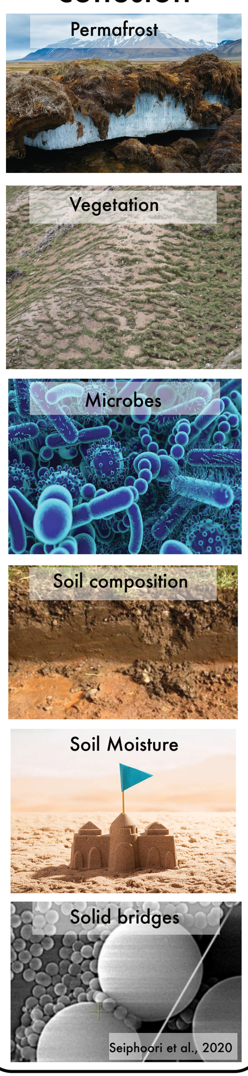
Small cohesive forces between dry grains of sand causes "droplets" to form (Royer et al., 2009)

In addition to exhibiting similar pattern, solifluction lobes have front morphology and dynamics characteristic of surface tension-dominated contact lines in fluids



Top left: Solifluction lobe at Niwot Ridge, Colorado (Benedict, 1970).
Top right: Contact line of glycerine finger moving downslope (Veretennikov, 1998)
Bottom left: Rollover motion of solifluction lobe evidenced by buried turf (Elliott, 1996)
Bottom right: Sketch showing rollover motion in glycerine seen with dye tracking

Sources of soil cohesion



Estimating effective surface tension

We can use the cohesive work required to pull apart two soil grains to estimate effective surface tension (following Royer et al., 2009):

$$\sigma_{eff} = \frac{W_{coh}}{d^2}$$

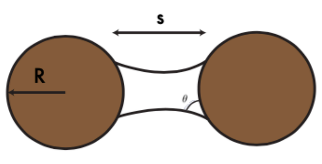
Cohesive work required to pull apart two grains (W_{coh}); Grain diameter (d)

$$F_b = \frac{2\pi R\gamma\cos\theta}{1 + 1.05\hat{s} + 2.5\hat{s}^2}$$

Cohesive force (F_b); Grain radius (R); Surface tension of liquid (γ); Contact angle (θ)

where $\hat{s} = s\sqrt{R/V}$; Separation distance (s); Volume of liquid bridge (V)

For now, let's assume the cohesive force is due to liquid capillary bridges between grains (Herminghaus, 2005):



To obtain an expression for cohesive work, we integrate this from s = 0 to a critical separation distance, s_c (Lian et al., 1994).

$$s_c = R\left(1 + \frac{\theta}{2}\right)\left(\frac{V^{1/3}}{R} + 0.1\frac{V^{2/3}}{R^2}\right)$$

Value ranges

Liquid volume: 10^{-17} - 10^{-19} m^3 (Rabinovich et al., 2015)
Grain radius: .002 - .05 mm
Contact angle: 10 - 80 degrees

Using a range of reasonable values for silt-sized soil grains (typical of solifluction lobes), we obtain estimates of effective surface tension ranging from ~10^{-6} - 10^{-2} N/m. (For reference, surface tension of water = 7.2 x 10^{-2} N/m)!

Can we predict solifluction lobe wavelengths?

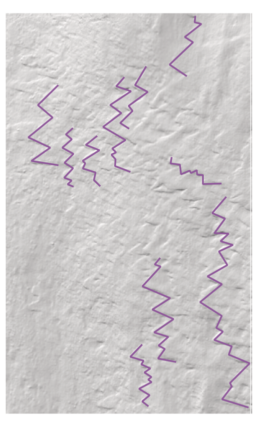
Now that we have an estimate of effective surface tension, we can use Eqn. 2 to calculate that the expected wavelength of solifluction lobes ranges from 2 - 170 m, with more reasonable values giving lower wavelengths. This agrees well with the range of solifluction wavelengths found on Earth and Mars!*

*e.g., Gastineau et al., 2020; Johnsson et al., 2012

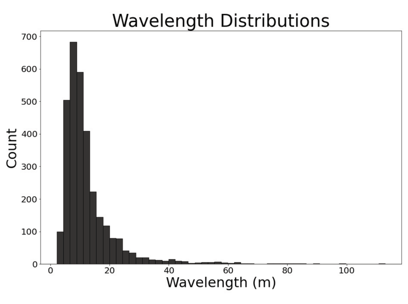
Value ranges

Thickness: 0.5 m
Viscosity: 1000 - 100,000 Pa-s (Harris et al., 1997; Ghezzehei and Or, 2001)
Velocity: 1 cm/yr
Wavelength constant: 14-35

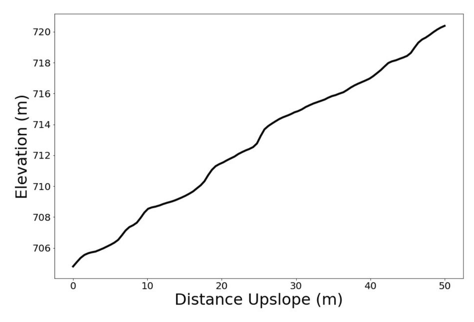
Field data from Norway



We manually traced ~3500 lobes from high res DEMs



Most wavelengths between 2-30 meters

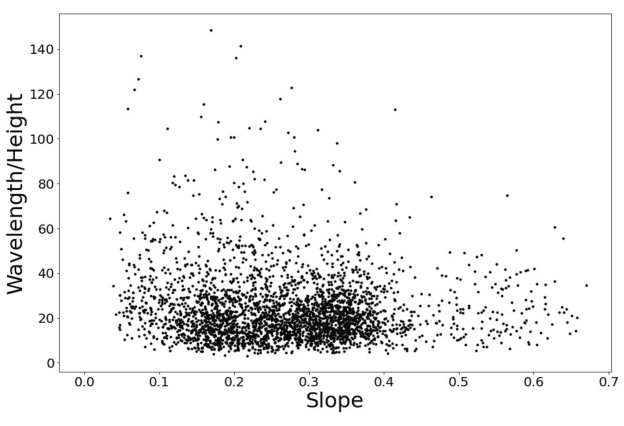


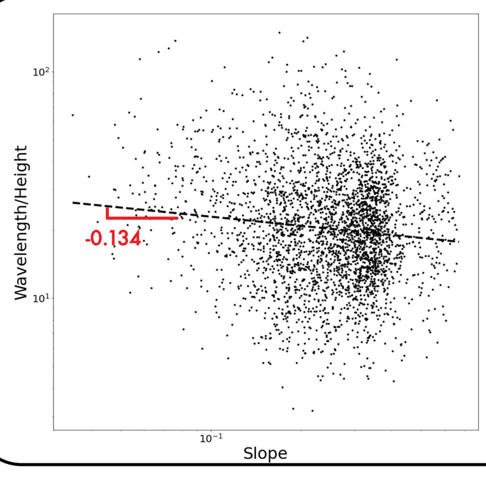
Example LiDAR profile shows lobe fronts

Does field data agree with fluid theory/ experiments? It's messy, but maybe...

Prediction: Larger variation in wavelength at low slopes

(e.g., de Bruyn 2012, Huppert 1984)

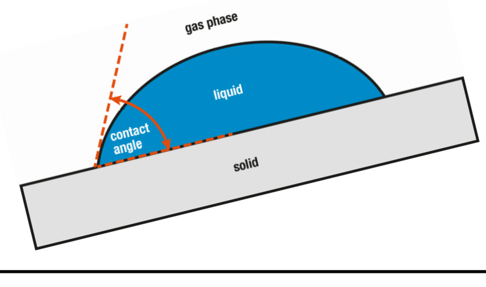




Prediction: Power law decrease in wavelength/height with topographic slope

(e.g., de Bruyn 2012, Huppert 1984,

As fluids flow downslope, their advancing contact angle–the angle at the very front of the flow–is determined by viscosity, velocity, and surface tension.
(e.g., Voinov 1976; Cox 1986;)

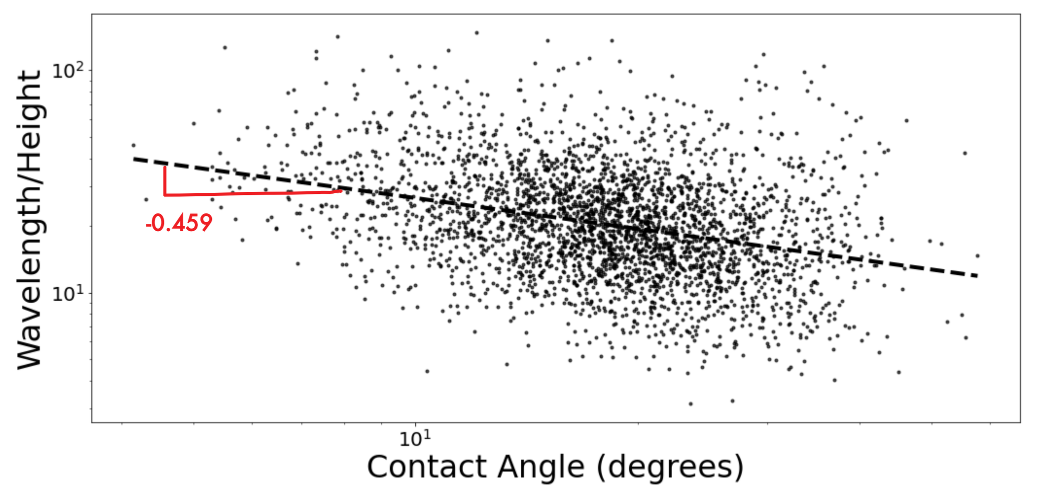


The wavelength of the contact line instability is also determined by viscosity, velocity, and surface tension. So we can combine these to predict the relationship between wavelength and contact angle

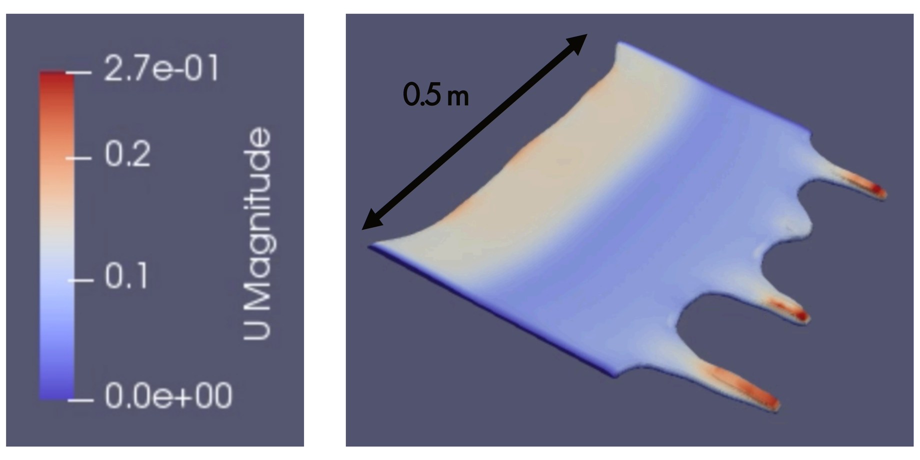
$$\lambda \sim H\left(\frac{3\mu U}{\sigma}\right)^{-1/3}$$

Prediction: for a viscoelastic fluid, wavelength/ height ~ contact angle$^{-1/2}$

(see Kim and Rothstein, 2015)

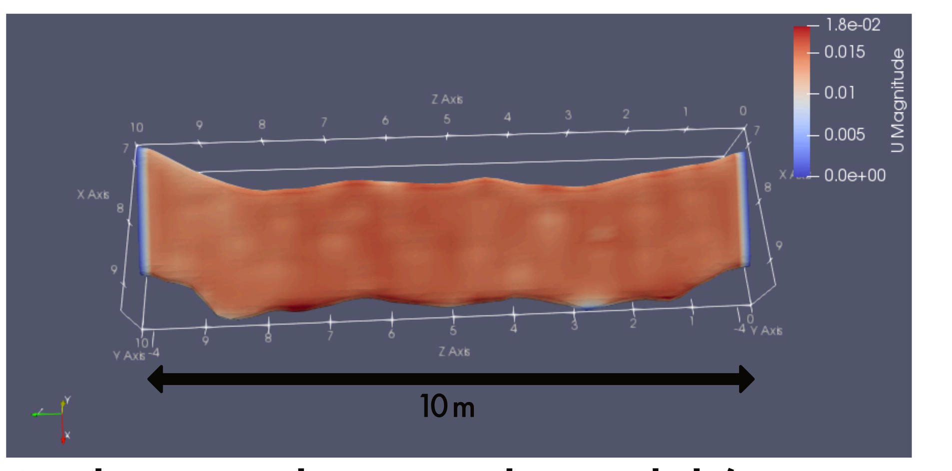


OpenFOAM Fluid Modeling: Viscous flow + surface tension



Classic contact line instability: small scale

We can use OpenFOAM to see if these patterns arise at large length scales relevant for solifluction. We can also play with different rheologies.



Preliminary large-scale model (viscous newtonian fluid)