

Stone Cold: Patterned Ground in Alpine and Arctic Regions

When preparing their fields for spring planting, farmers in temperate climate zones may have to deal with the nuisance of stones that have been pushed up to the surface during the winter months. The expansion of soil as subsurface water freezes is responsible for the frost heave that displaces the stones. In arctic and alpine environments, where vegetation is sparse, cycles of freezing and thawing repeated over hundreds of years can sort the stones from the soil and lead to self-organized patterns that have striking appearance and variety. The photographs show circles and labyrinths (both with characteristic length scales of about 1 meter); arctic and alpine regions also exhibit stone islands, stripes, and polygons.

"I'd show pictures of sorted patterned ground to my friends," says Mark Kessler, a postdoc at the University of California, Santa Cruz, "and they'd say, 'How does that happen?'" Working with his thesis supervisor, Brad Werner, at the Scripps Institution of Oceanography at the University of California, San Diego, Kessler came up with an answer: The myriad forms all arise from gravity and two simple feedback mechanisms through which the configuration of stones and soil at a given time influences stone transport and the subsequent evolution of the pattern.¹

Frost heave is responsible for both types of feedback. The frost heave that pushes stones occurs at a subsurface 0°C isotherm and exerts a force perpendicular to that isotherm. But because stony domains release less latent heat as they freeze than moist soil does, the isotherm is not parallel to the surface: It is deeper below regions where stones have congregated than it is in stone-poor regions. The expanding water can thus exert a significant force parallel to the surface. That force drives soil toward still unfrozen soil and pushes stones to regions of high stone concentration.

The second feedback mechanism comes into play when expanding soil squeezes and uplifts an adjacent stone pile. According to Kessler and Werner, the squeezing causes stones near the highest point to avalanche, while also driving other stones along the pile's long axis. As a result of the asymmetric motion of stones, the pile tends to further elongate.

To examine the consequences of the two feedback mechanisms, Kessler and Werner tracked stone movement in a numerical simulation. Tunable parameters determined the tendency of stones to congregate and the asymmetry of the motion of stones in football-shaped domains. Along with those motions—ultimately traceable to frost heave—the simulation included downslope motion to account for the effects of gravity on formations occurring on hills. The model also included stone density (the number of stones per

unit area) as a variable.

When domain elongation was turned off—that is, when the model was tuned so that stones in domains had equal tendencies to move in all directions—a random low-density configuration of stones evolved to stone islands. Increasing the density of stones yielded labyrinths and, with further increase, circles. Increasing the gradient of a hillslope initially containing a random low-density stone configuration, while keeping the elongation parameter off, led to striped domains.

When the asymmetry parameter determining domain elongation was large enough, polygons evolved from random initial conditions.

Although Kessler and Werner considered the physics of frost heave in designing their model, dynamics at the short time scales associated with frost heave play no explicit role in their simulation of sorted patterned formations. As Werner explains it, the feedback mechanisms, nonlinearity, and dissipation that characterize self-organizing systems in general lead to a dramatic reduction in the number of variables needed to characterize the system. The particular variables depend on the length and time scales appropriate to the description; he and Kessler have identified the key variables and feedback mechanisms that describe sorted patterned ground formations. Bernard Hallet (University of Washington), who has conducted detailed field studies of soil patterns for about 20 years, views the simulations as powerful new

tools for studying the initiation and development of soil patterns and as useful guides to more precise field observations and measurements.

Some researchers advocate an approach to complex phenomena, such as sorted patterned ground, in which they try to identify fundamental variables and make a tight case connecting cause and effect. William Krantz of the University of Cincinnati is one. He argues that a more satisfying explanation of how patterned ground formations emerge might be akin to the models that convincingly explained the growth of the Antarctic ozone hole. But, he adds, a variety of approaches is the best way to make progress in understanding complex systems. Kessler and Werner acknowledge that, to address specific questions—for example, how a long period of increased rainfall would affect sorted patterned ground formations—one needs to tie together the climate variables and the key parameters identified in their work. They add, however, that such a connection might be made at the slower, emergent scales treated in their model.

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Reference

1. M. A. Kessler, B. T. Werner, *Science* **299**, 308 (2003).



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