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Patterned ground is ubiquitous in Arctic and alpine areas. In order to improve our understanding of this phenomenon, we developed extensive field instrumentation that has been recording principal soil properties over the past four years. The resulting data constitute the first quantitative year-round records of important seasonal processes such as freezing, thawing, frost heaving, and settling in the active layer in a sorted circle area. In addition, the data provide unprecedented insight into the long-term dynamics of active sorted soil patterns. We have complemented our field research with analytical and numerical studies of sorted pattern formation. Deterministic and stochastic analyses of pattern development in the absence of significant soil deformation reveal strong textural instabilities; stones initially distributed at random through the soil tend to migrate quickly toward domains slightly richer in stones, which eventually leads to the distinct sorting characteristic of diverse forms of patterned ground. Our numerical model of sorted stripe formation successfully simulates stripe development, and sheds considerable light on formative processes. In addition, we have developed a novel model to assess buoyancy forces that arise in the thaw process, and may be responsible for the long-term circulatory soil motion we have documented in sorted circles in Spitsbergen

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PROCESS STUDY OF SORTED PATTERNS IN ARCTIC SOILS

FINAL REPORT

BERNARD HALLET

UNIVERSITY OF WASHINGTON

MARCH 1,1991

U. S. ARMY RESEARCH OFFICE

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TABLE OF CONTENTS

PARTICIPATING SCIENTIFIC PERSONNEL.........1
INTRODUCTION.........2
FIELD WORK.........2
INSTRUMENTATION.........4
MEASUREMENTS: SELECTED RESULTS.........4
THERMAL ANALYSIS: LATENT HEAT CONTRIBUTION.........8
MODELING SOIL DEFORMATION IN THE ACTIVE LAYER
    Viscous model of thaw consolidation.........11
    Finite element model of soil deformation.........11
TEXTURAL INSTABILITY
    Deterministic model.........13
    Stochastic Model.........14
SUMMARY.........14
REFERENCES.........16
PUBLICATIONS.........17
APPENDIX A: Abstract of "Buoyancy Forces..."........18
APPENDIX B: Abstract of "A stochastic model..."........19

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- William Bruner
- L. Al Rasmussen
- Bradley T. Werner

Graduate Student:
- Jacquie Smith, Masters of Science, 1989

INTRODUCTION

Patterned ground is ubiquitous in Arctic and alpine areas. It is expressed in various forms, including ice-wedge polygons and sorted circles, which are among the most striking geometric patterns in nature. Although diverse types of patterned ground have been studied for nearly a century, we do not yet fully understand how these features form and, in particular, what dictates their size, shape, distribution, and other characteristics. From a more practical point of view, much is to be learned about how these features reflect useful information about the terrain and soil.

In this context we conducted a detailed study of the physical properties of the upper meter of soil in areas of active sorted circles, which are broad gravel ridges encircling slightly domed areas of fine-grained soil, two to three meters across (Figure 1). This study was a continuation of research initiated under National Science Foundation sponsorship in western Spitsbergen. It benefited from seasoned instrumentation in situ at several study sites, and an unprecedented data set on active layer properties.

Herein we summarize the results of our coordinated field and theoretical studies.

FIELD WORK

In the first six months of this research effort we designed and assembled a custom instrumentation system aimed at defining more precisely and unambiguously the physical conditions in the active layer. Electronic control boards and sensors were tested and calibrated in cold rooms at the University of Washington. We then traveled to Spitsbergen in September 1987 to install this new system and to continue our ongoing study program. We conducted complementary field work in 1988 and accompanied two groups of international experts to our study sites as part of excursions to Spitsbergen organized in connection with the Fifth International Conference on Permafrost, held in Trondheim, Norway. In the summer of 1990 we completed our field work and recalibrated most of our thermistors.

Monitoring of our sensors is continuing beyond the December 31, 1990 end date on this project. This is possible because a collaborative agreement with Professor J. Sollid (University of Oslo) and the Norsk Polarinstitutt gives us access to technical personnel stationed year-round about 10 km from our study sites, who perform routine data transfer and maintenance at no charge. The occurrence of exceptionally well developed sorted circles together the considerable logistical and scientific benefits associated with this collaborative agreement make the Ny Alesund region of Spitsbergen an ideal area for conducting this research.

Figure 1. Circular domains of fine-grained soil 2 - 4 m across are surrounded by gravel ridges ~ 0.2 m high in this patterned ground area, Spitsbergen, Norwegian Arctic. These sorted circles are active; the ground surface moves up and down ~0.1 m as the upper 1-2 m of soil freezes and thaws seasonally. Over the long-term, considerable horizontal soil motion occurs at the ground surface, with marked convergence at the periphery of the fine-grained soil domain: whereas fine-grained soil moves radially outward at rates up to ~10 mm per year, surface gravels on the inner portion of borders move in the opposite direction at a similar rate. Subduction of soil occurs at sites of convergence and maintains a distinct peripheral trench along the interior edge of gravel ridges. The distinct sorted patterns constitute striking examples of self-organization particularly in view of the initial state: more than 4×10^4 years ago, this area was a wave cut platform covered with a 1-2 m-thick layer of a coarse mixture of beach sediments.

INSTRUMENTATION

Based on our past work we were able to design instrumentation that circumvents limitations evident in our previous systems, and answers questions we could not previously address. Extensive circuitry was required to interface a small computer (Tandy Model 100 with memory upgraded to 256K) with an extensive array of diverse transducers. They were largely comprised of commercially available units modified and packaged to make them suitable for long-term use in the harsh Arctic environment. The transducers include 4 soil pore pressure sensors, 2 differential pressure transducers configured to measure lateral differences in total soil pressure, 8 double-axes tilt cells with embedded thermistors, 8 soil heave transducers, and 4 temperature rods consisting each of 15 precisely-spaced thermistors (Figure 2). Care was taken to provide considerable redundancy so that the loss of any particular sensor would not undermine our monitoring effort. Numerous reference readings permitted us to verify that the system was operating properly.

After four years of continuous use, the computer, electronic control board, and practically all sensors still appear to be functioning properly. Electronic drift has been minimal as can be checked from independent signals from several ultra-stable and temperature insensitive resistors (Vishays). Moreover, examination of zero-degree plateau signals during four consecutive autumn periods reflects little or no drift in our thermistors; the apparent "drift" in individual thermistors corresponds to less than 0.02 °C, and commonly no more than 0.005 °C after four years.

MEASUREMENTS: SELECTED RESULTS

Temperature data obtained during the early thaw period in 1989 proved particularly interesting because they provided an excellent record of strikingly unexpected behavior in the thermal regime of the active layer. Previous temperature studies of the active layer by us and others have revealed a relatively simple conductive system. For example, in the early summer as snow melts off the ground, temperatures at all depths generally rise smoothly through time; temperatures and variations in temperature decrease steadily with depth due to warming at the ground surface (Figure 3A). In contrast the June 89 temperature record at the same site reveals a sudden warming at a depth of 1.0 - 1.5 m in the active layer from less than -2°C to 0°C in less than 12 hours (Figure 3B).

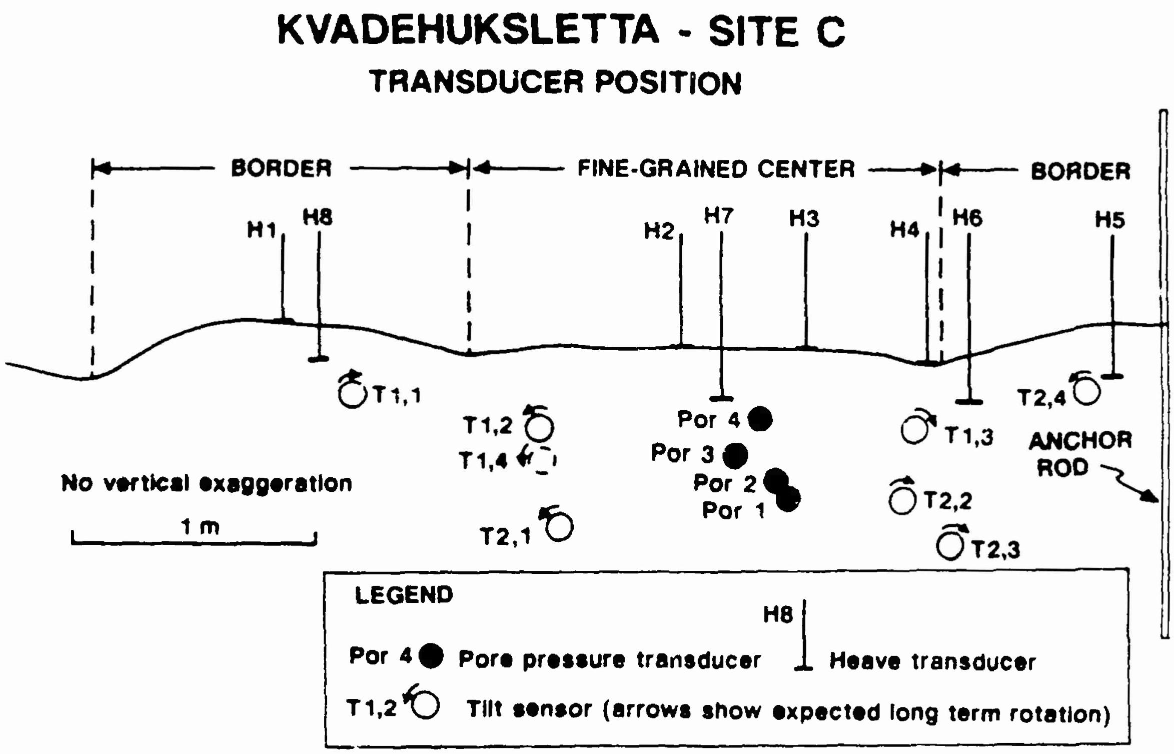


Figure 2A. Vertical section through a sorted circle showing the distribution of sensors at site C, located about 10 km NE of Ny Alesund in the Scandinavian Arctic. Heave sensors are bolted to a horizontal bar supported by two 2-m vertical steel rods hammered into permafrost.

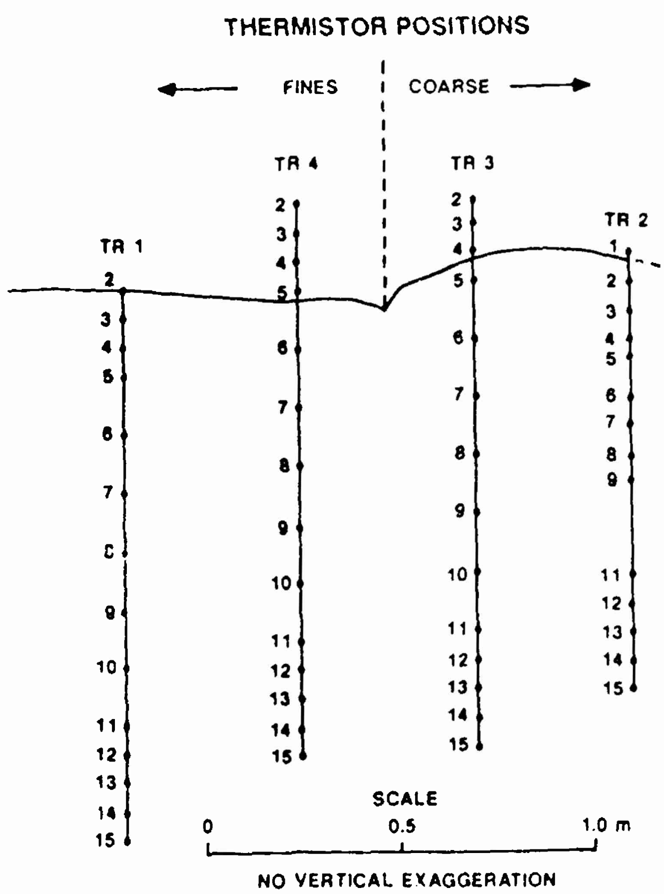


Figure 2B. Array of thermistor rods arranged to provide maximum information regarding both vertical and lateral components of heat flow.

TYPICAL EARLY SUMMER WARMING OF ACTIVE LAYER

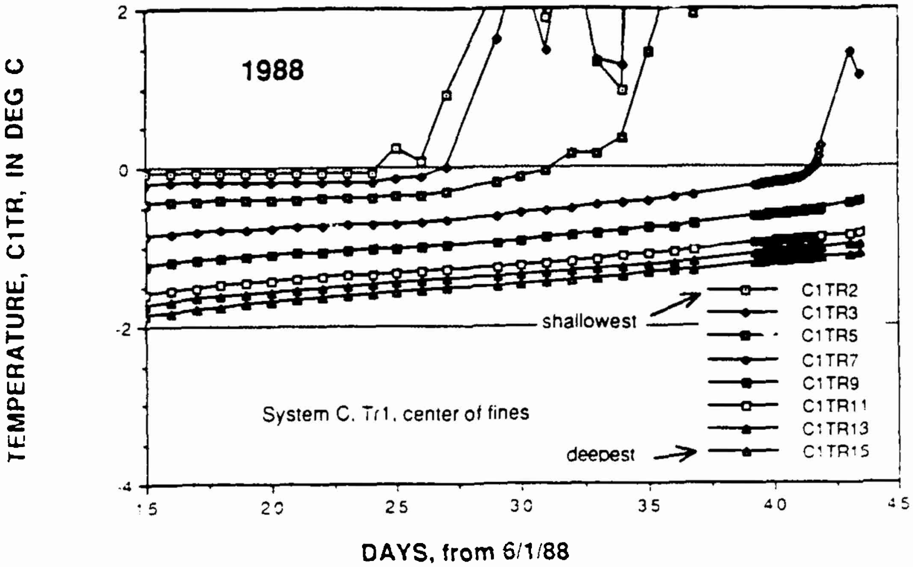


Figure 3A. "Normal" warming at the end of the spring in 1988. Upper curves represent thermistors at or close to the ground surface. After a very stable thermal period essentially at 0°C due to the overlying water-saturated snow, temperatures rise abruptly. This warming is delayed at depth. Lowest thermistors show slow steady warming at a rate of less 1°C per month. This thermal behavior is common and characteristic of a purely conductive system.

SUDDEN WARMING INITIATED AT BASE OF ACTIVE LAYER

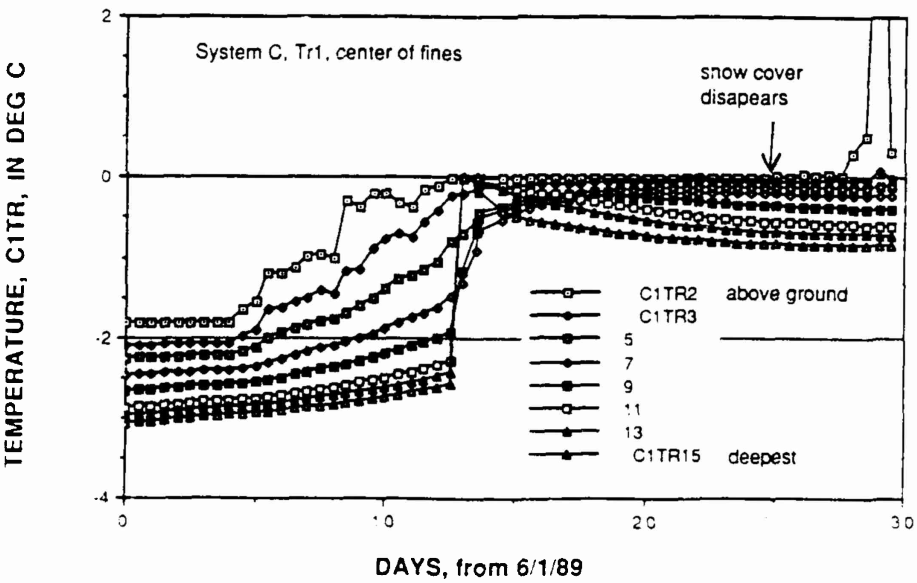


Figure 3B. This 1989 record and a similar one obtained in 1990 contrast sharply with Figure 3A from the same site. In mid-June 1989, the base of the active layer was suddenly warmed by about 2.5 °C in less than 12 hours, and the heating propagated upward conductively. As explained in the text this unexpected behavior is interpreted as resulting from rapid water movement in soil several degrees below freezing.

We attribute the sudden warming to latent heat of freezing of water flowing down slope through the lower portion of the active layer. Although relatively rapid water flow through frozen soil at temperatures as low as 2°C below the freezing point is both unexpected and previously unreported, considerable evidence supports this inference: (1) recorded pore pressures go from negative to positive values reflecting the influx of free water; (2) all heave transducers show surface heaving during the inferred refreezing; (3) the sudden warming at depth was recorded by the lowest 4 or 5 thermistors, representing the lower 0.5 m, in each of four adjacent thermistor rods; and (4) freezing of a minor volume of water (only about 1 - 2 % of the soil volume) would provide the necessary heat source.

This evidence for subsurface heating of the active layer is of considerable interest because, although short-lived (<12 hours), it is the dominant heat transfer process in a system that has traditionally been viewed as primarily conductive. Moreover, this advective heating may be responsible for unusually deep seasonal thawing, which is likely to be particularly favorable for the formation of patterned ground. It may also account for the exceptionally good development of sorted circles at our study sites. Viewed more generally, the rapid infiltration of water in frozen ground has significant implications for two important issues. First, the magnitude of warming due to water infiltration and freezing is so large that a long-term variation in the frequency or magnitude of such infiltration events may significantly contaminate the record of past surface temperatures contained in permafrost (e.g. Lachenbruch and Marshall, 1986). The second issue pertains to one of the most promising novel ideas for solving a major environmental challenge: the containment of leaking nuclear and other toxic wastes by creating a frozen ground barrier around the contaminant source (Dash, 1991). The technique has considerable promise provided frozen ground is indeed impermeable; our evidence for rapid water flow in frozen soil shows that this critical requirement is not universally satisfied and calls for caution in proceeding with this type of technology.

Returning to patterned ground, several lines of evidence suggest strongly that soil in the sorted circles we are studying in western Spitsbergen undergoes long-term convective motion, with a characteristic cycle time of centuries. The evidence includes measured surface soil displacements, as well as the pattern geometry, microrelief, subsurface distribution of plant material, subsurface structures, and diverse other geological data (Hallet, 1990). In this context, our tilt measurements are of interest because they directly record the rotational part of the strain field in the soil below the surface. In addition to useful information about differential heaving and settling that accompanies the freeze/thaw cycles in the active layer, tilt records reveal clear evidence for long-term rotation below the soil surface (Figure 4). These records, which are complemented by temperature and surface heave measurements, provide strong support for the notion that soil circulation occurs in active sorted circles.

THERMAL ANALYSIS: LATENT HEAT CONTRIBUTION

We have developed a method of using detailed temperature measurements to calculate how much ground ice formed as a function of time and depth in the active layer. These calculations involve computation of the divergence of the heat flux, which requires precise estimates of the soil thermal properties. There is considerable motivation to confirm and quantify these effects because they would permit the interpretation of relatively common soil temperature records as rich sources of information on the thermal regime, thermal parameters, and phase changes in ice content of the active layer. As a Masters thesis project, Research Assistant Jacquie Smith refined our numerical model of heat transfer in soils, and examined closely the damping of temperature variation with depth to obtain site-specific apparent thermal diffusivity values. She evaluated the apparent rate of latent heat production for each soil depth increment bracketed by thermistors through time and the corresponding rate of freezing or melting in soils. Clear thermal anomalies represent pervasive latent heat input to melt ice in the early summer and output to freeze water in early fall (Figure 5).

With the aid of A. Rasmussen, B. Hallet has continued to improve the numerical analysis of the thermal data. In their present model considerable care was taken in developing the finite-difference approximations, and the effective thermal conductivity was calculated as a function of temperature and extent of saturation based on published theoretical models. Calculated thermal conductivities are constrained to be in accord with four independent measurements: (a) NMR measurements of the unfrozen water content of soils from our sites (obtained from A. Tice at CRREL), (b) moisture content of representative soil samples, (c) in situ ice content reflected in vertical frost heave at the ground surface, and (d) apparent thermal diffusivity obtained from the observed attenuation of temperature variation with depth.

We have also considered lateral heat flow, and vertical gradients in thermal properties in recognition that the total H_2O content in soils commonly varies with depth due to surface drying or wetting. This work also provided us ample motivation to assess the accuracy of our temperature measurements more precisely, and eventually to recalibrate the thermistors in Spitsbergen. We are currently finalizing this analysis,

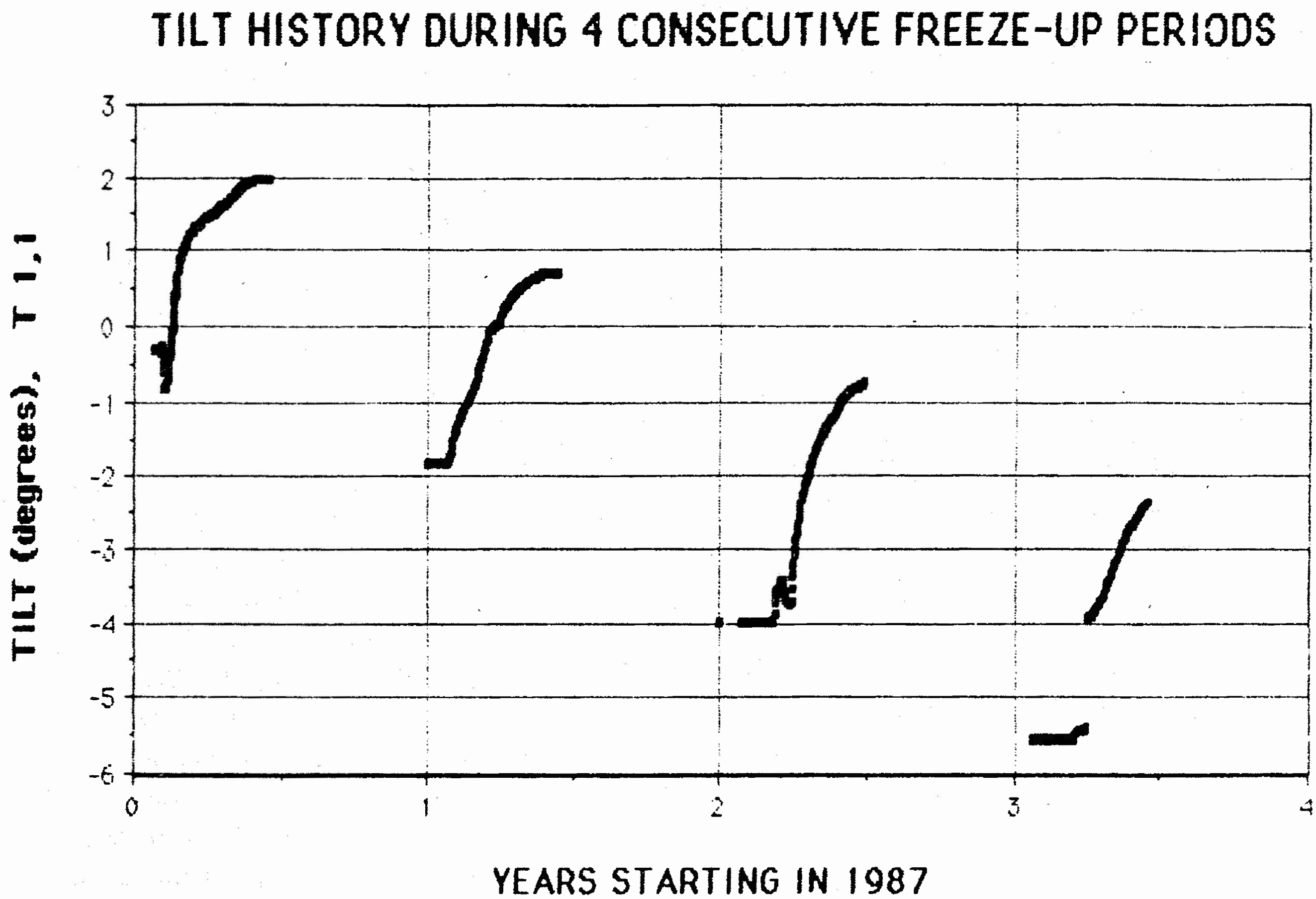
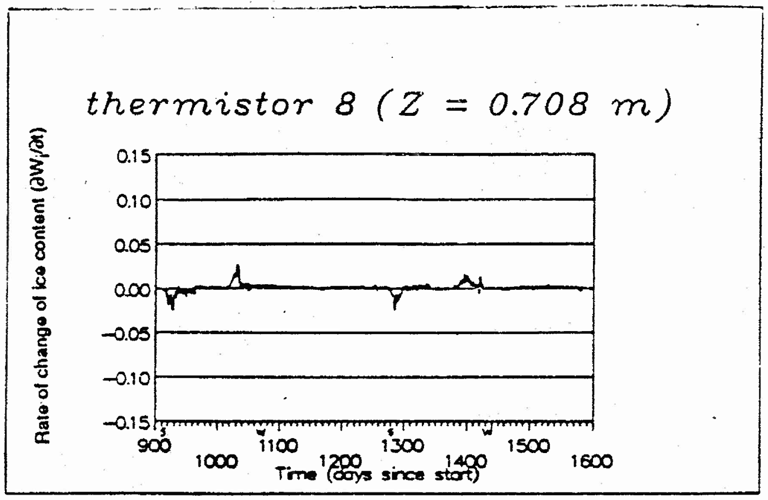


Figure 4. Tilt history during four consecutive freeze-up periods extending from 1977 to 1990 for sensor T1.1 shown in the left-hand border in Figure 2A. The record for each year extends from September 1 into December. Each year this sensor rotated 2 to 3° in a counter-clockwise direction presumably because frost heaving in the fine-grained circle centers exceeds that in the border. It rotated back in the clockwise direction during each thaw period, but data from these periods are omitted for clarity. Over the 4-year duration of this data set, its ratchet-like motion produced a net rotation of about 5° in a clockwise direction, which is compatible with the long-term convective motion in gravel borders that we inferred from measured surface displacements and diverse geologic evidence.



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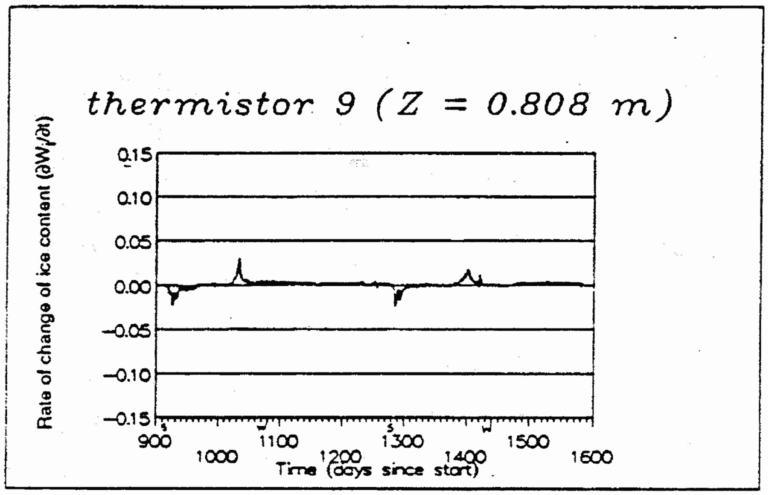

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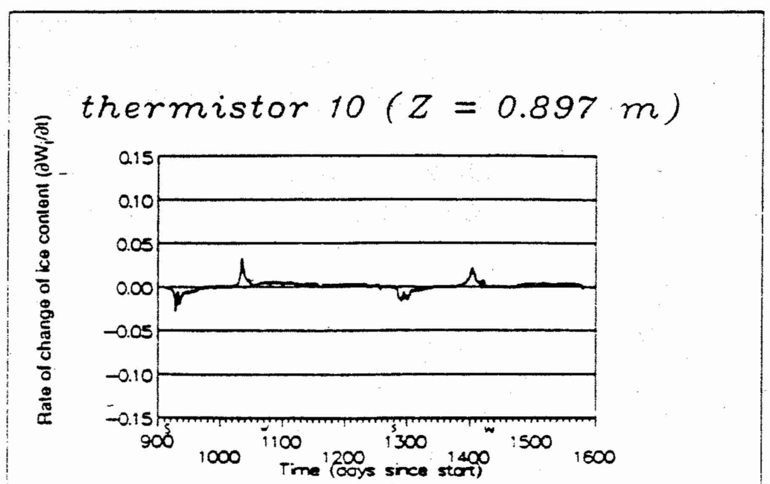

(g)

Figure 5. Rates of change of ice content versus time at three distinct depths, z, obtained from our detailed temperature record analyzed through a model of heat conduction with temperature-dependent thermal conductivities. The time period represented extends from June 1985 to May 1987. Downward and upward spikes distinctly record periods when ice is melted and periods when water is frozen, respectively. The area subtended by these spikes is proportional to the amount of

using refined estimates of thermal conductivity and temperature measurements that benefit from the thermistor recalibration conducted in July 1990.

MODELING SOIL DEFORMATION IN THE ACTIVE LAYER

Viscous model of thaw consolidation.

We have developed a novel thaw consolidation model to study how the interaction between soil consolidation and thaw penetration can generate complex density profiles. Situations where the soil bulk density decreases with depth represent destabilizing buoyancy forces (Figure 6). Such forces are of particular interest because they may be partially or largely responsible for the long-term diapiric and circulatory soil motion in the active layer that has long been widely recognized but remains imperfectly understood. Please see the attached abstract to a paper on this subject that we have recently submitted for publication.

Finite element model of soil deformation.

Considerable work by co-PI Waddington has focussed on a finite element code to model soil deformation idealizing the soil as a layered non-Newtonian viscous material subjected to a variety of boundary conditions and applied forces. The intent of this modeling effort is to elucidate factors responsible for the long-term convective motion of the soil in sorted circles areas that we have documented in our field studies. In the model various surface tractions and body forces can be imposed to study, for example, soil displacements resulting from the subsidence of soil domains previously heaved upward during the freezing period, and those resulting from buoyancy forces that arise naturally as the active layer thaws and consolidates.

A time-marching version of a finite element fluid flow model is operational. Work is in progress to modify the boundary condition treatment to incorporate the moving thaw front with its accompanying large gradients in material viscosity. This allows us to model net soil displacements throughout a typical year. We intend to incorporate three important effects: (a) elevation of borders during freeze-up, (b) net motion upward in centers during thaw driven by subsiding borders, and (c) mass wastage carrying surface material toward borders. In addition, since field evidence points to particularly large lateral displacements within the border materials, we are extending the model boundary conditions to incorporate shear forcing at fine/coarse borders.

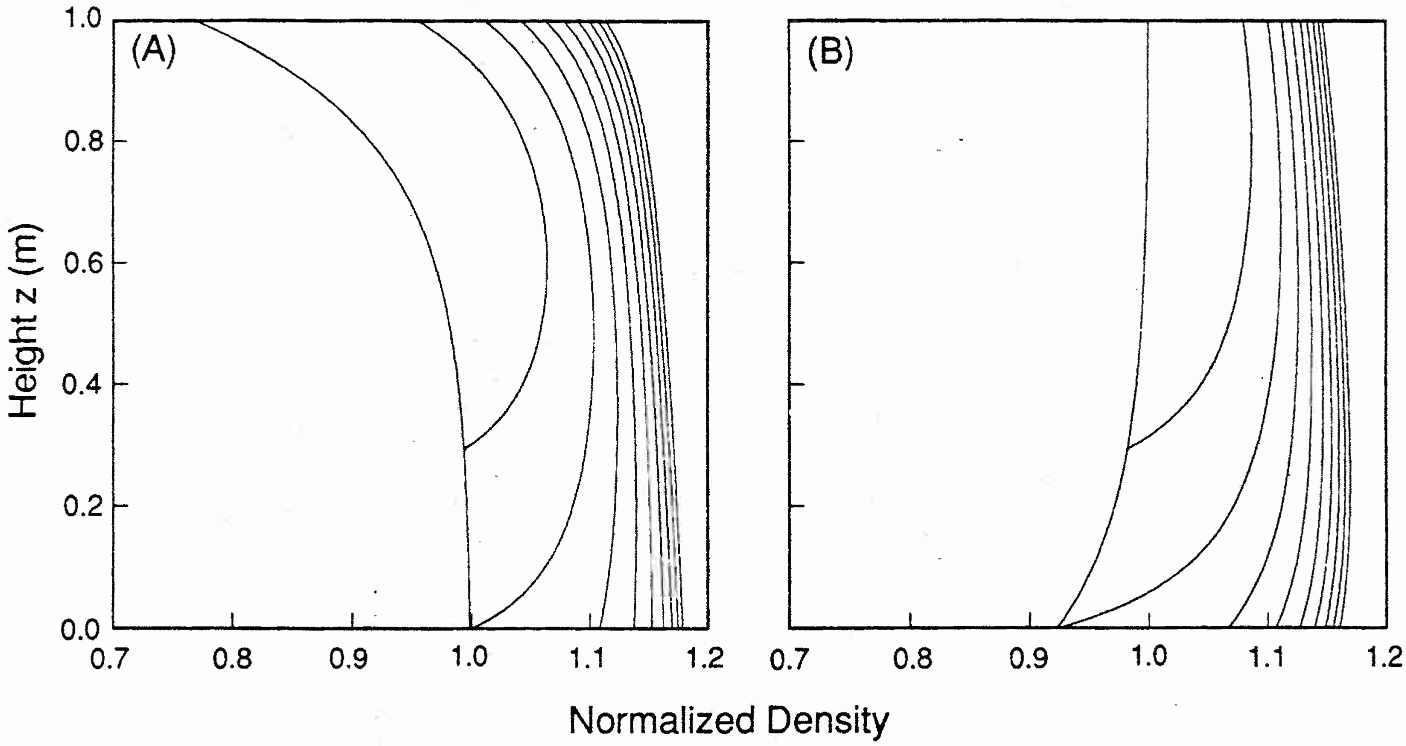

Figure 6. Thaw consolidation of a uniform silty clay layer with initial vertical variation in ice content. Curves represent the loci of soil bulk densities at time intervals of 0.5 months, starting when thawing starts at the surface. Where curves rise toward the right the density increases with height above the permafrost, and hence, is gravitationally unstable. Soil parameters are: particle radius, 13.4 μm, effective soil viscosity, 10^{10} Pa-s, and initial permeability, 10^{-13} m^2.

(A) excess porosity (ice content) concentrated near the surface, preventing or reducing the subsequent development of an unstable density profile.

(B) excess porosity concentrated near the bed (possibly due to water migration to an upfreezing front). The high porosity at depth enhances and prolongs the density inversion.

TEXTURAL INSTABILITY

Deterministic model

Progress was also made in the theoretical analysis of patterns of stones (sorted patterned ground) in freezing soils that may form as a result of a textural instability. This type of patterning is quite distinct from that presumably related to convection of soil or pore water in the active layer, and may be much more widespread in cold environments outside of Arctic regions. The analysis explores the feedbacks between texture and thermal properties: initial slight textural inhomogeneities tend to grow if the resulting thermal anomaly is conducive to further textural differentiation due to the selective displacement of soil particles during the freeze-thaw process. Preliminary results suggest that in frost-susceptible stony soils, stones will naturally tend to congregate in distinct domains with a natural length scale about 6 to 10 times the size of the large stones (Hallet, 1990). This result is encouraging as it is in accord with published data on sorted stripes, and with observations by Hallet of stripes in geographically diverse areas (including Central Otago, New Zealand, Mauna Kea in Hawaii, the Olympic Mountains in Washington, and our study area in Spitsbergen).

Former University of Washington assistant professor W. Bruner has initiated a formal analytical treatment of the mass and energy transfers that underlie this textural differentiation. Although his work is in progress it already represents a very significant step forward in our theoretical understanding of the formation of sorted patterned ground. He has obtained an analytic solution for the case of purely vertical sorting (no lateral perturbations in stone concentration). In this case stones near the surface, where heaving strain is greatest, are quickly carried upward to form a surface layer free of matrix, underlain by an essentially stone-free zone whose thickness increases logarithmically with time. Below this zone is a transition region in which the stone concentration increases rapidly with depth. Below the transition region, the stones have not been transported significantly and their concentration is essentially unchanged from its initial value.

Because each stone replaces its own volume in water-saturated fines, an increase in stone concentration decreases the latent heat that must be removed to freeze a unit volume of soil. Consequently, if horizontal perturbations in stone concentration are present, the freezing front propagates downward most rapidly where the stone concentration is highest. The resulting curvature of the freezing front causes stones to migrate laterally as they move upward through the soil, and this lateral migration amplifies the initial perturbations. W. Bruner has obtained an analytic solution for the evolution of the freezing front shape, for a horizontal perturbation in stone concentration which is sinusoidal in shape and infinitesimal in amplitude. This solution can be combined with the stone transport relations and the continuity equation to obtain an integro-differential equation for the growth of such perturbations. This equation is not amenable to analytic solution, but Bruner has been able to develop an approximate solution valid for horizontal perturbation wavelengths comparable to or smaller than the heaving strain decay depth.

The instability arising from this process is quite strong. By the time stones from moderate depths (4-5 times the decay depth) have reached the surface, the relative perturbation amplitude (the absolute amplitude normalized by the mean clast concentration) has grown by about 10^4 for representative soil parameters.

Stochastic Model

To better understand how random frost-induced rearrangements of rock fragments on a slope might lead to the spontaneous formation of evenly-spaced stone stripes, we enlisted the assistance of Brad Werner (a recent physics Ph. D. from Caltech). He developed a stochastic model of textural differentiation using a cellular automata approach. It permits exploration of how needle ice growth, subsurface ice growth, topography, and gravity all work together to rearrange material on the scale of individual particles. The models permit us to clarify how patterns develop and how specific factors are responsible for distinct types of self-organization. The model simulations produce stripe patterns that closely resemble natural ones (Figures 7 and 8). The results have been compiled into an animated series on video tape that show vividly how orderly stripes emerge from random arrays of stones. An extended abstract of this work is appended at the end of this report.

SUMMARY

Our field instrumentation provides us the first year-round record of what happens thermally and dynamically in the active layer in areas of patterned ground in the Arctic. Our records document in quantitative detail how important seasonal processes such as freezing, thawing, frost heaving, and settling progress in the active layer, and how these processes vary across individual sorted circles. In addition, the four years of monitoring are starting to reveal long-term trends that provide unprecedented insight into the dynamics of active sorted soil patterns.

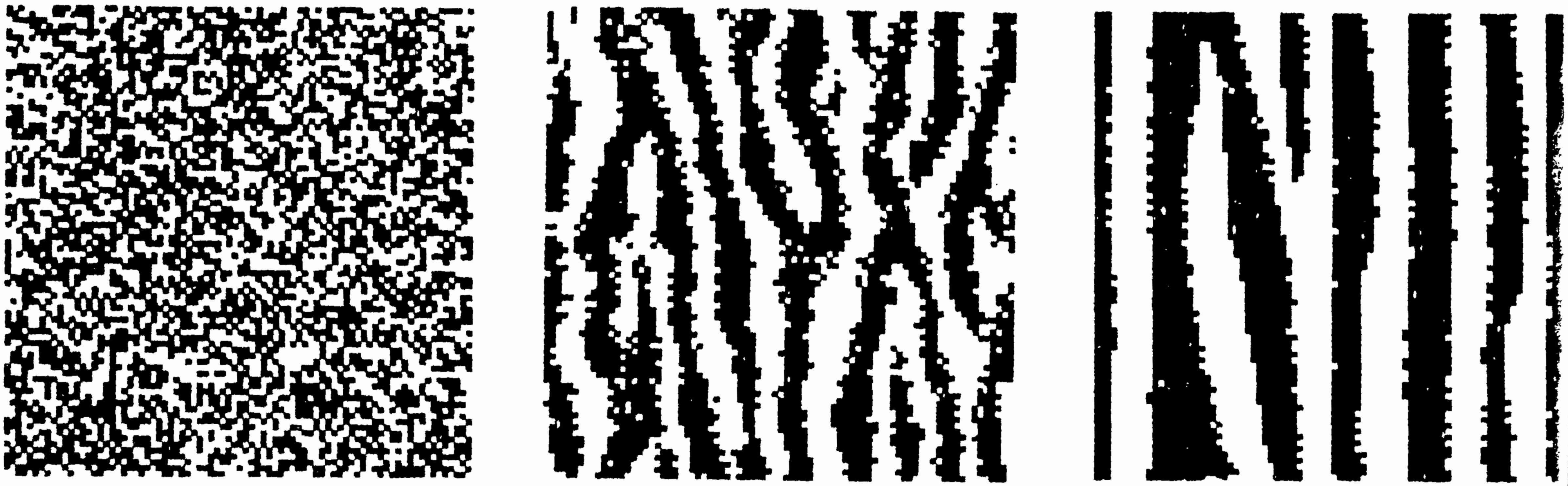

Figure 7. (above) The state of an 80x80 cell sorted stripe simulation is shown at three times: the initial configuration, after 256,000 stones moved, and after 5,120,000 stones moved. A blackened cell indicates stone occupation; a white cell represents exposed soil. Fifty percent of the cells are occupied by stones. Parameters are chosen such that the local slope near a stone domain margin and the mean slope are roughly equal. The random energy (temperature parameter) is set to one third of the potential energy change associated with moving one cell down slope. The spacing grows and the stripes straighten with time.

Figure 8. (to the right) Sorted stripes, spaced 120 to 150 mm apart, extend down slope for tens of meters on a 15° slope near the summit of Mauna Kea, Hawaii. Coarse-grained stripes are comprised of stones 20 to 30 mm across. This type of patterned ground probably results from recurrent needle ice growth on cold clear nights, which induces size-dependent random displacements of stones biased down slope.

Our analyses of the temperature records provide information about related physical processes such as water infiltration in frozen ground, and phase changes in the active layer.

The second part of this research is theoretical in nature. It comprises analytical and numerical studies of sorted pattern formation. Two end member situations are examined, one in which rock fragments are moved relative to stationary soil by freeze/thaw activity, and the other in which the diapiric or circulatory motion of the soil matrix is critical. In the context of our novel model of thaw consolidation, we have studied the modes of deformation of soil due to buoyancy forces that arise spontaneously in thawing soils. Both our deterministic and stochastic analyses of the stationary soil case reveal a strong textural instability in soils subjected to recurrent freeze/thaw cycles; stones initially distributed at random through the soil tend to quickly migrate toward domains slightly richer in stones and eventually lead to the distinct sorting characteristic of diverse forms of patterned ground. The numerical model of sorted stripe formation successfully simulates the development of stripes closely resembling those observed on natural alpine slopes.

We have nearly finalized our data analysis and modeling. Several papers presenting this material have been published or submitted. Others are in preparation.

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Hallet, B., and E.D. Waddington, Buoyancy forces induced by freeze/thaw in the active layer: implications for diapirism and soil circulation. 38 pages. Submitted for inclusion in Periglacial Geomorphology, Proceedings of the 1991 Binghampton Geomorphology Symposium, to be held Sept. 21 and 22, 1991 at the State University of New York at Buffalo.

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Anderson, S.P., Hallet, B., and R.S. Anderson, The 3-dimensional anatomy of sorted circles, western Spitsbergen. Intended for Arctic and Alpine Research.

Hallet, B., Stubbs, C.W., Gregory, E.C., Waddington, E.D., and R. Burton, Rapid water infiltration in frozen ground: its influence on the thermal regime of permafrost. Intended for Science.

Werner, B. and B. Hallet, A stochastic model for sorted stripe formation. Intended for the Bull. Geol. Soc. Am.

APPENDIX A: Abstract of "Buoyancy Forces..."

(paper submitted recently for publication.)

BUOYANCY FORCES INDUCED BY FREEZE/THAW IN THE ACTIVE LAYER: IMPLICATIONS FOR DIAPIRISM AND SOIL CIRCULATION

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ABSTRACT:

Indications of diapirism and soil circulation are common in periglacial areas but governing mechanisms remain unclear. We explore the possibility that such motion may be driven, at least in part, by buoyancy forces that arise seasonally in thawing ice-rich soil. Because thawing proceeds downward from the ground surface, the duration of the thaw phase and, hence, the time available for progressive soil compaction decrease with depth. More compaction and higher soil density may arise near the ground surface, but this tendency is generally offset by an increase in the rate of compaction and decrease in segregation ice with depth.

A theoretical model of thaw consolidation that parallels recent geophysical analyses of buoyancy-driven segregation of relatively light fluid from a viscous matrix provides quantitative insight into the soil compaction process. The model indicates that the density profile in a soil layer above the thaw front can be gravitationally unstable for much of the thaw season. Buoyancy can be a very effective driving force for diapirism where low permeability soil occurs at the base of the active layer. This is consistent with field evidence indicating that fine-grained soil commonly ascends to the ground surface in periglacial areas. On the other hand, buoyancy is generally incapable of driving wholesale soil circulation in unpatterned active layers, but may incrementally contribute to long-term circulatory soil motion in established sorted circles.

APPENDIX B: Abstract of "A stochastic model..."

(paper in preparation by B. Werner and B. Hallet)

A STOCHASTIC MODEL FOR SORTED STRIPE FORMATION

Sorted stripes are alternating bands of stones and soil with spacings ranging from centimeters to meters (typically about 10 grain diameters) and oriented along the steepest gradient (Washburn, 1973). These features occur on hillslopes mantled by a bimodal mixture of stones and soil and subject to frequent freeze/thaw events. Field observations at several locations indicate that transport of stones in sorted stripes is due to the growth and subsequent toppling of needle ice columns that form beneath the stones (e.g., Mackay and Mathews, 1974; Brokie, 1967). Needle ice develops under conditions in which the near surface soil is brought to the freezing temperature by radiative cooling, and water can migrate to the freezing front from below (Outcalt, 1971). The necessity for capillarity to import water for needle ice growth suggests that needle ice is more prevalent in soil domains than in stone domains. Further, needle ice toppling is expected to transport stones greater distances in soil domains than in stone domains, where neighboring stones inhibit stone transport. The surface of soil domains has been observed to be elevated relative to stone domains due to differential ice growth. Because ice needles are expected to grow perpendicular to the local surface (the local freezing plane), the most likely topple direction is along the local fall line. The local slope is attributable to a combination of the mean inclination of the hill slope, the slope created on the margins of soil domains by preferential uplift, and by random factors such as surface roughness or arrangement of adjacent particles.

The transport mechanisms underlying the development of these regular longitudinal patterns have been investigated using two-dimensional, plan view computer simulations of stochastic individual stone transport. The simulation incorporates approximately the physical processes described above. A two-dimensional rectangular grid with periodic boundary conditions forms the surface in the simulations. A cell can be occupied by one stone or can represent exposed soil. Stones are arranged initially on the grid in random positions. The system is evolved forward in time by moving individual stones to neighboring cells according to stochastic rules based on the likelihood of needle ice formation and the computed local slope. To represent the increased frequency of needle ice columns in soil domains and the decreased toppling distance in stone domains, the probability of moving a stone decreases linearly with the stone concentration in the region surrounding the stone and it increases linearly with the number of neighboring unoccupied cells. If a stone is chosen to be moved, the probability of transport to one of the up to eight empty neighboring cells is a function of the potential energy change associated with that move; the most negative potential energy change is favored. The potential energy change is a sum of that associated with the mean slope, and that associated with the local slope caused by soil domain uplift. The local slope is taken to be proportional to the concentration gradient. Lacking a mechanical model for needle ice growth and toppling on a rough surface, the probability is calculated according to the Boltzmann distribution, which facilitates introduction of a parameter specifying the magnitude of fluctuations in the system, kT: probability ~ $\exp(-\Delta E/kT)$, where ΔE is the total change in potential energy associated with the move.

In the simulations, sorted stripes develop in the following manner. Random fluctuations lead to the formation of small regions of high and low stone concentration. These regions coalesce to form alternating soil and stone domains elongated down slope. Further growth in the stripe spacing is effected by merger between adjacent stone bands and by the propagation of existing Y-junctions. When the local slope due to soil domain uplift is set to zero, transverse bedforms rather than stripes develop; stripes are destroyed in this case because maintenance of a stone domain boundary requires that the probability foı a stone to leave the domain is small. Soil uplift can shift the transport bias along the margins of incipient longitudinal stone domains from being biased down slope to being biased toward the stone band. The stripes that develop in the simulations are self-organized in the sense that they are produced by local interactions, and they are not the result of an externally supplied template.

The simulated sorted stripe spacing is observed to increase with time at a decreasing rate. The mechanism for spacing growth is stone stripe mergers. Increasing the fluctuation parameter kT results in an increased growth rate, which suggests that fluctuations are driving stripe mergers. A preliminary analytical model is predicated on the assumption that stripe mergers are caused by bends in the stripes, and that these bends are due to fluctuations in transport of stones along the stripe margins. The resulting model, similar to a model of wind ripples (Werner, Gillespie and Haff, in preparation), predicts that the stripe spacing increases lcgarithmically with time; therefore, the stripe spacing would be expected to appear stable at order 10-15 stone diameters.