Stone circles: form and soil kinematics

Bernard Hallet

Quaternary Research Center, Department of Earth and Space Sciences, University of Washington, Seattle, WA, USA

Distinct surface patterns are ubiquitous and diverse in soils of polar and alpine regions, where the ground temperature oscillates about 0°C. They constitute some of the most striking examples of clearly visible, abiotic self-organization in nature. This paper outlines the interplay of frost-related physical processes that produce these patterns spontaneously and presents unique data documenting subsurface soil rotational motion and surface displacement spanning 20 years in well-developed circles of soil outlined by gravel ridges. These sorted circles are particularly attractive research targets for a number of reasons that provide focus for this paper: (i) their exceptional geometric regularity captures the attention of any observer; (ii) they are currently forming and evolving, hence the underlying processes can be monitored readily, especially because they are localized near the ground surface on a scale of metres, which facilitates comprehensive characterization; and (iii) a recent, highly successful numerical model of sorted circle development helps to draw attention to particular field observations that can be used to assess the model, its assumptions and parameter choices, and to the considerable potential for synergetic field and modelling studies.

1. Introduction

Conspicuous patterns on the ground surface are relatively common in most cold regions, where the soil is subjected to repeated freezing and thawing. They vary widely in size and shape. On essentially horizontal ground surfaces, they range from isolated circles to polygonal nets or closely spaced mounds, whereas on gentle slopes they commonly occur as stripes aligned downslope. Among the most spectacular patterns are those defined by a distinct segregation of soil material according to size, a phenomenon known as sorting (figure 1). Such patterns are referred to as sorted circles.
patterns, distinguishing them from patterns that lack the distinct particle-size sorting. Despite a long history of relevant studies and observations (for a comprehensive overview, see [1]), including realistic numerical models of the formation of patterned ground [2,3], many specific aspects of their genesis remain somewhat elusive. The general dearth of systematic quantitative measurements of the principal physical properties and processes as functions of space and time throughout the year has hampered detailed understanding of the phenomenon.

Inspired initially by Link Washburn, we launched a series of studies of periglacial sorted patterned ground. They included (i) quantitative field measurements of microtopography, soil motions, thaw front geometry, subsurface bulk density and organic content of the soil in Spitsbergen, where sorted patterns are particularly well developed [4,5]; (ii) extensive instrumentation of the active layer with automated data acquisition systems; (iii) experimental investigation of frost-induced sorting [6,7]; and (iv) theoretical considerations of soil and water motion in the active layer [8]. These field studies were instrumental in the development of the most realistic numerical model to date of self-organization in sorted patterned ground [2,3].
Below, we illustrate outstanding examples of sorted circles, report on methods used to monitor surface and subsurface displacements of the soil, and highlight results of our displacement measurements. We liberally use material from our own studies and from recent reviews in permafrost science that are not widely available in the literature [9,10]; the reader is referred to these for additional context and supplementary information. Although we do not address the formation of narrow sorted stripes (figure 2b) that result from the growth of needle ice at the soil surface [11] nor non-sorted patterned grounds that lack the conspicuous lateral sorting of material according to size (e.g. figure 2c), we stress that they share many of the characteristics and processes we discuss herein. To provide a conceptual background helpful in thinking about frost-induced self-organization in soils, we first review salient aspects of freezing in porous media.

2. Freezing in porous media and frost heaving

The recurrent expansion and contraction of soils and rocks induced by ice growth and melting drive the principal periglacial processes, including size sorting, patterned ground formation, slow downslope motion and frost weathering. Contrary to popular belief, the 9% volumetric expansion associated with the water–ice phase transition has essentially nothing to do with frost heaving in soils. In fact, a number of experiments have demonstrated ‘frost heaving’ by materials that contract upon freezing [12], more recently using helium [13] and argon [14]. For all practical purposes, frost heaving in nature is due to the addition of water to freezing soils as water is thermodynamically drawn to the freezing front from nearby areas [15].

Remarkable insight into the frost heaving phenomenon was gained long ago from simple experiments by Taber [12,16]. More recently, two forms of frost heaving in soils have been recognized. Primary heaving occurs due to relatively rapid freezing along a simple ice–water interface under minimal confining pressure; its most common manifestation in nature is the appearance of needle ice at the surface of moist soils during a cool, clear night. Needle ice growth requires subfreezing temperatures at the soil surface, ample moisture and soil sufficiently permeable to permit rapid moisture migration to the freezing front yet fine-grained enough to inhibit ice growth significantly within the soil [17]. This inhibition arises largely from the depression of the freezing point owing to the ice–water interface curvature for ice grains confined to small pores [18–20]. The physics of needle ice growth has much in common with the observed tendency for an upward propagating freezing front to reject small non-buoyant particles in the water [21–23].

Secondary heaving [19] generally occurs throughout a freezing soil mass; it is characterized by the relatively slow growth of ice lenses, also known as segregation ice, fuelled by the flow of water through a frozen fringe and by the migration of this icy fringe through the soil caused by temperature gradients. Heaving has been the focus of considerable theoretical study [15,24–26]. Recurrent ice lens growth and decay lead to upfreezing, the differential motion of stones relative to the surrounding soil; this motion is generally in the direction of heat flow during the freezing period, usually upward toward the ground surface. Larger stones are expected to move toward the surface faster than smaller stones, and the upfreezing rate scales with the product of the projected height of an object and the heaving strain of the soil, which is the amount of inflation of the soil due to ice lens growth [27]. Over time scales of years to millennia, stones can accumulate on the ground surface, and sorted circles and other patterns can emerge spontaneously owing to feedbacks involving heat and water transport modulated strongly by the evolving soil texture. These feedbacks are considered more extensively in the section on modelling the evolution of sorted patterned ground.

3. Stone circles: form, geometry and relief

We focus on the sorted circles of Spitsbergen because they have for long attracted the attention and imagination of geomorphologists as they are recognized to be the best developed in the world. Indeed, Spitsbergen is viewed as the ‘pays classique des cercles de pierres’ [28].
Figure 3. (a) Vertical photograph showing the geometric diversity of stone patterns on Kvadehusletta, Spitsbergen; they range from nearly circular patterns 2–4 m in diameter, defined by raised rings of light-coloured gravel to irregular forms bordered by long sinuous gravel ridges that trend generally down the fall line of this 1–2° slope, toward the bottom of picture. Courtesy of J. L. Sollied. (b) Similar irregular patterns produced in a simple numerical simulation of frost-induced self-organization on a horizontal surface by B. Werner, who initially used it to model the sorted stripes on slopes in figure 2b [11]. (Online version in colour.)

The most distinctive sorted patterns in the Kvadehusletta area generally comprise equidimensional domains of essentially unvegetated, fine-grained soil (herein called fines) outlined by broad curvilinear ridges of gravel (figures 1, 2a and 3a). Certain areas are completely covered with arrays of coalescing sorted circles that share common borders. Elsewhere, low-relief areas of coarse material lacking the lateral sorting separate adjacent circles. In extreme cases, individual sorted circles may be separated from all others (figure 4b); they tend to be rather uniform in size, with outside diameters, including the 0.5–1 m wide border, typically ranging from 3 to 4 m. This size is on occasion greatly exceeded by anomalous sorted figures that are complex in shape and elongated generally in the downslope direction (figure 3a). However, the width of the fine domains of these anomalous figures remains limited to 2–3 m range.

4. Microtopography and subsurface

The surfaces of the fines domains are smooth and convex upward with the highest point near the centre of fines being 50–100 mm higher than the edges of the fines (figure 4a). The transition between the fines domain and gravel border is abrupt, in terms of both texture and topography. Both the surfaces of the fines domains and gravel border slope toward the sharply defined contact between the two domains. The gravel slope tends to be steeper than the surface slope of the fines. The border heights vary considerably from area to area, ranging from a few millimetres to 0.5 m. The few excavations we have made suggest that the surface marking the contact between fine and coarse material commonly dips about 20° radially outward near the surface and steepens sharply to near-vertical below about 0.2 m. The depth to the frozen ground increases throughout the thaw season, tending to be greatest under the fine centres. The active layer thickness, defined as the maximum thaw depth at the end of the warm season, slightly exceeds 1.5 m in the study area; below this the ground remains permanently frozen (hence it is a permafrost area).

5. Soil motion: manual measurements and inference

One of the striking results emerging from considerable fieldwork on sorted circles is the associated coherent, convection-like soil motion in the active layer, a form of cryoturbation with central soil upwelling focused near the centre of each circle and subsidence at the periphery
Figure 4. (a) Sequential topographic profiles across a stone circle show that the microrelief is persistent over a decadal timescale. It is dynamically maintained by systematic subsurface soil motion that offsets the universal tendency for relief features in loose material to vanish with time. (b) Isolated stone circle. The darker central domain is 1–2 m-wide; it is gently convex upward. The raised, approximately 0.2 m high gravel ring is nearly 1 m wide; a sharp depression and break in texture mark the contact between the central domain and gravel ring. (Online version in colour.)

Figure 5. (a) Highly idealized long-term soil motion inferred from measured surface soil displacements. (b) More realistic pattern of soil motion consistent with surface data [29]. Image provided courtesy of Albert Pissart.

of the fine-grained domains (figure 5). The evidence for the kinematics of this cryoturbation is summarized below.

The net lateral surface motion of soil on active stone circles over the course of multiple seasons has been documented extensively using arrays of dowels and other markers inserted in the soil, and sets of marked rocks. The most notable net motions after years of monitoring in Spitsbergen are systematic radial soil displacements at rates approaching 10 mm yr$^{-1}$. Dowels initially inserted vertically to a depth of 0.2–0.4 m also diverge and tilt outward across fine-grained domains (figure 6) and across borders. Across fine–coarse boundaries, the dowels converge. In all domains, soil and rocks at the surface tend to creep downslope (figure 7b). These results are consistent with fieldwork by several researchers in other Arctic regions [29–31].

This pattern of horizontal displacements can only be sustained in the long term if considerable complementary subsurface soil motion occurs. For example, in domains where the upper 0.25 m of soil is extending horizontally at a high average rate of 4% per year, the soil must be rising about 10 mm yr$^{-1}$, otherwise these areas would subside at that rate. Such rapid changes in microrelief are inconsistent with observations that the distinct microrelief of several circles (raised gravel borders encircling domed centres of fines; fines–coarse contacts generally marked by distinct trough) in our study area has not changed appreciably during the 20$^+$/year duration of our study. That little, if any, geometric difference exists among circles developed on different beach terraces at Kvadehusletta that vary in age by 10$^2$–10$^4$ years [4] also suggests that the circle microrelief is essentially in a steady state.

Radial convergence and inferred subsidence are localized close to the periphery of the fine-grained domains. Deep-seated return soil motion is required to maintain both the observed long-term surface displacements and the distinct microtopography with the domed fine domains,
Figure 6. (a) Radial outward tilt of soil displacement markers across a fine-grained domain 2 m in diameter. Twenty years before this picture was taken, the stiff nylon rods were buried vertically with a rigid base to anchor them to the soil at a depth of 0.2 m. (b) Outward tilt (triangles) relative to vertical increases linearly with distance from the centre, which is normalized to the radius of the fine-grained domain. Radial velocity (solid circles) also increases outward from the centre of the circle, based on a 9-year dataset; they peak approximately two-thirds of the way to the edge of the circle. Positive values are for markers moving or leaning to the right in (a). (Online version in colour.)

Figure 7. (a) The displacement marker in the interior side of the gravel border (left centre of image) leans steeply toward the circle centre, in contrast to those in the fine-grained centres, reflecting circulation within the border and strong convergence at the gravel–soil interface. (b) Manually measured rates of horizontal, radial surface motion of soil and marked stones. Motion tends to be downhill at a rate proportional to slope, hence the microrelief would quickly disappear if the surface convergence (divergence) of material were not offset by complementary soil and gravel subsidence (uplift). Positive (negative) slope and speeds are those directed away from (toward) a reference rod outside the circle. (Online version in colour.)

the bulbous ridges of coarse material and the sharp troughs marking the fine–coarse contact (figures 4a and 7a). The simplest overall pattern of soil motion compatible with the net surface displacements and the maintenance of the microrelief consists of soil circulation as illustrated schematically in figure 5. We stress that actual soil motions are much more complicated as they reflect large fluctuating displacements associated with freezing and thawing, separated by long periods of quiescence particularly when the active layer is frozen. The characteristic cycling time
is about 500 years, which corresponds to maximum surface displacement rates of 10 mm yr$^{-1}$, a
1 m thick active layer and a sorted circle radius of 1.5 m. Mackay [32] and Washburn [31] obtained
slightly longer cycling times for soil in earth hummocks and sorted circles.

6. Soil temperature and motion: automated measurements

The manual measurements of surface soil displacement just described define the long-term
kinematics in active soil circles, and the leaning displacement markers provide visual evidence
of the surface motion but they yield no direct information about motion at depth, the processes
underlying the motion (the dynamics) and the time-varying conditions under which it occurs.
Regarding the latter, advances in electronics over the last few decades have enabled the
development of microprocessor-based data acquisition systems capable of monitoring soil
physical properties throughout the year in remote settings. Roth & Boike [33], for example, report
more than 2 years of continuous data of soil temperature and liquid water content measured
with high accuracy and high temporal resolution using time domain reflectometry. This study
is particularly relevant because it documents the conditions in the active layer within a few
kilometres of, and at the same elevation as, our sorted circle study sites, and hence reflects nearly
identical environmental and snow conditions.

Now, we turn to our automated measurements of soil motion: soil heave and settling, and
subsurface rotational motion. They are invaluable in providing continuous information that
permits linking observed surface displacement patterns to particular times and to particular
physical states and processes. They help understand the simple concepts that emerge from field
studies of frost-induced size segregation and convective soil motion both in the fine-grained
centres [29–32] and in the gravel borders [4,34].

We have mostly used simple linear potentiometers housed in 0.2–0.3 m sections of PVC pipe
to define the magnitude and timing of vertical soil motion at and below the soil surface with a
resolution of 0.02 mm for displacements ranging up to 0.1 m. Surface heave and settlement were
measured using transducers that extended to the ground surface from a horizontal bar supported
by two vertical rods firmly hammered through the active layer into the permafrost. The same
system was used to define vertical soil motion below the surface by attaching the transducer to a
vertical rod connected to a horizontal plate installed at depth (H7 in figure 8); interference from
soil motion above the plate was minimized by isolating the connecting rod from the soil with
a rigid tube lubricated on the inside with grease. Using arrays of such surface and subsurface
transducers in a single sorted circle enables us to define the variation in vertical soil displacement
with depth, and hence the vertical variation in frost-induced inflation/deflation of the soil and to
determine the variation in surface heave and thaw settling with radial distance from the centre,
as reported elsewhere [5].

The magnitude of the seasonal surface heave and thaw settling measured at several sites
ranges from 50 to 120 mm, in accord with studies in a region very similar to that of our study
sites near Hornsund, Spitsbergen [35,36]. The duration of the heave period generally exceeds two
months (figure 9). At the surface, heaving starts off at rates up to approximately 4 mm d$^{-1}$, and
then slows down progressively. Just below the surface, the soil inflates owing to water drawn
toward the freezing front where rapid ice lens growth occurs; this is expressed as differential
heave in figure 9, defined as the difference between the heave at the surface and at depth (H2–H7,
heavy dashed line; see heave sensors H2 and H7 in figure 8). It is noteworthy that this difference
continues to increase well after the 3 days it took for the soil to freeze around the lower transducer
plate and to start heaving. This shows that significant frost-induced inflation of the soil in the
measured interval (surface to 0.2 m depth) continues for over a month after the soil is frozen
(figure 9); this is a rare field documentation of active frost heaving on the cold side of the warmest
ice lens.

Heave and settling are known to vary spatially within individual stone circles [31,35–37]. The
central areas of fines heave the most and do so over a one to two month period; this heave reflects
significant inflation of a soil layer reaching about 0.3 m in thickness. These areas also settle the
fastest during the onset of thaw, although the raised borders are generally the first to appear above the melting snow cover. Settling of the borders quickly accelerates and approaches the settling rate in the fines. After a period of relatively uniform slow settling in the middle of the thaw period, the coarse border continues to settle while settling in the fine-grained centres vanishes. In accord with these large relative motions, the microrelief of sorted circles changes considerably during the summer. When the soil first thaws, an initial rapid lowering of the fines increases the microrelief. Later in the summer, a slight relative lowering of the coarse border reduces it. Subsequent frost heaving appears then to elevate the fine-grained centres preferentially, thereby resetting the microrelief to its pre-thaw season state.

Overall thaw settling, which amounts to approximately 10% of the active layer depth, represents a significant increase in the average bulk density of the soil during the thaw season. Such vertical variations in soil bulk density are of particular interest, because they give rise to buoyancy forces that could contribute not only to the inferred soil convection in sorted circles but also to widely recognized but poorly understood other periglacial processes [8], such as cryoturbation and frost churning, that give rise to involutions, diapirs, mud boils and homogenized soils [1,30,38]. Freeze–thaw-induced strains are the greatest and most rapid near the surface, but significant strains have been measured down to a depth of about 0.75 m.

Continuous measurements of rotational motion of soils at depth are of particular interest in the light of our conceptual model of intermittent soil convection and Kessler et al.’s [2] numerical model of sorted circles. We used biaxial electrolytic tilt cells housed in an approximately 0.2 m long, approximately 0.1 m diameter PVC pipe to measure rotational motion as large as approximately 20° with a resolution of approximately 0.005°. A coating of sand and pebbles glued onto the exterior of the pipe helped to provide firm coupling between the transducer and the soil to avoid rotation of the tilt cell relative to the soil.

Figure 8. (a) Vertical section across a sorted circle showing the microrelief and textural domains. (b) Sensor locations: H, heave transducers; T, tilt and temperature cells with anticipated long-term rotation direction shown and Por, pore pressure transducers.
Figure 9. Frost heaving (see heavy lines and left vertical axis) and temperature (light lines, right axis) field in upper decimetres of soil through one representative freeze-up period. Vertical heave at surface (H2) and at 0.2 m depth (H7), and differential frost heave (H2–H7; dashed line) illustrate the frost-induced inflation of soil that drives stone circle development. The slow, sustained vertical dilation owing to ice lens growth amounts to a strain of 20% (40 mm dilation in 0.2 m of soil) over a month-long period, known as the zero-degree curtain; the soil is frozen above 0.2 m but hovers very close to the freezing point, largely between 0°C and −0.5°C, which permits considerable water migration to growing ice lenses. Temperature is shown for three levels: 0.039 m above ground surface (solid), and in soil at depths of 0.185 m (dashed), and 0.336 m (dotted). (Online version in colour.)

Figure 10 shows the temperature and soil rotational motion recorded by a series of tilt and temperature cells, including T1,1, installed in the coarse-grained border; this cell is located on the left-hand side of the sorted circle in figure 8. This cell underwent the largest rotations we have recorded, which is consistent with measurements of lateral surface displacements that point to the borders being the sites of the greatest differential horizontal displacements. After a period of stability while the soil is frozen, the tilt cell rotates quickly in a clockwise direction reflecting a tilt of this part of the border toward the centre of the adjoining fine-grained centre. This seems to be closely related to the more rapid settling of the fines than the borders at the onset of the thawing, which effectively undermines the border causing the portion of the border overlying fine-grained material to settle while the central and outer portions of the border remain relatively stationary early in the thaw season owing to delayed thawing there.

Following the rapid approximately 6° rotation clockwise, which lasts about 15 days until mid-July, T1,1 ceases to rotate briefly and then rotates nearly 2° in the opposite direction (anticlockwise) during the rest of the thaw period. The reversal in tilt direction in the early part of the thaw season is seen in other tilt records, T1,2 (figure 10); it seems to correspond to a marked reduction in the settling rate of the fines and a pervasive reversal in the direction of horizontal, surface displacements in the coarse material recorded in mid-July 1985 [39]. This reversal is also evident in high-resolution (10−6) measurements of radial, horizontal surface strains using linear motion transducers. These marked shifts in displacement patterns are most intriguing because they appear widespread and occur while thawing is proceeding monotonically with time (thaw depth on 15 July 1985 was about 0.5 m). Furthermore, they do not appear to correspond to significant meteorological events that could, for example, have changed the soil moisture. This tilt behaviour correlates very well with patterns of soil displacements measured at the surface of nearby sorted circles [5,39].
Figure 10. Temperature (thin upper curves, right vertical axis) and tilt of three sensors over nearly 1 year. Line patterns correspond to individual tilt cells: T1.1 (solid; heavy where data are continuous) at 0.27 m depth in the interior portion of coarse border, T1.2 (dashed) and T1.4 (dotted) at depths, respectively. Location of sensors are shown in figure 8 of 0.35 and 0.45 m in the exterior portion of the fine-grained centre. Vertical arrows point to times when soil first thaws and freezes at the depth of T1.1. Soon after they thaw, T1.1 and T1.2 rotate quickly clockwise with the top tilting toward the centre (decreasing values) about a subhorizontal axis aligned with the circle border as the soil consolidates and settles preferentially near the circle centre. Part of this rotation, but not all, is reversed first during the thaw phase and later as the fine-grained domain heaves preferentially, pushing the borders upward and outward during the prolonged freezing period. Tilt records limited to the freeze-up period, which starts around day 270 in 1988, are shown for five sequential years in figure 11. (Online version in colour.)

Once ground surface temperatures drop below 0°C, T1.1 rotates further anticlockwise during the first approximately two months of the freeze-up period, which brings the cell nearly back to its pre-thaw season position. This reversal is not complete, however, resulting in a net annual rotation of the sensor approaching 1°, which was documented over a 5-year period (figure 11).

The accord between continuous readings of tilt and manual measurements of surface displacements suggests that motion detected at the surface reflects coherent subsurface motion extending to a depth of at least 0.4 m. This is also evident from automated measurements of differential heave and near-surface tilt that record the same activity in entirely different and independent ways; see, for example, fig. 3 in [39] illustrating differences in surface heave with distance from a circle centre closely paralleling near-surface rotations.

In comparison to near-surface tilt sensors, those at greater depth generally yield simpler records and relative stability suggesting diminishing differential soil motion at depth. Substantial tilts have only been recorded in the upper 0.5 m of the soil in the fine-grained centres, which is consistent with the type of soil circulation pattern sketched by Pissart [29], where in the central region of fine-grained soil domains the soil is generally moving upward and toward the centre with little net differential motion (figure 5b). Net radial outward soil motion and soil subsidence are respectively limited to relatively narrow boundary layers at the surface and along the radial outward-dipping fine–coarse contact. Unfortunately, none of the tilt cells is located near these boundary layers for practical reasons. Notably, all sensors are placed at least 0.25 m below the surface to avoid rapid upward displacement of the tilt cell relative to the soil owing to the very efficient upfreezing expected in the upper 0.2 m of soil.
Figure 11. Overall negative trend reveals a residual clockwise rotation of tilt sensor, T1,1, viewing it as shown in figure 8. Over five seasons, this rotation amounts to approximately 1° per year, which suggests a time scale of centuries for a full rotation. Only tilt records during the autumn periods are shown because they are too patchy to display effectively for the rest of the year owing to recurrent power shortages; for the second year, the full, ratchet-like motion is shown in preceding figure.

Summing up the tilt records through one well-instrumented year, tilt sensors rotated back and forth from the onset of thaw to the completion of the freezing phase, with the fastest rotation closely associated with the thawing of the soil around the sensor in the coarse gravel of the circle border, and a distinct reversal in rotation direction during the thaw period owing presumably to a shift in the polarity of differential thaw settling. The most distinct longer term tilt record extending over several years, T1,1, shows that the seasonal ratchet-like rotation does not cancel out; rather, T1,1 underwent a net, residual rotation of nearly 6° in five seasons (figure 11). Importantly, idealizing this motion as that of a simple convecting cell suggests a time scale for a full rotation of centuries in the most active part of this stone circle.

7. A field perspective on the model

Simple numerical simulations of discrete particle motion in soil subjected to freeze–thaw activity dominated by needle ice formation have emerged as useful new tools for probing the spontaneous emergence and the dynamics of sorted stripes on gentle slopes [11]. Guided by field observations, Kessler et al. [2] developed a more realistic model of the emergence and evolution of the sorted patterns in frozen ground described above, starting from a highly idealized initial condition: a laterally uniform layer of fine-grained soil overlain by a layer of coarser grained material. In this ‘three-dimensional, cellular model of the active layer, cyclic freezing and thawing drives transport of stone and soil particles by (1) addition of ice particles representing soil expansion by frost heave, (2) removal of ice particles representing soil consolidation during thawing, (3) addition of void particles (a discrete abstraction of soil compressibility) representing soil expansion by water absorption, (4) removal of void particles representing compaction and desiccation of underlying soil by frost heave, (5) relaxation of surface morphology by soil creep and stone avalanche and (6) vertical sorting of stones and soil by illuviation. These transport processes give rise to sorted circles, which are characterized by a mean spacing of 3.6 m, a 2.4 m wide soil domain surrounded by a 1.0 m wide, 0.3 m high annulus of stones, and a 750-year period of circulation in the soil domain, all consistent with measured characteristics of sorted circles in western Spitsbergen’ [2, p. 13, 287].

In the model, circles initiate as small, random variations in the thickness of the basal layer fine-grained soil under the gravel that grow and lead to the formation of diapir-like upward-moving domains of fine-grained soil that closely resemble the ‘soil plugs’ described by Washburn [38]. With time, characteristic arrays of sorted circles and stripes arise spontaneously
Figure 12. Three-dimensional perspective view of numerically simulated sorted patterned ground after 500 iterations representing freeze–thaw cycles. It shows pattern transitions and the influence of key model variables that vary from left to right as follows (light grey: stone domains; dark grey: soil domains). (a) Stone concentration decreases. (b) Hillslope gradient increases from 0° to 30°. (c) Lateral confinement increases. Image provided courtesy of Mark Kessler.

in the simulations, complete with realistic microtopography, subsurface architecture and patterns of sorting. Moreover, the average paths of soil particles is convection-like with active boundary layers of relatively rapid soil displacement near the surface and periphery of sorted circles, much as inferred (figure 5) and observed electronically in active sorted circles.

A central component of the model is the explicit inclusion of the feedbacks between soil texture and heat flow in the slow nonlinear dynamics of mixtures of fine-grained soil and rock particles that are freezing and thawing recurrently. On the one hand, textural segregation is a function of the heat flow, because the pattern of upfreezing and soil compaction is largely dictated by the orientation of ice lenses that tend to parallel the freezing isotherm. On the other hand, the heat flow is a sensitive function of texture, because latent heat release upon freezing is high for fine-grained material that retains substantial moisture and decreases strongly with increasing grain size. Kessler & Werner [3] take into account the effects of slope and lateral confinement, which in essence represents the lateral push of freezing fine-grained domains on stony borders. Figure 12 illustrates the striking range of distinct patterns that emerge spontaneously from the models as a function of specified controlling parameters [3].

Interestingly, even relatively simple two-dimensional models of frost-induced sorting can simulate much of the richness in patterns. For example, Werner [11] developed such a model to study the generation of exceptionally evenly spaced, parallel stone stripes aligned downslope as observed on hill slopes near the 4200 m summit of Mauna Kea, Hawaii (figure 2b). Subsequently, he investigated the pattern produced by the same model but for a horizontal surface; figure 3b shows the more complex resulting geometry with irregular, curvilinear boundaries encircling closed domains, which are also seen in patterned ground. Intriguingly this geometry has much in common with that characteristic of spinoidal composition, a very different expression of self-organization that has received considerably more research attention [40].

8. Discussion

The models just discussed are powerful tools for studying the origin and dynamics of patterned ground, its rich geometric complexity, and its sensitivity to environmental factors and soil
properties. The models are especially useful because laboratory simulations have not been productive to date, and field studies provide only few clues about the incipient stage of ground patterning. The models merit careful validation and further development through detailed comparison of pertinent field observations with model assumptions, parametrization and results. Quantitative field data like those presented above provide excellent opportunities to assess and refine numerical models. Specific model results can be compared directly with measured temperatures, soil heave and overall soil circulation. Future models have the potential to (i) help understand why sorted circles and other forms of patterned ground abound in a few areas, while absent in others; (ii) explore the sensitivity of the self-organization in patterned ground to climate and soil characteristics, including grain size distribution and moisture; and (iii) explicitly include individual rocks or instruments, as well as the fine- and coarse-grained granular material; the measured rotation of tilt cells could then be directly related to model results, providing exacting means of validating models. In addition, recent work points to another type of synergy between fieldwork and numerical modelling. The modelling requires the explicit articulation of set of inferred numerical rules that underlie the self-organization; each of these provides specific objectives, some of which are novel, for well-targeted field studies.

These recent simulations of sorted patterned ground formation complement other theoretical work on patterned ground and circumvent the limitations of other approaches that require unrealistic idealizations, that address only the incipient development of soil patterning, or that do not represent size sorting explicitly. For example, a series of studies [41–43] has examined patterned ground initiation through a rigorous mathematical analysis of the stability of secondary frost heaving to explore the early stages of patterned ground formation and studied how initial perturbations on the ground surfaces can be selectively amplified, providing a potential seed for pattern initiation. An important virtue of this approach is that it addresses the physics of frost heaving and the coupling of energy and mass transport processes explicitly and provides considerable insight into incipient self-organization in freezing soils. This type of analysis is not suitable, however, for the study of finite amplitude features and their effects, including the lateral sorting and related feedbacks. The latter include the strong influence of the developing topography and textural differentiation on the transport of heat and moisture that fuel the development of sorted patterned ground. These studies of the stability of secondary frost heaving have much in common with recent models that focus on the formation of non-sorted patterned ground [44–47].

An earlier phase of modelling of patterned ground [48–50] was founded on the notion that patterned ground is an indirect manifestation of percolative pore water convection through thawed soil during the embryonic stage of pattern development. A remarkably close agreement was reported between model predictions of convection cell geometry and considerable field data from diverse areas on the diameter of individual sorted polygons and depth of distinct sorting [49]. Hallet [34] has stressed, however, that the pattern geometry and size are not diagnostic. Water convection in soil patterns probably does not occur and, if it does, it is likely incidental. Moreover, the buoyancy forces involved are so weak as to be only capable of driving convection in very coarse sand or gravel that offer little resistance to the flow [51]; yet, patterned ground is usually associated with much finer grained material that is orders of magnitude less permeable than coarse sand.

This association between patterned ground and fine-grained material is widely recognized, and probably reflects the fine soil texture requirement for frost heaving, which is necessary for the development of relief and the segregation of material according to size that characterizes sorted patterned ground. The significant inflation of moist frost-susceptible soil as it freezes slowly is reversed when the ice melts. Interestingly, this deflation can give rise to relatively large buoyancy forces on the soil matrix [8]; these are not to be confused with the much weaker forces considered in the previous paragraph in the context of free convection of water through the soil. Following a period of frost heaving and attendant decrease in soil density, the soil thaws and consolidates. As the upper part of the soil consolidates first, the freshly thawed soil near the surface tends to be densest particularly if the frozen soil is ice-rich and sufficiently fine grained for the consolidation
process to be slow owing to the low permeability. This unstable density profile could drive local ascent of soil (diapirism) in easily deformable fine-grained soil during much of the thaw season. However, Hallet & Waddington’s [8] analysis should also be viewed with caution because of the extreme idealization of soil as a continuum behaving as porous linear viscous fluid.

9. Concluding remarks

The study of patterned ground has evolved from a descriptive science based mostly on field observations and limited temperature measurements in the summer to a quantitative science capitalizing on advances in understanding fundamental principles in condensed matter physics, nonlinear dynamics, soil physics, geochemistry, and on technological advances that make it possible to measure precisely soil properties and to monitor continuously key physical and biogeochemical processes year-round, including the important periods of phase transitions in the spring and autumn. In addition to well-accepted theoretical models for heat and mass flow in the soil, recent quantitative models have been developed for a few key phenomena—frost heaving, contraction cracking and patterned ground formation—but the models need to be rendered more realistic and require validation.

Significant advances in understanding patterned ground and other periglacial phenomena will require further integration of field and theoretical studies and will greatly benefit from ideas and techniques in other disciplines within the geosciences and beyond. Much is to be gained from cross-fertilization between scientists and engineers as well. For example, it is bound to be instructive to explore parallels between freezing in soils and similar phenomena considered by chemical engineers studying the freezing of food products for storage, and by medical scientists studying the freezing of tissues and organs.

More generally, permafrost research is being re-energized and evolving as a result of the recent widespread recognition that interdependent physical, chemical and biological processes in the active layer underlie the sensitivity of the Arctic lands to ongoing climate change, and, importantly, that changes in the polar regions likely affect the global climate. The growing interest in the role of the terrestrial Arctic in the global CO₂ budget, which is sensitively dependent on groundwater conditions, also highlights the need to improve understanding of how current change in climate, vegetation and permafrost landscape in the Arctic will affect the hydrology of this vast region. In this light, we stress that frost heave-induced soil circulation, more widely known as cryoturbation, in the active layer is not restricted to sorted patterned ground. Similar heave and resulting soil motion are widespread in other periglacial terrain including areas of tundra vegetation where surface heave can be large and highly variable spatially, especially near patches of bare ground, evocatively known as frost boils [52]. Aside from being central in the dynamics of sorted circles, cryoturbation may well control the rate at which soil organic carbon is buried and exhumed. This is potentially important for the carbon budget of the Arctic and its response to ongoing climate change as it impacts the cycling of large quantities of soil organic carbon at high latitudes, which has long been underestimated. Notably, the amount of carbon in high Arctic soils has recently been estimated at about 12 Pg, more than five times greater than most amounts previously reported [53].

Acknowledgements. This paper reflects the results of countless discussions and many collaborative efforts involving a large number of talented and knowledgeable individuals. We wish to thank in particular the late A. Link Washburn, whose expertise, encouragement and interest have fostered our periglacial process studies. The instrumentation used to produce the data presented above was developed largely because of the expertise, energy and enthusiasm of E. Gregory and C. Stubbs. The field studies involved fruitful collaboration with J. Sollid of the University of Oslo and several of his co-workers, as well as valuable assistance from S. P. Anderson, B. Murray, J. Putkonen and E. Waddington. The field-inspired modelling was the product of B. Werner and M. Kessler’s creativity and effort. We have also benefitted greatly from stimulating discussions with, or assistance from, R. Anderson, G. Dash, N. Caine, A. Heyneman, A. Rempel, R. Sletten, E. Waddington, J. Walder, J. Wettlaufer and G. Worster. Finally, we thank A. Pissart, M. Kessler, and B. Werner for permission
to use their figures, and I. Berthing and R. Sletten for making it possible to revisit study sites in Spitsbergen in 2010.

**Funding statement.** We gladly acknowledge the considerable support we have received for permafrost and patterned ground research from the US. National Science Foundation and Army Research Office, and the logistical support from the Norsk Polarinstitutt.

**References**


