Patterned Ground at Beartooth Butte and East Summit, Wyoming: Geometry, Analysis, and Origin

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Introduction

The spectacular nature of patterned ground makes the recognition of its occurrence an intriguing experience at each new location. Patterned ground refers to the self-organization of stones and fines into regular geometric patterns at the ground surface. The patterning results from self-organizational processes in periglacial and alpine regions associated with recurrent freezing and thawing of the active layer. The actual processes of self-organization are complicated because many mechanisms act concurrently. Patterned ground was ubiquitous along the margins of ice sheets that advanced into North America during repeated full-glacial episodes throughout the Quaternary Period. Although patterns have been impeccably preserved in relict forms during the Holocene interglacial period, some patterned ground remains active. Active patterned gound occurs most commonly at high altitudes in temperate regions and at all elevations in arctic regions. This study utilizes data collected during several weeks of field work in August, 1994, to describe the three-dimensional geometry of patterned ground at locations of both relict Pleistocene periglacial and Holocene alpine environments in Wyoming. The Pleistocene periglacial environment brought rise to patterned ground on East Summit, while patterned ground in Alpine regions during the Holocene is occurring on top of Beartooth Butte. The nature of patterned ground at both locations grades from polygonal to elongated polygons, and then to stripes with prominent steps or lobes. Field descriptions are based on surveying, trenching and sampling, followed by an experimental analysis of the nature of the rheological properties of the material undergoing active patterning. The ultimate goal of this study is construction of a model that will be used to estimate rates of solifluction at the location of active pattern formation.

East Summit of Beartooth Pass (approx. 109°27'00"N 44°58'30"W) is located at approximately 11,000 ft along Beartooth Highway. East Summit is speckled with patterned ground which increases in width of pattern and size of stones towards mafic and granitic tors protruding above the regolith. An area of patterned ground 30 square meters was surveyed and mapped in detail with a total geodetic station along the ridge of the summit on the southwest-facing slope. Five trenches were dug perpendicular to the slope to a depth of 1 meter and the trench walls were logged.

Beartooth Butte (109°37'00"N 44°57'30") has patterned ground along its westward sloping ridge at approximately 10400 ft. The landscape on the ridge is comprised of limestone clasts and a very fine-grained matrix bare of vegetation. Zones of pattern differentiation were recorded from the ridge top, 5 trenches were dug to various depths and the trench walls were logged. Samples of the bimodal material were taken to study its physical properties.

Patterned Ground Features at East Summit and Beartooth Butte, Wyoming

At East Summit, the polygons and stripes are defined by stone borders. The borders are comprised of angular to subangular granitic stones ranging, up to 1.5 meters (long axis), and averaging 0.30 meters for the majority of stones. The borders have large spaces between adjacent boulders. Boulders size decreases noticeably from the horizontal ridge, downslope to a maximum gradient of 15°. The patterns on East Summit are about 1.5 - 2 meters from the center of one pattern to the center of a adjacent pattern, and 1.2 - 0.8 meters from neighboring stripe centers. The centers of the patterns are composed of weathered granite and organic material. The organics in the centers originate from a thick cover of vegetation which magnifies the contrast between borders and centers.

The trenches reveal the shapes of the polygon borders and centers in cross-section, and an extensive root structure which has traces at 55 cm depth (See Fig 1). The trenches also reveal the development of soil horizons within the centers. The borders have a thick accumulation of dark organics which seem to have washed down from the overhanging vegetation to a depth of 60 cm. All the trenches on East Summit reveal a broadening of the borders with depth. At a depth of 80-100 cm, the centers of polygons consist almost exclusively of bedrock weathering in place. This leads to the hypothesis that the stone borders merge into a stony layer as described previously by Washburn (1973). The borders broaden with depth below stripes also, but here the stones seem to connect in a continuous layer of matrix free angular granitic clasts at approximately 40 cm depth. This may be caused by running water washing out the fines from between the larger clasts, a process, defined as eluviation by Washburn (1979).

Earlier work on patterned ground (Washburn, 1973) has provided criteria to determine the periglacial activity at a site. Inactive patterned ground is called relict. The patterned ground at East Summit fulfills three of the five criteria defined by Washburn (1973) to be classified as relict. Although the site continues to fall below 0°C during the winter months, the thickly woven mat of vegetation, lichen cover over 70% of the upper surface of border stones, and the development of soil horizons provide evidence that the amount of movement occurring is negligible.

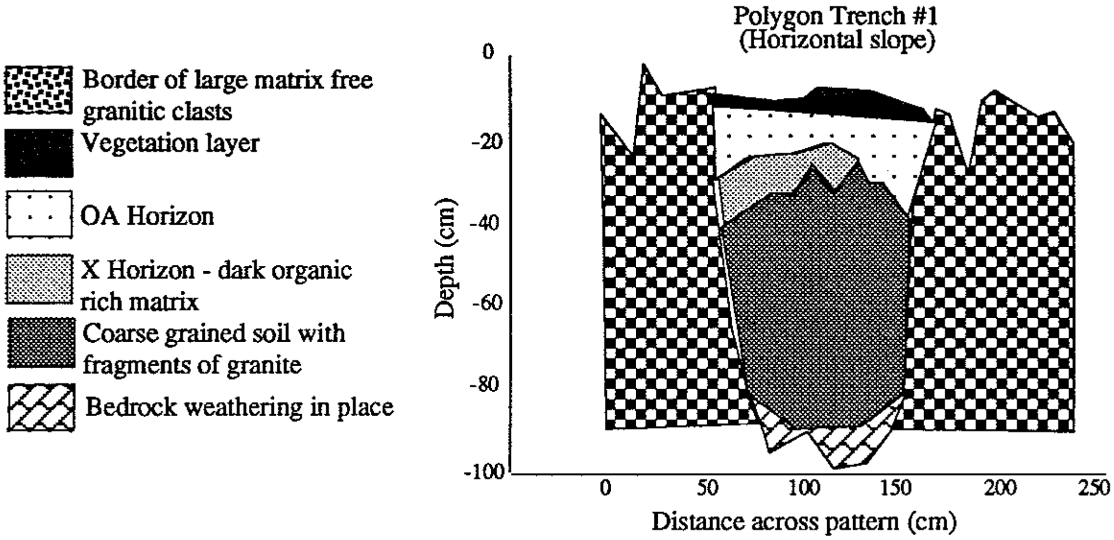
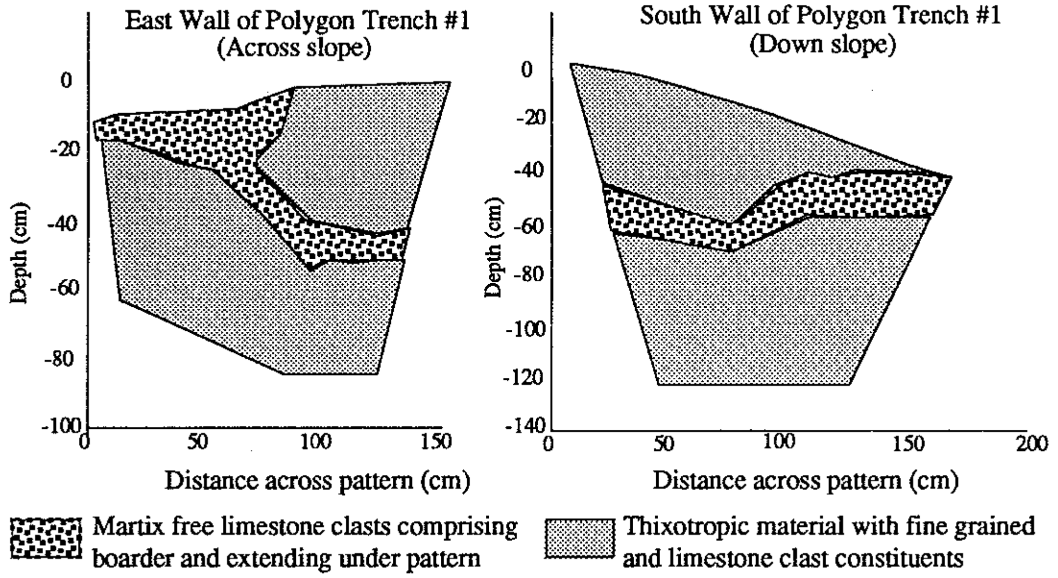


Figure 1 (above) Logged Profile of East Summit trench.
Figure 2 (below) Logged Profile of Beartooth Butte trench.



The Beartooth Butte area is covered by a limestone gravel lag; the patterns are therefore defined by the vegetation which is limited to the border areas. The patterns extend along a westward-facing ridge on a 15° slope. The patterned ground on Beartooth Butte has a diameter of 1.0 -1.5 meters for polygons and 0.8 - 0.4 meters for stripes. The centers of the shapes are composed of a fine-grained matrix with limestone clasts similar in size to those in the border. The limestone comprising the borders are tabular and average 4 - 5 cm along the long axis. The polygons are lobate at the downslope end and seem to over-ride one another, forming pits where several borders intersect. Solifluction steps form along the ridge just north of the study area.

Trenches at this location reveal that tabular clasts oriented with the long and intermediate axis in the plane of the boarder. The borders at this site narrow downward and sometimes pinch out at a depth of approximately 25 cm. Two of the five trenches show a matrix-free gravel layer at a depth of 30 cm. This gravel layer connects to the surficial border gravel and reveals its lobate form three-dimensions. Three of five trenches had buried organic lenses containing bark at depths of 75 cm, 85 cm and 105 cm. Samples of these organic lenses were taken for Carbon-14 dating. The buried organics and gravel layer may be a previous surface which has since been buried by a successive solifluction lobes.

Solifluction may be the controlling factor in forming patterned ground at this location. Because the patterns shape grade downslope without change in slope gradient, a factor other than slope must effect the degree of shape gradation. The area downslope is likely to get more water during times of heavy rain or snow melt because of its increased drainage area. The substance is relatively thixotropic therefore, a greater water content in the soil may change the viscosity of the soil. Areas of low moisture and high viscosity may produce lobes and nets, while more saturated areas with lower viscosity may produce elongate flows and form stripes. One day after thundershowers, small areas of activation were seen forming miniature stripes defined only by darker color, presumable wetter, and slightly higher relief of the fine grained material. The activation after storm events suggests that the landscape of Beartooth Butte must seasonally undergo significant movement stemming from the saturation and flow of the surface material. It also stresses the importance of the availability of water at this site as a control to movement associated with the formation of this patterned ground. An analysis of the rheological properties of this thixotropic material would allows a greater understanding to when, how, and why this landscape begins to activate and the rate at which it can be expect to move.

Rheological Equations for Newtonian Viscous Substances

The rheological property that provides the greatest degree of understanding about the flow characteristics of the soil is dynamic viscosity. Samples were taken only from Beartooth Butte because relict patterned ground may loose some of the important rheological characteristic when soil horizons develop. Dynamic viscosity is the internal friction of a fluid that resists forces tending to cause flow. So, in order to better understand when, and why, and at what rate this material will flow, we need to know the forces which will resists its natural tendency to deform and flow by the force of gravity. In order to calculate the viscosity of the thixotropic material at Beartooth Butte, several assumptions were made:

- These clasts greater than 2.83 mm are either entrained, or that they ride on the top of the flow and therefore do not affect the viscosity. Therefore, the limestone fragments greater than 2.83 mm were removed.
- To allow for a calculation of viscosity, the material is treated as if it flows as an ideal Newtonian fluid.

- For an ideal Newtonian fluid the relationship between sheer stress and strain rate (velocity gradient) can be used to determine viscosity from the following equation:

$$(1)\quad \tau = \mu \frac{\partial u}{\partial z}$$

- Variation of shear stress with depth caused by gravity: H = depth of fluid z = height of μ measurement

$$(2)\quad \tau(z) = \rho\ g\ (H-z)\sin\theta$$

- Equating the two statements for shear stress and solving for velocity:

$$(3)\quad \frac{\partial u}{\partial z} = \frac{\rho\ g\ \sin\theta}{\mu}(H-z)$$

- Integrating for velocity at the surface (z=H) =

$$(4)\quad u(H) = \frac{\rho\ g\ \sin\theta}{\mu}\left[\frac{H^2}{2}\right]$$

These variables can be attained by a simple apparatus which allows us to measure each quantity during a flow and calculate μ(See Figure 3). A channel was constructed out of Plexiglas with lengths and heights marked out in regular intervals. Water was added to the sample and the density of the mixture and slope of the channel were measured. The reconstituted debris was put into the channel and time and heights of flow were taken at regular intervals. Height was measured as the average height during the one interval and the velocity was the average velocity over that interval.

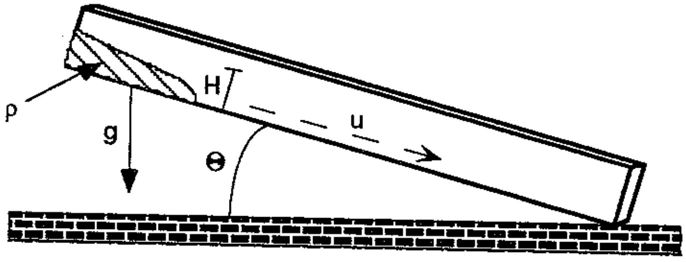


Figure 3 Experimental apparatus for calculating viscosity

Density	Slope	Average Viscosity
kg/ m^3	degrees	Pa * s
2560	10	625
2560	15	1327
1420	5	237
1420	10	351

Figure 4 Preliminary viscosity calculations

The density of 2560 kg/m^3 has an associated viscosity equivalent to thick honey or peanut butter. Observing the behavior of flow for the more dense substance exhibited flow which appeared to be non-viscous. When the density is lowered to 1420 kg/m^3 the substance flows as a viscous fluid and its viscosity falls to values which are similar to those of pea soup.

Modeling

In order to understand the rate at which a substance flows, an understanding of how it flows is important. Flow can be modeled as one of the following types of substances or any combination of two: viscous, pseudoplastic , or Bingham substance. A simple experiment monitoring velocity profiles and its properties will allow the determination of the nature of flow. Plotting velocity vs. distance from center of channel will allow a best fit profile to match the nature of flow (See Figure 5)

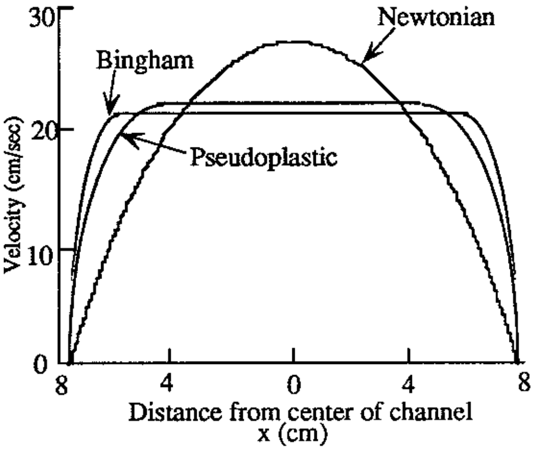


Figure 5 **Sample velocity profiles of viscous, pseudoplastic, and Bingham substance**

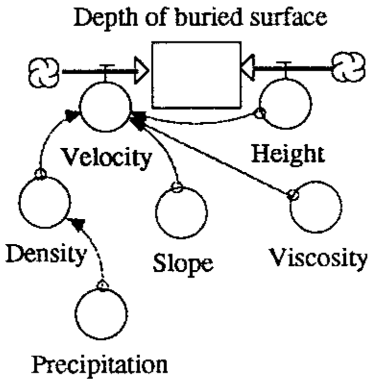


Figure 6 **Generalized model for solifluction velocity**

The next step is to model the rate of solifluction over time. Using a system dynamics software package, *Stella II*, a generalized model for rate of solifluction can be constructed using known climatic data and radiocarbon date of the buried organics. The model will focus on the amount of water causing the thixotropic soil to activate. The more water exposed to the substance the less viscous it becomes and the greater the rate of solifluction. (See Fig. 6)

Conclusions

About one-fourth of the earth's surface is perennially frozen ground which partially thaws in the summer. The National Research Council, in a 1991 report on the *Opportunities in the Hydrologic Sciences*, emphasizes the need for research in the hydrology and geotechnical processes of cold regions. The complexities involved in understanding surface water and ground water interactions challenge our understanding. With research "the cause of the impacts of these problems on hydrologic and water resource applications, geotechnical considerations, the development of cold region landscape, ecosystem dynamics, and biochemical cycling" can be further developed. The present study is designed to help develop an understanding of some basic periglacial processes that may lead to a greater depth of questioning, more specifically the controls which govern its mechanics.

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