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Slow-moving arctic soils commonly organize into striking large-scale spatial patterns called solifluction terraces and lobes. Though these features impact hillslope stability, carbon storage and release, and landscape response to climate change, no mechanistic explanation exists for their formation. Everyday fluids—such as paint dripping down walls—produce markedly similar fingering patterns resulting from competition between viscous and cohesive forces. Here we use a scaling analysis to show that soil cohesion and hydrostatic effects can lead to similar large-scale patterns in arctic soils. A large new dataset of high-resolution solifluction lobe spacing and morphology across Norway supports theoretical predictions and indicates a newly observed climatic control on solifluction dynamics and patterns. Our findings provide a quantitative explanation of a common pattern on Earth and other planets, illuminating the importance of cohesive forces in landscape dynamics. These patterns operate at length and time scales previously unrecognized, with implications toward understanding fluid-solid dynamics in particulate systems with complex rheology.

solifluction | fluid instabilities | climate | granular fingering | periglacial

Periodically frozen soil–a temporally evolving mixture of granular material, fluid, and ice–is one of the most complex natural materials found on planetary surfaces. While its rheology is not well understood, arctic soil deformation commonly produces large, distinctive meters-to-tens of meters-scale spatial patterns visible in aerial images (Figure 1A). Patterns are organized in both the downslope and cross-slope directions. Regular downslope-oriented terraces of soil are characterized by raised fronts that protrude 1-2 meters above the surrounding topography (Figure 1A,C). Terrace fronts are commonly broken into finger-like lobes evenly spaced cross-slope (Figure 1A,B). Known as solifluction features, these patterns form due to a combination of frost heave, in which segregation ice growth lofts soil upwards, and gelifluction, a slow flow-like relaxation of partially saturated soil once it thaws in the summer (1, 2). While a rich history of experimental and global field observations over the past century have characterized solifluction processes and velocities ($\sim 10^{-1} - 10^{1}$ cm/year) (2, 3), there exists no agreed-upon rheological model for solifluction that can offer quantitative and qualitative explanations for the striking patterns it produces. Renewed interest in these features primarily stems from a need to predict Arctic landscape response to climate change and storage and release of permafrost carbon, as well as to predict and mitigate arctic slope instabilities due to thawing permafrost (4).

Strikingly similar patterns develop in simple fluids, where competition between viscous and cohesive forces drives a suite of common instabilities in thin films. For example, the evenly spaced fluid fingers that form when painting a wall, icing a cake, or sloshing oil in a frying pan are known as "contact line instabilities" at fluid fronts (7, 11) (Figure 1A). Only recently have soft solids (12) and granular materials (13–18) been shown to exhibit patterns and morphology that resemble those of thin-film fluids. Notably, (13) found that small cohesive forces between sand grains produce an effective surface tension relevant at macroscopic length scales, causing a steady stream of sand to break into droplets similar to a Rayleigh-Plateau instability. However, connections between fluid and granular instabilities–especially regarding the role of cohesion–remain a frontier in materials science.

Here we take the first step toward utilizing quantitative connections with fluid and granular mechanics to better understand solifluction processes and patterns. We present a conceptual model of solifluction pattern formation in which solifluction lobes (resembling fluid fingers) arise as a cross-slope instability on the fronts of terraces (resembling fluid roll waves) formed during an initial downslope instability (Figure 1A,B). While we present data for both instabilities, we focus mainly on the cross-slope patterns. First, we discuss how key ingredients that control fluid contact line instabilities—viscosity, velocity, fluid thickness, and surface tension—may translate to soil. By adopting an analogy between fluid and soil dynamics, we suggest a formal scaling analysis relating solifluction wavelengths to active soil thickness, topographic slope, and cohesion-drive effects at the soil front. Using high-resolution topographic data from over 3000 solifluction lobes across 25 sites in Norway, we show that scaling between solifluction wavelengths and slope, lobe height, and lobe front angle generally agrees with our theoretical analysis. Data from these sites show that lobe morphology is strongly correlated with elevation, which likely represents a climate control on solifluction processes due to the dependence of frost heave on mean annual daily temperature

Significance Statement

Slow-moving arctic soils form patterns resembling those found in common fluids, such as paint and cake icing drips. Inspired by fluid instabilities, we develop a new conceptual model for soil patterns and use mathematical analysis to predict their wavelength. In particular, we propose that soil patterns arise due to competition between gravity and cohesion, or the "stickiness" of soil grains. We compare our theoretical predictions with a new data set of soil features from Norway, finding that soil patterns are controlled by both fluid-like properties as well as climate. Our work provides the first physical explanation for a common pattern on both Earth and Mars, with implications for our understanding of landscapes and complex materials composed of both granular and fluid components.

R.C.G., M.F., and J.R. designed research; M.F. and R.C.G. analyzed data; all authors contributed to development of theory and writing of paper

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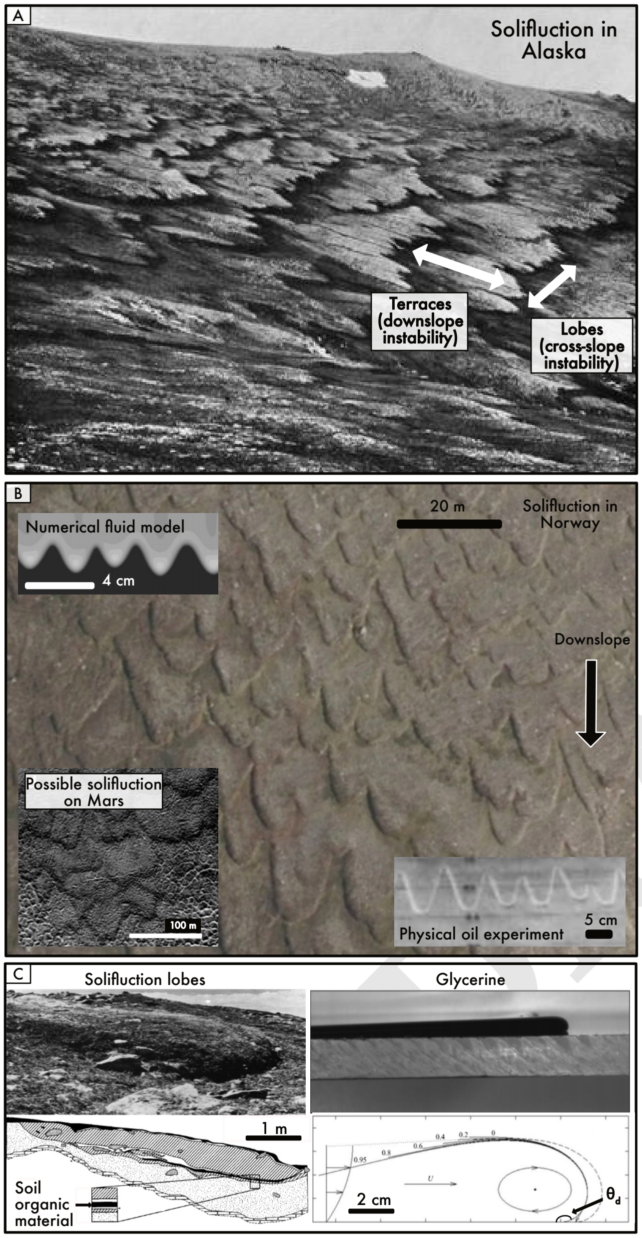

Fig. 1. A) Solifluction terraces and lobes in Chicken Creek, Alaska. Photo by Philip S. Smith. B) Examples of solifluction and fluid patterns. Background: Orthophoto of solifluction lobes in Norway, copyright Kartverket. Upper left: Numerical model image reprinted from (5). Lower left: Possible solifluction on Mars, reprinted from (6). Lower right: Photo of front of oil flowing down plane, reprinted from (7). C) Morphology and dynamics of solifluction lobes vs. surface tension-dominated flows. Upper left: Solifluction lobe in Colorado, reprinted from (8). Lower left: Map of trenched lobe, with soil organic layer showing rollover motion. Adapted from (9). Upper right: Gravity driven glycerine front. Lower right: schematic of glycerine front showing rollover motion. Shape of nose derived from Young-Laplace equation for surface tension effects. Numbers indicate profile evolution through time, and dashed line illustrates profile at next moment in time. Dynamic contact angle θ_d is shown. Both reprinted from (10).

amplitude (T_a) and mean annual air temperature (MAAT). We discuss how cohesion not only slows down soil motion but results in a state change in soil behavior, with implications for Arctic landscape response to climate change and interpretation of past climates on Earth and other planets. Our work shows that even in creeping granular-fluid-ice materials, competition between driving stress and cohesion can result in large-scale patterns similar to those found in fluids, with implications for our understanding of the rheological behavior of complex materials.

Fluid Fingering Instabilities

First, we briefly describe fingering instabilities in fluid films. The qualitative explanation for contact line instabilities is simple: at a fluid interface in a thin film, cohesive forces in the form of surface tension hold back the flow, allowing the front to thicken into a capillary ridge. With a slight initial perturbation, competition between body forces, which cause thicker zones to move faster, and surface tension, which induces transverse flow under bumps, drives the growth of fingers with a regular wavelength. Experiments (e.g., (7, 19, 20)), linear stability analysis (e.g.(11, 21)), and numerical models (e.g. (5, 22)) have determined that the wavelength of fluid contact line instabilities is given by

$$\lambda = BH(\frac{3\sigma}{v\mu})^{1/3} \qquad [1]$$

where H is the fluid thickness, B is a dimensionless constant (14 for Newtonian fluids, 35 for shear thinning yield stress fluids (19), μ is the fluid dynamic viscosity, v is a characteristic velocity, σ is the surface tension, and $\sigma/v\mu$ is the inverse capillary number Ca. This means that flows with greater thickness or surface tension produce larger wavelengths, while more viscous or faster moving flows produce smaller wavelengths. Note that v depends on both μ and H; therefore, for a laminar Newtonian fluid in which average velocity $v = \rho g H \sin\theta/\mu$, Eqn. 1 becomes $\lambda = BH^{2/3}(\frac{3\sigma}{\rho g \sin\theta})^{1/3}$. Ca has also been shown to control the dynamic contact angle θ_d at the fluid front (Figure 1C) according to the Voinov-Tanner-Cox law, such that $\theta_d^2 \sim Ca^m$, where $m = 1$ for a Newtonian fluid (23), $m > 1$ for a viscoelastic fluid (24) and $m < 1$ for shear thinning fluids (25). The positive relationship between θ_d and Ca shows that the steeper the contact angle, the faster/more viscous the flow (or the lower the cohesion/surface tension). This provides a link between finger morphology and dynamics, and because both wavelength and contact angle depend on Ca, we would expect a negative power law trend between the two of the form $\frac{\lambda}{H} \sim \theta_d^{1/m}$.

Solifluction Lobes as Fluid-like Instabilities

We argue that the solifluction phenomenon qualitatively exhibits all the necessary ingredients for a fluid-like instability. Here we describe how each ingredient may translate to soil, resulting in a new conceptual model of solifluction pattern formation (Figure 2C).

Contact line instabilities initiate at a raised fluid front. For solifluction, we propose that a downslope instability forms evenly spaced solifluction terraces that operate similarly to a fluid front. With raised fronts $\sim 1-2m$ tall and wavelengths much larger than soil thickness ($\sim 10^1 - 10^2$m) (Figure 1A; 3E), this downslope instability features prominently in the landscape. Though the cause of the downslope instability is unclear, we argue it is likely a result of soil rheology, similar to non-inertial waves recently observed in shear thickening fluids or fluids with resisting forces at the free surface (26) (see Discussion). With enough heterogeneity in topography, soil properties (such as moisture, cohesion, and grain size), or vegetation, smooth terrace fronts may break into solifluction lobes evenly spaced cross-slope (Figure 1A,B) with wavelengths on the order of $1 - 10^2$m. Although the thickness, h, of these features is large relevant to fluid thin films, $\sim$1m, the hillslope-wide lateral length scale of motion, l, supports the idea that they may behave like thin films ($h \ll l$) (27).

While solifluction rheology and mechanistic relationships between velocity and depth are still unclear, data and models show that velocity likely increases with total active soil thickness due to freeze-thaw processes (2, 28). Field measurements across the globe have found solifluction velocities ranging from $10^{-1} - 10^{1}$ cm/yr (2). Considering the soil as a slow-moving fluid, these slow velocities suggest very high viscosities. We compile every available field-measured and experimental vertical velocity profile from the literature and find that most exhibit an exponential decrease in velocity with depth (Figure 2A) while a few studies exhibit more complex profiles (SI Appendix, Fig S2). We then calculate effective viscosity μ_{eff} as the ratio between shear stress τ and strain rate du/dz: $\tau = \mu_{eff}\frac{du}{dz}$. We find large μ_{eff} ranging from $10^5 - 10^{12}$ Pa-s. In contrast to a Newtonian fluid with constant viscosity, velocity profiles show that effective viscosity increases with depth (Figure 2B), indicating a non-Newtonian-like flow behavior. While a proper description of solifluction rheology should explicitly take into account granular physics, our first order assumption of non-Newtonian fluid-like behavior is likely acceptable for a wet granular material (e.g., (29)) (see Discussion).

Surface tension at the front is the last key ingredient for a contact line instability. While recent studies have shown that intergranular cohesion can produce an effective surface tension in granular materials at small length scales (e.g.(13)), this concept is not physically relevant for $\sim 1m$ thick soils where overburden pressure vastly outweighs any possible pressure due to surface tension. However, we argue that increased cohesion and decreased soil velocities at solifluction fronts allow soil buildup and transverse flow due to hydrostatic pressure, akin to the behavior of surface tension-dominated fluids. There are many sources of cohesion that can lend substantial strength to soils, including microbes (e.g., (30)), permafrost, vegetation (e.g., (31)), capillary bridges due to moisture content (e.g., (32)), clay composition, and solid bridging due to polydispersity ((33)). We propose that increased drainage at the open boundary at the front of a solifluction terrace or lobe likely increases the effectiveness of many of these cohesion sources. First, drainage at the front may decrease ice lens formation and subsequent frost heave and soil transport. Ice lenses require the presence of adequate moisture and specific temperature conditions in order to form (e.g., (34)) that may be easily disrupted at an open boundary. This would result in a decrease in soil velocities at the front of the lobe. Second, drainage and consolidation at the front may increase the strength of capillary bridges, which can increase capillary suction and the resulting apparent cohesion (35, 36). Finally, moisture conditions at the front may encourage vegetation growth there, lending added cohesion in turf-banked lobes ((37, 38)). While soil moisture patterns in solifluction lobes are complex (37) and cohesion patterns have never been measured, available field evidence supports the idea of a stalled lobe front. Displacement markers in the field show soil buildup behind solifluction lobe fronts and transverse flow toward the middle/front of lobes, akin to behavior in fluid fingers (8). Solifluction lobe morphology (thickened front and steep, sometimes overhanging contact angle) (e.g., (8)) and dynamics (tractor tread-style rollover motion at the front) (8, 9, 39) resemble those of surface-tension dominated flows (Figure 1C). Additionally, commonly documented retrograde motion uphill in solifluction lobes points toward strong effects of cohesion (2, 40), likely resulting from temporally evolving strength of capillary bridges.

Conceptual Model

We propose that the solifluction lobe instability is initiated and controlled by competition between these elements: 1) the body force due to gravity, which moves thicker material downhill faster 2) cohesion at the front, which resists flow, and 3) lateral flow due to hydrostatic pressure under topographic bumps (Figure 2B), with cross-slope wavelengths set by these competing processes (Figure 2B). This is similar to fluid contact line fingering in that competition between a body force and resisting force due to cohesion at the front initiates and controls the preferred wavelength of the instability, where increased cohesion at the front takes the place of surface tension. Finally, while formulations of fluid contact line instabilities ignore hydrostatic effects because surface tension dominates, here we include hydrostatic pressure that drives lateral flow in the presence of inevitable topographic roughness in natural landscapes.

We develop our analysis to be as general as possible, without assuming a specific source of cohesion at the front of the lobe. While vegetation has been shown to be important for solifluction patterns (38), the existence of non-vegetated lobes precludes vegetation as a necessary ingredient for their formation. Here we focus on solifluction lobes without large boulders; however, stone-banked lobes exhibit grain size segregation with large boulders at the front and sides of the lobe (8). This likely leads to a similar effect in which boulder jamming at the front of the lobe stalls flow. Thus our general conceptual model should apply to both turf-banked and stone-banked lobes on Earth and Mars, as well as unvegetated lobes with relatively homogeneous grain sizes as are observed on Mars (41).

Wavelength scaling analysis

Inspired by fluid theory for contact line instabilities, we take the first step toward deriving an expression for solifluction lobe wavelengths. Because solifluction rheology is uncertain, our analysis avoids assumptions of Newtonian flow. In contrast to instabilities in surface-tension dominated fluids, we allow for hydrostatic effects given the likelihood of natural topographic roughness in the field. We examine laminar flow down a plane, accounting for hydrostatic pressure in both the downslope (x) and cross-slope (y) directions. Cohesion has been shown to control effective viscosity in granular materials (e.g., (29, 42). Therefore, to account for cohesion at solifluction fronts, we

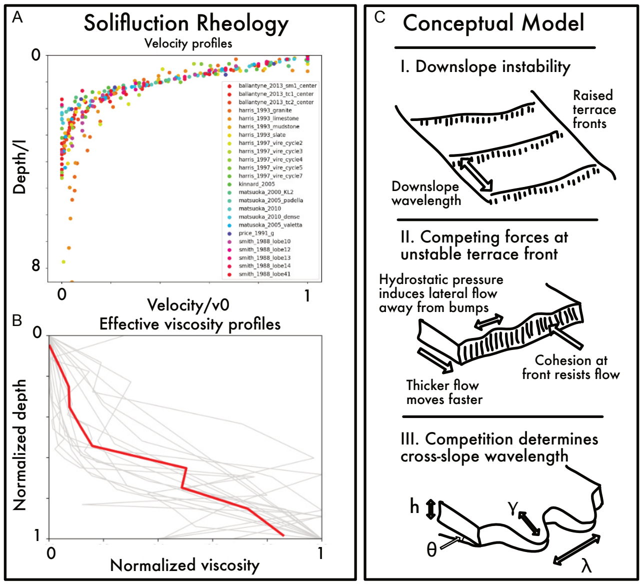

Fig. 2. A) Vertical velocity profiles compiled from the literature, observed both in the field and laboratory experiments. See non-normalized plots in SI Appendix Figure S3. B) Vertical viscosity profiles computed from velocity profile show general increase in effective viscosity with depth. See non-normalized plots in SI Appendix Figure S4. C) Conceptual model of solifluction lobe pattern formation.

allow effective viscosity to vary in the (x) direction. Here we present the simplest approach to scaling; see SI Appendix Section I for alternative approaches that produce similar results.

For a laminar fluid flowing down an inclined plane, under hydrostatic conditions upstream from the front, the basal shear stress is:

$$\tau_0 = -\rho g h \sin\theta + \rho g h \frac{\partial h}{\partial x} \qquad [2]$$

where ρ is the bulk density, g is gravity, h is the fluid depth, and θ is the underlying slope. To avoid assumptions of Newtonian rheology, but without assuming a particular form of a power-law fluid, we define a bulk viscosity μ such that $\tau_0 = -\mu U/h$, where U is the vertically averaged velocity in the x (downhill) direction. To account for cohesion at the front, we allow viscosity to change in the x direction. Solving for the downslope velocity and assuming that cross-slope velocity arises only from the hydrostatic pressure gradient, we can solve the continuity equation at steady-state and retain only first-order terms (see methods) to find:

$$\frac{3\sin\theta}{\mu}\frac{\partial h}{\partial x} - \frac{h\sin\theta}{\mu^2}\frac{\partial \mu}{\partial x} - \frac{h}{\mu}\frac{\partial^2 h}{\partial x^2} + \frac{h}{\mu}\frac{\partial^2 h}{\partial y^2} = 0 \qquad [3]$$

where the first two terms represent the body force, the third term is the downslope hydrostatic component (x direction), and the fourth term is the cross-slope hydrostatic component (y direction). Now we can scale terms by dimensionless quantities (indicated with hats) as follows:

$$\begin{aligned} h &= h_0\hat{h} \\ \mu &= \mu_0\hat{\mu} \\ x &= \gamma\hat{x} \\ y &= \lambda\hat{y} \end{aligned} \qquad [4]$$

where h_0 is a characteristic height, μ_0 is a characteristic viscosity, γ is a characteristic length scale in the x direction that describes a distance over which the viscosity varies, and λ is a characteristic length scale in the y direction (Figure 2C). Retaining only the dimensional leading coefficients and simplifying:

$$\frac{2\sin\theta}{\gamma} - \frac{h_0}{\gamma^2} + \frac{h_0}{\lambda^2} = 0 \qquad [5]$$

We note that the viscosity cancels out, and its only effect lies in γ. We are mainly interested in λ, which we assume to be the cross-slope wavelength between solifluction lobes. Assuming the body force (first term) dominates over the hydrostatic pressure gradient (second term), we find:

$$\lambda \sim \sqrt{\frac{h_0\gamma}{2\sin\theta}} \qquad [6]$$

This suggests that the cross-slope wavelength increases with soil thickness and the characteristic length over which viscosity changes due to dynamics at the front, and decreases with basal slope (which we assume to be equivalent to x directed topographic slope averaged over a distance $\gg$ length of a lobe). Though the particular scaling differs from that for fluids in Eqn. 1, our relationship is similar in that cross-slope wavelength is projected to exhibit a power law increase with height and cohesion and a decrease with topographic slope. These fundamental similarities between solifluction lobe and fluid finger wavelengths also suggest that while we do not yet have a prediction for the contact angle at the front of lobes, we might expect an inverse relationship between cross-slope wavelength normalized by height and the contact angle as described above for fluids.

Solifluction patterns in Norway

To explore these ideas in real landscapes, we collected high resolution morphologic and topographic data from 26 highly-patterned solifluction sites across Norway (Figure 3). We manually measured 3000 individual lobes from submeter LiDAR-derived digital elevation models (DEMs) (freely available at Hoydedata) to obtain cross-slope lobe wavelength, height, lobe length, and lobe front/riser angle (hereafter referred to as contact angle), terrace (downslope) wavelength, and topographic slope (see Methods). We find that cross-slope wavelengths range from 2-100 m, with a mean of 13m. This range agrees with previous studies (41), and values are generally smaller but overlap with those found on Mars (Figure 3B). Trends between lobe morphology metrics and topography agree with theoretical predictions. Cross-slope wavelength increases with lobe height/topographic slope, as expected from our scaling analysis (Eqn. 6). Though the data include a large amount of scatter, binned average wavelengths show that our theoretical prediction describes the general trend well (Figure 3C). Note that in order to better explain the data we would need constraints on γ, which may also depend on lobe height and explain the jelly bean shape of the data. A better understanding of rheology could also be incorporated in our analysis to improve predictions. Our theory predicts only scaling rather than absolute wavelengths; however, the empirically best fit power law coefficient (≈ 8) suggests that cross-slope wavelength $\lambda \approx 6\sqrt{h_0\gamma/\sin\theta}$.

As expected from theory, we see a negative power law trend between wavelength/height and contact angle. This observation is consistent with theory for dynamic contact angle of a droplet rolling down a flat substrate. However, to properly predict the relationship between cross-slope wavelength and contact angle, we would need theory equivalent to the Voinov-Tanner-Cox law that accounts for cohesion rather than surface tension. We also find that lobe aspect ratio (L/W) slightly increases with topographic slope, as observed in fluid experiments (SI Appendix, Fig S5) (43). Most lobes are wider than they are long, exhibiting a sawtooth shape similar to that observed for fluids on gently sloping planes (SI Appendix, Fig. S5) (Figure 1B). Finally, we observe a positive relationship between downslope terrace wavelength and lobe height averaged by site (Figure 3E), but no clear relationship with topographic slope is discerned (SI Appendix, Fig S6). While we currently lack a prediction for the scaling of downslope wavelength, our data provide the first step toward developing a better understanding of the phenomenon (see Discussion).

Large amounts of scatter in the field data likely contain interesting information about lithology, vegetation, climate, and other unknown parameters that differ between sites. However, that average wavelength trends agree with our theory inspired by simple fluids is remarkable and supports the idea that solifluction patterns operate similarly to fluid contact line instabilities.

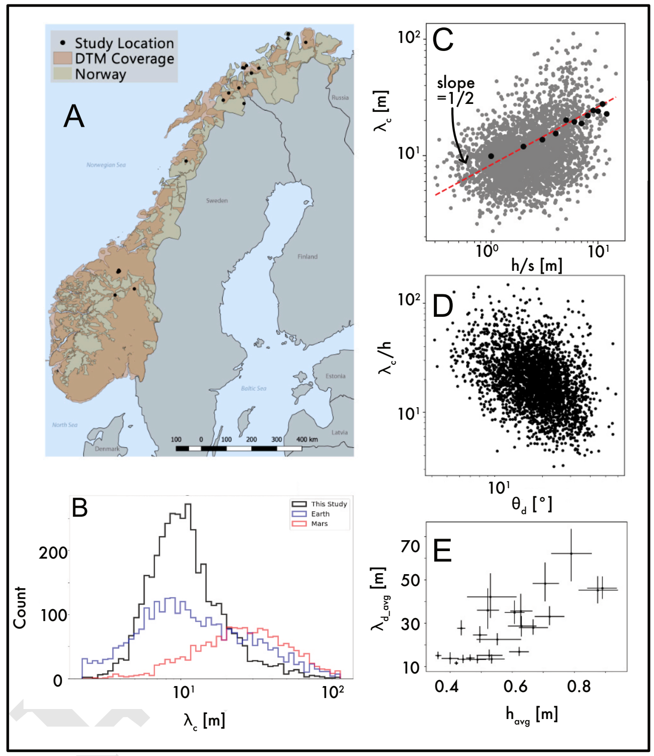

Fig. 3. A) Map of Norway showing study sites used in this paper and DTM coverage. B) Cross-slope wavelength (λ_c) distributions measured in this study, shown with distributions for Earth and Mars from (41). C) Cross-slope wavelength (λ_c) vs. lobe height h /topographic slope s. Red dashed line shows theoretical prediction from Eqn. 6. Black dots show average wavelength split into 13 bins of h/s values. D) Cross-slope wavelength (λ_c) normalized by height h vs. contact angle θ_d at the front of the lobe. E) Downslope terrace wavelength (λ_d) averaged at each site vs. average lobe height for each site.

Climate controls

Our data show a meaningful increase in solifluction lobe height and cross-slope wavelengths with elevation (Figure 4), pointing toward a climate control on lobe morphology and pattern formation due to the lapse rate, or change in temperature with height in the atmosphere. Though solifluction features are traditionally thought to be climate-controlled and have often been used to interpret past climate, limited data exist for co-located climate metrics and solifluction lobe morphology and dynamics (44). However, recent work on frost cracking in rock (45–47) illuminates the climatic conditions required for segregation ice growth and frost heave, the main drivers of solifluction (2, 48). (46) find that the depth and intensity of frost cracking increases with annual temperature amplitude and decreases with MAAT. To explore this idea, we compare high temporal resolution climate metrics from extensive monitoring stations in Norway over the last 20 years (49) with solifluction lobe morphology for each site shown in Figure 3A. Consistent with frost cracking predictions, we find an increase in finger wavelength and lobe height with annual temperature amplitude, corresponding with a general decrease in MAAT (Figure 4). Other differences between high and low elevations may explain observed morphology trends. While we do not see strong relationships with mean annual snowfall, precipitation, or time spent in the frost cracking window (SI Appendix, Figs 7-9), shortwave radiation or vegetation coverage may be important. We interpret the data to show that climate primarily affects the depth of solifluction processes, which in turns affects the wavelengths. This is supported by a much weaker relationship between elevation and wavelength normalized by height (SI Appendix, Fig 10).

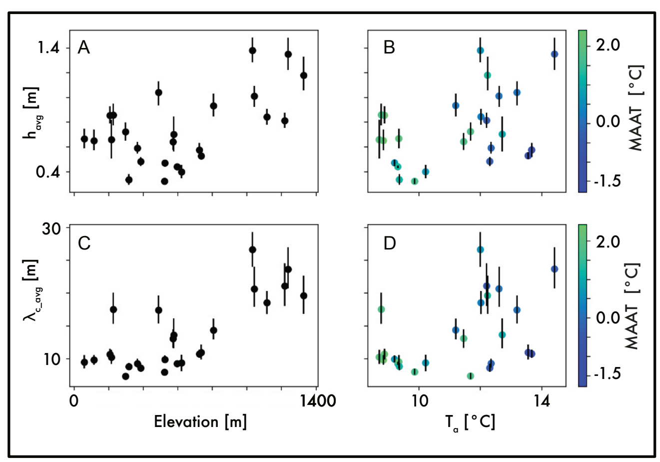

Fig. 4. Relationships between lobe morphology, elevation, and climate indices. Climate data are drawn from daily observations between the years 2000-2020.

Discussion

Our work suggests that even extremely slow-moving soils may exhibit subcritical fluid-like instabilities, but at length and time scales orders of magnitude larger than those observed in thin films. Our new conceptual model for solifluction pattern formation provides a framework for further study. Here we provide some discussion on the most interesting questions resulting from this study, with suggestions for the most promising avenues of exploration.

The initial downslope instability that forms solifluction terraces, which we argue promote the growth of solifluction lobes as a contact line instability, deserves further inspection. While terraces resemble roll waves seen in inertial fluid flows (e.g., (50)), buckling instabilities seen in multilayer flows (51) like rock glaciers (52) and lava flows (53), or wrinkling instabilities found in multilayer solids like pumpkins and human skin (54), our observations of solifluction terrace wavelengths do not fit within these frameworks. Exceedingly slow solifluction velocities exist in a non-inertial regime, which precludes a comparison with roll waves (50). While the positive relationship between downslope wavelength and lobe height is similar to that seen in buckling and wrinkling instabilities, absolute terrace wavelengths can be much larger than lobe height, which is unusual for buckling and wrinkling instabilities; our data show that terrace wavelengths are 1-2 orders of magnitude larger than lobe heights (Figure 2E). Further, the observed low effective viscosities at the surface do not align with buckling instabilities, which typically require a more rigid flow on top (e.g. (52)). However, recent work describes a newly-observed non-inertial instability in shear-thickening flows (e.g., cornstarch mixed with water) that can produce wavelengths much larger than flow thickness (26). These instabilities are shown to result from flow rheology alone, and simply require a rheological curve that exhibits shear-thickening behavior. Our observations of soil velocity profiles, in which effective viscosity increases with depth and therefore shear stress, may align well with a shear-thickening type rheology. Further, our proposed increase in cohesion at soil fronts may also result in an added free surface stabilizing force, which could allow the instability even without shear thickening behavior (26). Further study of these "oobleck waves" may inform the critical conditions necessary for solifluction terrace formation; in turn, field studies of solifluction may provide a natural example of similar instabilities at exceedingly low Reynolds Number, illuminating our understanding of subcritical fluid instabilities.

While we treat solifluction as a non-Newtonian fluid for a first approach, more study is needed to understand the complex rheology of solifluctING soil from a granular perspective. Granular flow rheology is currently understood within the $\mu(I)$ framework, a dimensionless form of the classic shear stress/strain rate relationship that accounts for confining pressure relevant for granular materials (55, 56). In essence, $\mu(I)$ is very similar to fluid rheology, but allows for the role of changing confining pressure with depth. However, the extremely low solifluction velocities observed in the field indicate that solifluction occurs not as a granular flow but well within the granular creep regime (57) that has been shown to describe soil transport velocities on temperate hillslopes (58). Granular creep rheology is still at the forefront of granular physics research. Experiments have shown that creep occurs below the assumed static coefficient of friction (57). While creep rheology is still uncertain, new models for creep indicate that rather than a viscous-like flow rule, an elastoplastic model may be physically relevant (59). Interestingly, a similar type of model was found to best describe solifluction experiments, rather than a viscous model (60). Experimental and field work is needed to understand whether solifluction is best described as a creeping granular material, a highly viscous non-Newtonian fluid, or some combination of the two, especially given the complex, temporally changing processes (frost heave, gelifluction) that are known to drive it.

Our results also suggest strong connections between climate and solifluction lobe morphology. While much more detailed work is needed to quantitatively understand the role of climate in setting solifluction patterns and lobe morphology, these results suggest that lobe morphology metrics measurable from remote sensing data may contain information about present and past climate, both on Earth and other planets. Additionally, these data show that a changing climate may have substantial effects on solifluction dynamics and morphologies. This relates to a fundamental, yet unanswered question: why do we only see solifluction patterns in cold places? We argue that solifluction provides an example of a contact line instability in a parameter space well outside that of previous studies, with the potential to help shed light on recently observed subcritical fluid instabilities (e.g., (26, 43)) and unstable behavior of soft materials (56). Strong heterogeneity in topography and material properties may be required for the instability to form, as is observed in subcritical fluid fingering over rough substrates (43, 61); it is notable that many arctic hillslopes exhibit solifluction terraces with smooth fronts that are not broken into fingers (8), further supporting the idea that solifluction lobes grow as a secondary instability on top of the downslope instability and require heterogeneity to form. However, we acknowledge that isolated solifluction lobes are also observed in areas with increased soil moisture (8), perhaps behaving similarly to an isolated droplet moving down a plane (62). A better understanding of critical conditions for the onset of the instabilities will also inform our understanding of solifluction lobes seen on Mars, whether they require a cold climate to form, and what explains the larger wavelengths seen on Mars (6, 41). Our findings may also have relevance for earthflows, temperate, slow-moving landslides that exhibit similar morphologic and dynamic characteristics to solifluction lobes (63).

Our analysis is targeted at behavior at the onset of the solifluction lobe instability. Once initiated, the pattern will be self-enhanced as the increased resistance at the raised lobe fronts will further stagger the flow. Nevertheless, more work is needed to understand the evolution of these features through time, as well as possible merging of lobes that would skew measurements toward larger wavelengths. Field studies could examine how disparate lobes interact; for example, once formed, the presence of lobes can redirect water flow through the landscape, influencing lobe development and initiation upslope/downslope (37). For the downslope instability, studies that examine downslope patterns in terrace front exposure dates could determine whether these waves form all at once or initiate at the bottom of a slope and propagate upward. The presence of lobes may also exert a weathering feedback on the underlying bedrock and permafrost, as soil thickness changes substantially along the length of a lobe.

Finally, our results highlight the importance of cohesion in landscape evolution. Rather than simply increasing shear strength, as typically assumed in Mohr-Coulomb soil mechanics models, we suggest that the presence of cohesion can lead to non-linear dynamics that cause large-scale instabilities in landscapes. While further field and experimental work is needed to better understand the rheology of arctic soils, we suggest that incorporating formulations of cohesion into soil transport models is key to accurately predict landscape evolution and response to climate change.

Materials and Methods

Lobe wavelength data. Wavelength calculations: Study sites were selected using a combination of high resolution orthophotos and a hillshade of the digital elevation model. We selected 30 hillslopes on the order of 500 to 1000m long where solifluction was the dominant topographic pattern throughout the domain. Sites with exposed bedrock, gullies, or ponds were avoided. Using a gradient and hillshade map, cross-hillslope groups of solifluction lobes were manually delineated (Figure S1). To streamline and standardize the delineation process, we represent each lobe as a georeferenced triangle. The three vertices defining the triangle were placed along the riser of the lobe at the apex and the two points on either side of the apex where adjacent lobes begin (Figure S1). Lobes were not delineated when riser edges and transitions into adjacent lobes were ambiguous. In addition, some sites contained smaller lobes superimposed on larger terraces or lobes. In these instances we delineated the smaller scale feature. In addition to individual lobes, a minimum of 5 downslope transects were delineated at each study site. Transects were oriented in the direction of the lobes with vertices added each time the transect crossed the riser of a lobe. Over 3500 individual lobes were delineated across 28 hillslopes.

For each lobe we used the triangle vector to estimate several planform morphological metrics including lobe orientation, width, and length. To determine orientation we first calculated the line bisecting the interior angle at the apex of the lobe. Lobe orientation was taken to be the direction of this line. Lobe width was calculated as the distance between the two endpoints on either side of the apex. Lobe length was calculated as the minimum distance between the apex and the line connecting the two endpoints. At each lobe a local transect was extracted from the elevation data using a 50m window centered at the lobe apex and in the direction of the bisecting line. Elevation profiles along the transect were extracted using linear interpolation with the number of points in the profile determined by the length of the transect and the DEM resolution (length/cell-size) (figure S1b,c).

From the profile, lobe height and contact angle (referred to as riser angle in the solifluction literature) were determined. Transects were first detrended by finding the best fit line to the entire 50m transect in a least squares sense. The slope of the trend line was taken to be the parent slope. To calculate lobe height and contact angle, the detrended profile is subset to only include the portion of the profile representing the manually delineated lobe and 2m down slope of the lobe apex (figure S1d). Height is calculated as the elevation range in the subsetted profile. Contact angle is calculated as the maximum derivative along the subsetted profile using a central differencing scheme (numpy gradient citation).

Climate data. We use SeNorge2, a gridded meteorological data set with a spatial resolution of 1 square kilometer and a temporal resolution of 1 hour to estimate typical climate conditions for each study site. Data comes from the Norway Meteorological Organization and can be found at URL LINK?. While hourly data is available, in this study we used products released at the daily timescale. The variables include maximum daily temperature, minimum daily temperature, mean daily temperature, and daily precipitation. The gridded data is interpolated from monitoring stations throughout Norway and is corrected to account for elevation. For full description of the climate data see (49). We identified each grid cell containing a study site and extracted the previous 20 years of daily climate data. We calculated the number of frost cycles per year at each site where a frost cycle was defined as a zero crossing of the temperature data. Since the hourly data is summarised at the daily scale this is equivalent to a change in sign between the maximum daily temperature and the minimum daily temperature. We used the surface temperature data as a proxy for ground temperature (i.e. no corrections/adjustments are made). Justification comes from experimental studies measuring soil movement due to frost heave and gelifluction. We averaged the morphology data at each site in order to compare with the of frost cycles, and bootstrapped 95 confidence intervals for the means.

Data Archival. All data and code used to produce figures will be available at the NGEE Arctic Data Repository. Norwegian LiDAR data are available for download here. Norwegian climate data are available here. Additional figures and supplementary information are provided in the SI Appendix.

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