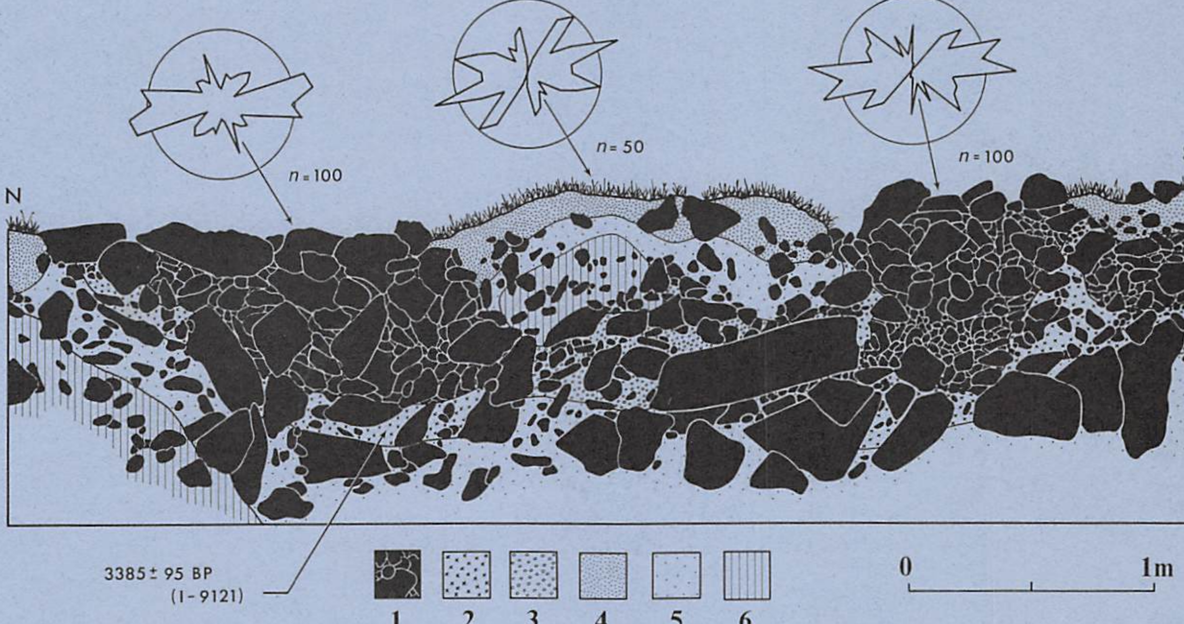
FIELD AND LABORATORY STUDIES OF PATTERNED GROUND IN A COLORADO ALPINE REGION

James B. Benedict



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Abstract

Sorted nets, sorted stripes, earth hummocks, and frost boils were studied from 1961 until 1969 on Niwot Ridge and in the Boulder City Watershed, Colorado Front Range. The study produced maps, profile descriptions, and fabric data for representative patterns, measurements of modern activity, and observations on age and paleoenvironmental significance. Field evidence and laboratory studies suggest that most of the patterns formed rapidly, by upward mass displacement of plugs of fine earth in response to density imbalances in the thawing soil; some of the patterns then continued to evolve slowly due to circulatory overturn driven by vertical frost heaving in their centers.

The occurrence of large-scale sorted nets and stripes on well-drained knolls and ridgecrests at altitudes as low as 3245 m implies that icy permafrost existed at least 100 m below modern timberline during the late Pleistocene. Sorted nets have developed at even lower altitudes during the past century, but only in microenvironments where autumn saturation does not require the presence of a frozen substratum. Moisture-induced changes in frost intensity during the Holocene caused areas of patterned-ground activity to contract and expand; the general trend in the Front Range during the past 25 yr has been toward revegetation of frost-patterned ground.

Preface

Over the decade of the 1960s, Jim Benedict's research on geomorphic processes in the Indian Peaks sector of the Colorado Front Range became internationally known through the field guides for the VIIth INQUA Congress of 1965 and a sequence of papers in journals such as the *Journal of Glaciology*, *Geografiska Annaler*, and *Arctic and Alpine Research.* This work on mass wasting, patterned-ground development, and Holocene glacial history remains the standard against which later work in the Indian Peaks should be judged. It forms a foundation on which geomorphologists working in the Front Range have based their later work and has survived remarkably well the testing which that later work implies. The value of that heritage will be augmented by the present publication which brings together in one volume the results of Jim Benedict's work on patterned ground. This work also dates from the 1960s and has previously only been known by anecdote and personal communications. It carries the hallmark of Jim's previous work: painstaking experimental procedures in the field and laboratory, careful analysis of data and imaginative interpretation. For the first time, these studies are made widely available in this publication which will also serve as a warning to those of us who persist in reinventing wheels, in the Indian Peaks and elsewhere.

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INTRODUCTION

Periglacial landforms, active and relict, are well developed at high altitudes in the Colorado Front Range; nowhere in North America south of the Arctic Coastal Plain of Alaska and the Barren Grounds of northern Canada is there a greater diversity of solifluction and patterned-ground features. The landforms vary in size from giant ice-wedge polygons 10 to 25 m in diameter, and turf-banked terraces with frontal banks more than 4 m high, to miniature sorted polygons and Dryas-banked terraces two orders of magnitude smaller. They vary in age and longevity from sorted nets that have changed relatively little since their formation at the close of the Pleistocene, to frost blisters that develop under modern conditions but that disappear from the landscape as quickly as their ice cores melt.

Five factors are primarily responsible for the diversity of solifluction and patterned-ground features in the Front Range:

1. In winter, much of the alpine region is swept free of insulating snow by westerly winds, and freezes to depths of several meters. Where groundwater from snow-accumulation areas irrigates snow-free terrain, ice segregation is extreme, and winter frost-heave values of 20-40 cm can be expected (Benedict, 1976: Fig. 4).

2. Although permafrost is not geomorphically significant in the lower alpine zone, it is important in specialized, high-altitude microenvironments such as the saddle between Mount Albion and Kiowa Peak (Figure 1), where it supports a perched water table that contributes to ice segregation and patterned-ground activity.

3. Many ridges and summits in the Front Range were unglaciated during the late Pleistocene, and were exposed for long periods to climatic conditions more rigorous than those of the present. Periglacial landforms are better developed in such environments than on the floors of adjacent glaciated valleys.

4. Some tundra uplands, such as the western end of Niwot Ridge, are mantled with thick diamictons (Madole, 1982) that have allowed extraordinarily large patterns to develop.

5. In addition to large-scale patterned-ground features typical of high-polar and subpolar environments, miniature patterns characteristic of tropical high mountains (Troll, 1944) occur in the Front Range. They form in response to frequent shallow freeze-thaw cycles in autumn and spring (Figure 2).

The field data discussed in this paper were collected between 1961 and 1969 during a study of downslope soil-movement processes and landforms on Niwot Ridge and in the Boulder City Watershed, western Boulder County, Colorado (Benedict, 1970a). Laboratory experiments were conducted in 1971. Except for short papers on hummock microfabric (Benedict, 1969), dilation cracking (Benedict, 1970b), and fossil ice-wedge polygons (Benedict, 1979), the bulk of the patterned-ground research remained unpublished.

Figure 1. Patterned ground on the floor of the Albion-Kiowa saddle, Boulder City Watershed (altitude 3650 m). The saddle is blown free of snow in winter, and is irrigated by groundwater that flows from talus slopes to the northwest and south. Shallow permafrost is thought to support a perched water table. The photo, taken from the summit of Mount Albion on 16 July 1987, shows large sorted nets flanking a lane of active frost boils.

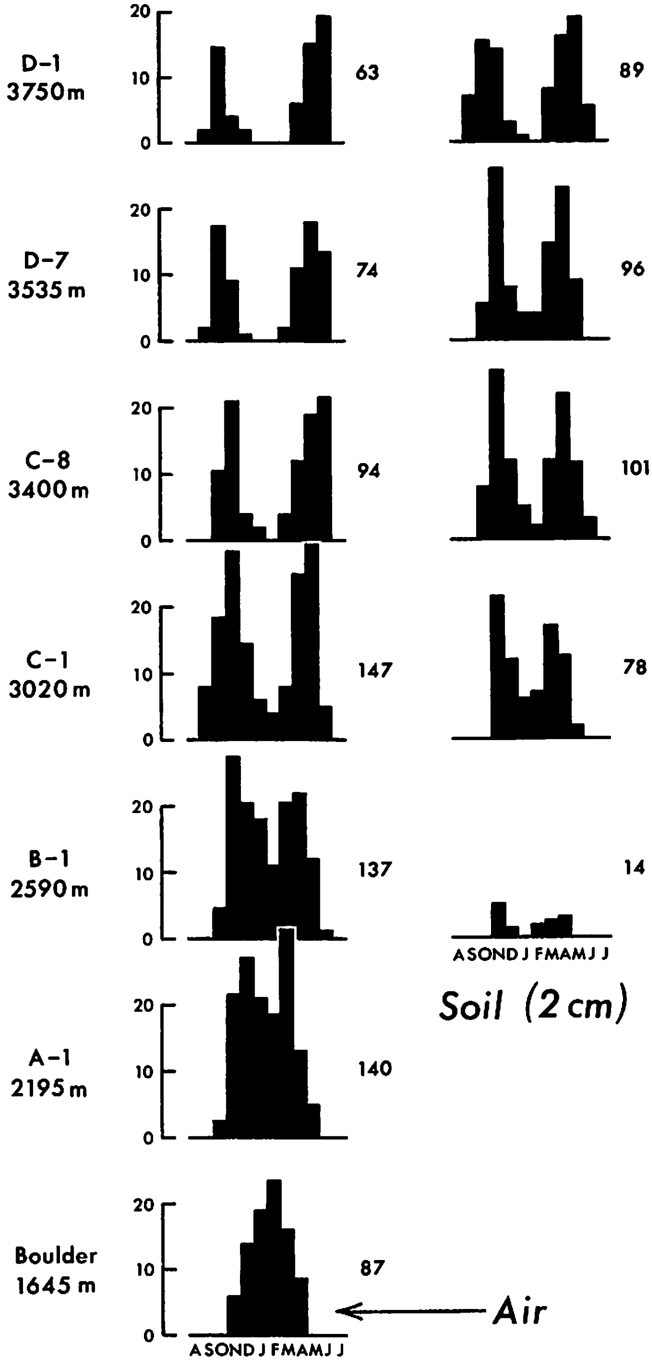


Figure 2. Histograms showing the seasonal distribution of freeze-thaw days along an altitudinal transect on the East Slope of the Colorado Front Range, 1 August 1963 to 31 July 1964. Numbers are annual totals. Air temperatures were measured with thermographs in Stevenson screens. Soil temperatures were measured with thermograph probes at 2 cm depth in standard, unvegetated, sandy soils installed at windswept (normally snowfree) sites. Data from Benedict (1965).

The present report summarizes field and laboratory data on sorted nets, sorted stripes, earth hummocks, and frost boils -- a group of periglacial landforms thought to have developed primarily as a result of mass-displacement processes. I have made no attempt to provide an up-to-date literature review, and have cited only a few, critical references. The locations of patterned-ground study sites on Niwot Ridge are shown in Figure 3.

SORTED NETS AND STRIPES

Description

Sorted nets are the most common and conspicuous patterned-ground features in the Front Range. They consist of more-or-less closely spaced, irregularly shaped patches of fine-textured earth, separated from each other by networks of stones (Figure 4). Maps of representative sorted nets, in various stages of activity, are given in Figure 5. I consider the patterns to be nets, rather than polygons, because their mesh cannot easily be characterized as 4-, 5-, or 6-sided, because their borders are rarely linear, and because cracking (the primary cause of true polygonal patterns) does not seem to have been involved in their formation. Centers are generally convex, and borders depressed; raised borders occur infrequently. Sorted nets on Niwot Ridge range from less than 1 m to slightly more than 10 m in mesh diameter. The centers of large, active sorted nets in wet environments are commonly subdivided into secondary polygonal patterns with gravel borders, and with diameters one-tenth to one-fifteenth the diameter of the primary net. Sorted nets occur at altitudes as low as 3130 m, but below 3245 m they are restricted to the floors of ponds. They occur on all local rock types, including biotite gneiss, granodiorite, quartz monzonite, and syenite.

Sorted stripes are less common in the region than sorted nets. The most striking examples are in winter snow-accumulation areas on slopes that are steeper than about 10° (Figure 6). Oriented in the direction of steepest slope, sorted stripes may be sinuous and irregularly branching, or closely parallel and regularly spaced. Bands of coarse detritus, ranging from less than 1 m to about 3 m in width, are separated from each other by broader bands of fines. Depending upon downslope variations in movement velocity and the relative contributions of frost creep and solifluction to total displacement, the stripes of coarse debris may stand as ridges above adjacent fines, lie at the same level, or form channels lower than the general ground surface. The emergence and disappearance of sorted stripes on slopes, and their frequent termination in stone-banked lobes and terraces, are complex reactions to changes in gradient and the balance between frost creep and solifluction (Benedict, 1970a: Fig. 55).

Profile studies

Sorted net on a well-drained slope

In 1965 I trenched a large, inactive sorted net on a well-drained tundra slope at 3530 m altitude on Niwot Ridge (Figure 3, Locality 6). The rocky borders of the net were 75 and

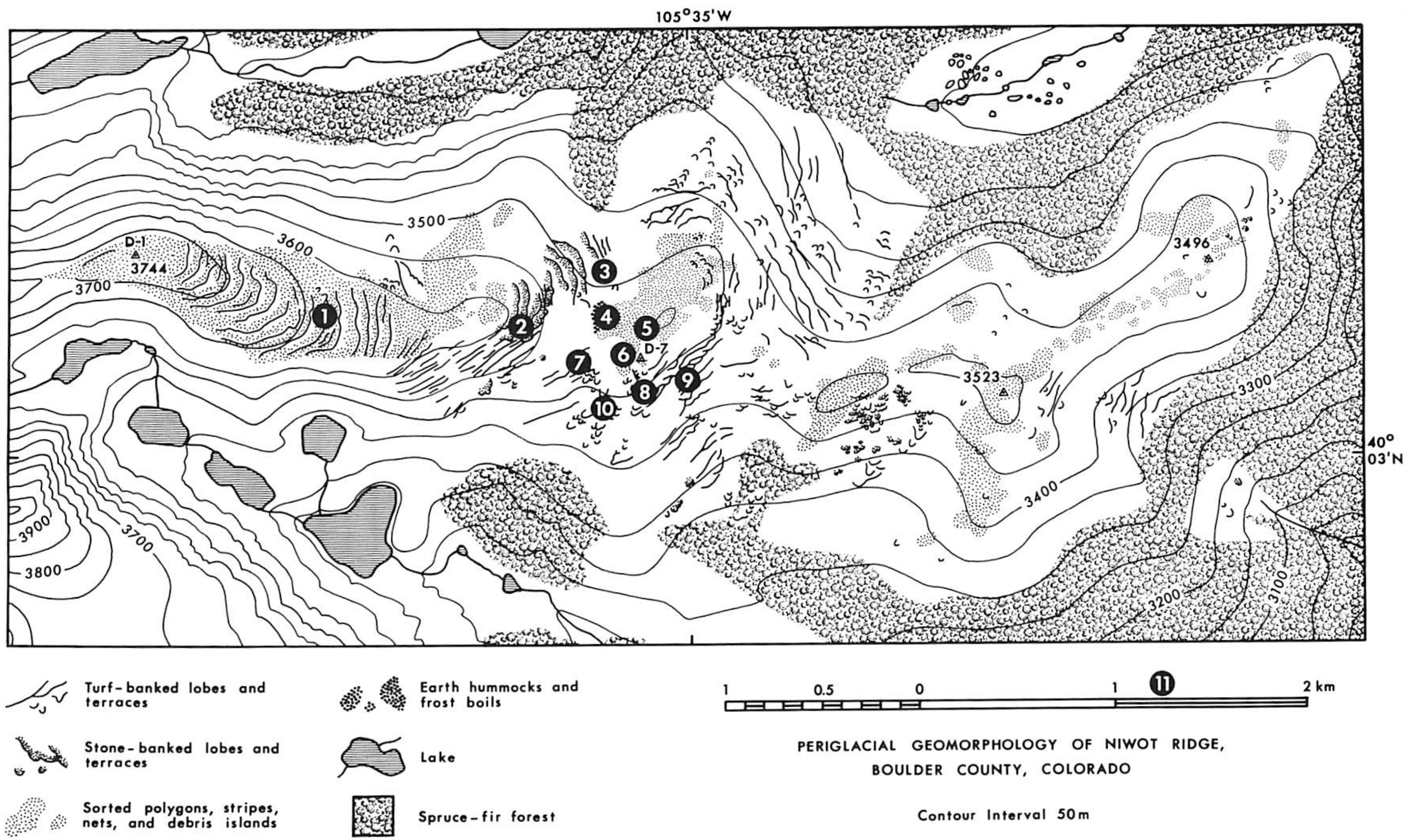


Figure 3. Map of Niwot Ridge showing periglacial landforms (Benedict 1970a) and the locations of patterned-ground study sites referred to in the text. Locality 11 is shown in its approximate position, south of the map area.

Figure 4. Large sorted nets in the Albion-Kiowa saddle. Active frost boils in the vegetated centers of the patterns suggest partial reactivation, probably during the Little Ice Age. Photo 18 September 1984.

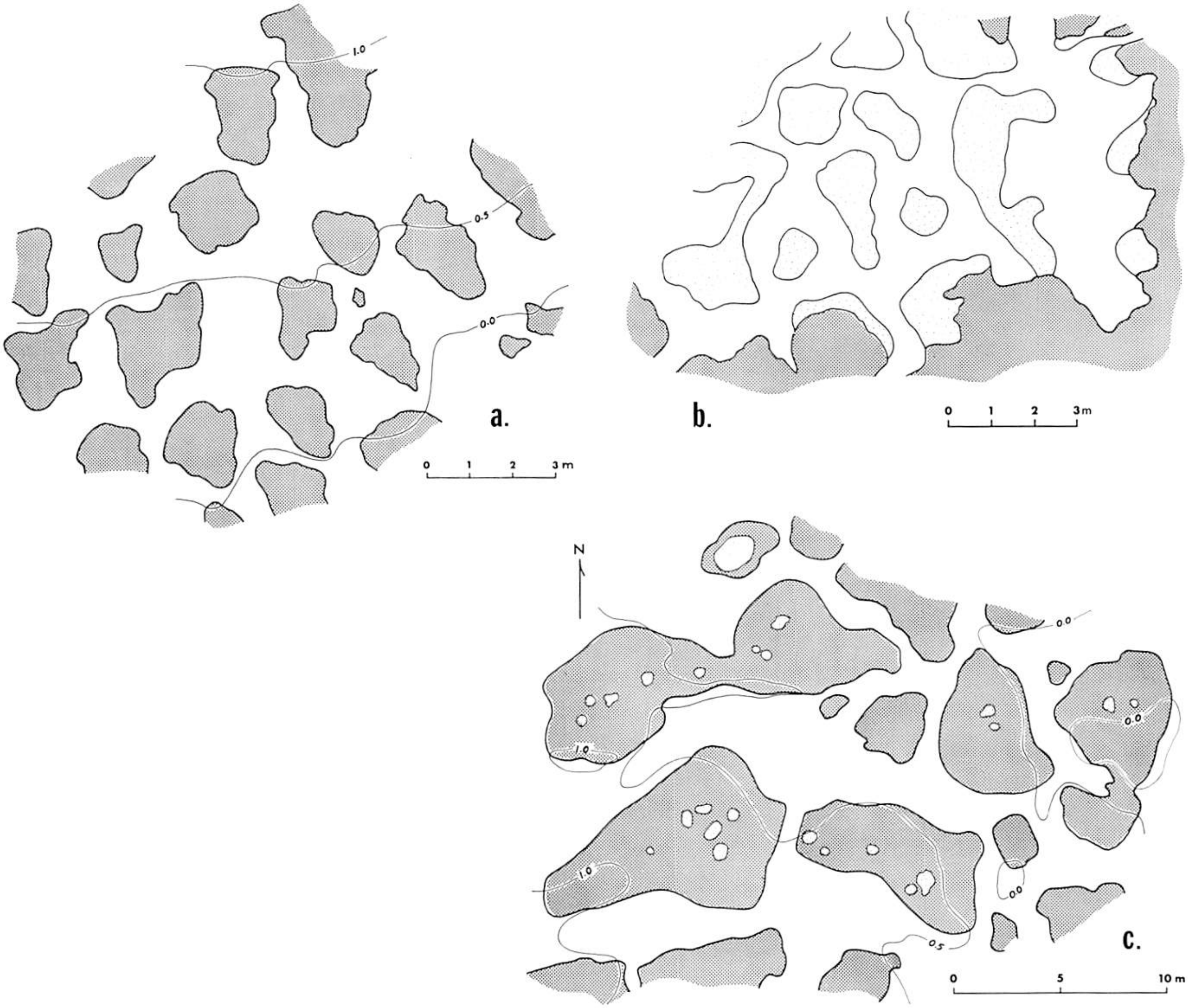


Figure 5. Theodolite maps of sorted nets on Niwot Ridge. Vegetation is shaded, openwork rubble unshaded, and bare earth coarsely stippled. a, well-drained tundra ridgecrest north of the former D-7 weather station, 3550 m a.s.l. (Figure 3, Locality 5). b, floor of an ephemeral pond on a turf-banked terrace, 3510 m a.s.l. (Figure 3, Locality 7). c, moist tread of a large turf-banked terrace east of the D-1 weather station, 3630 m a.s.l. (Figure 3, Locality 1). Two groups of patterns (b and c) show evidence of reactivation following periods of stability and vegetation growth. Maps were made in 1966. Contour interval 0.5 m.

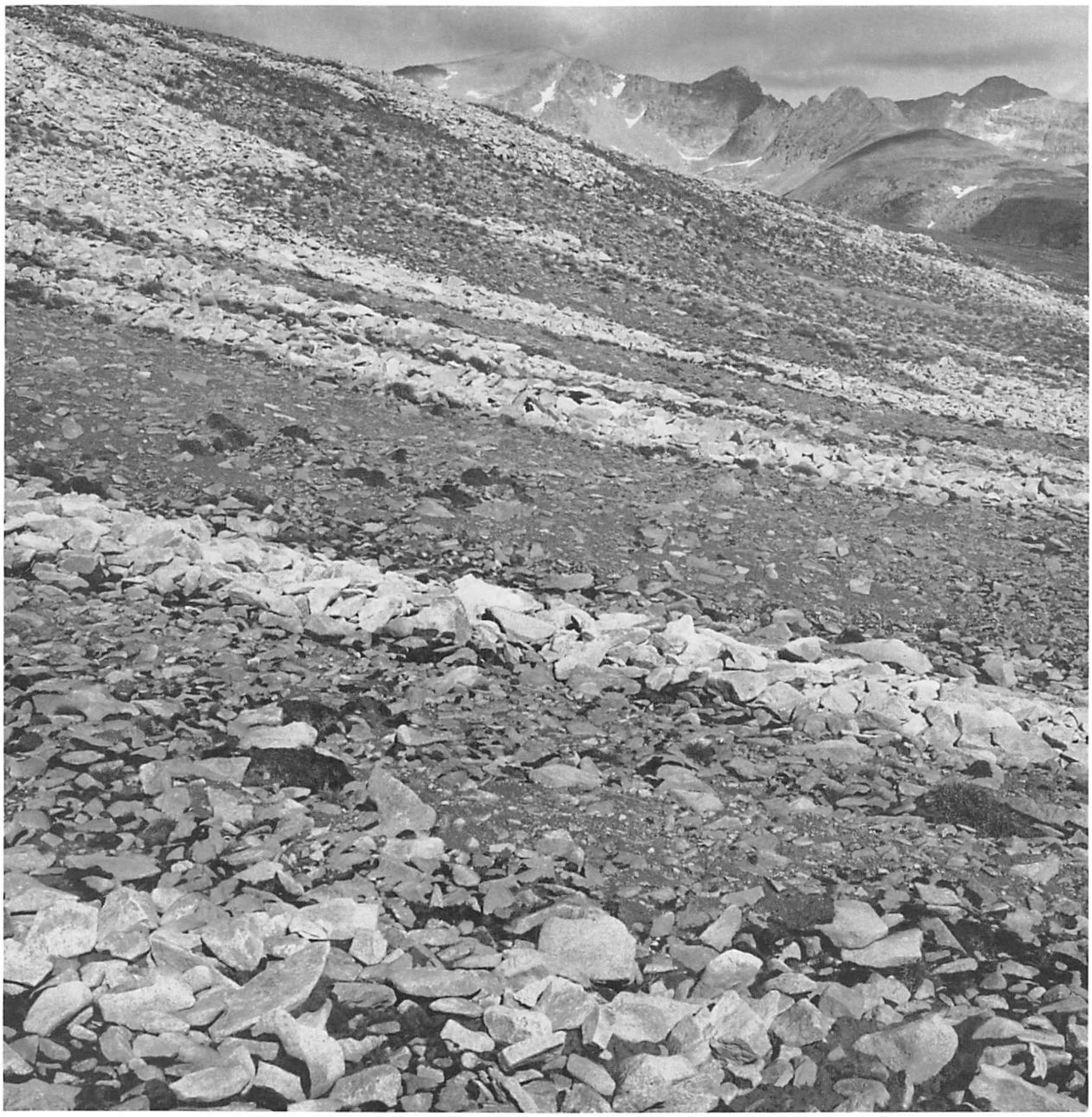


Figure 6. Active sorted stripes on a 12-13° northeast-facing slope, Niwot Ridge (Figure 3, Locality 3). Photo 17 August 1991.

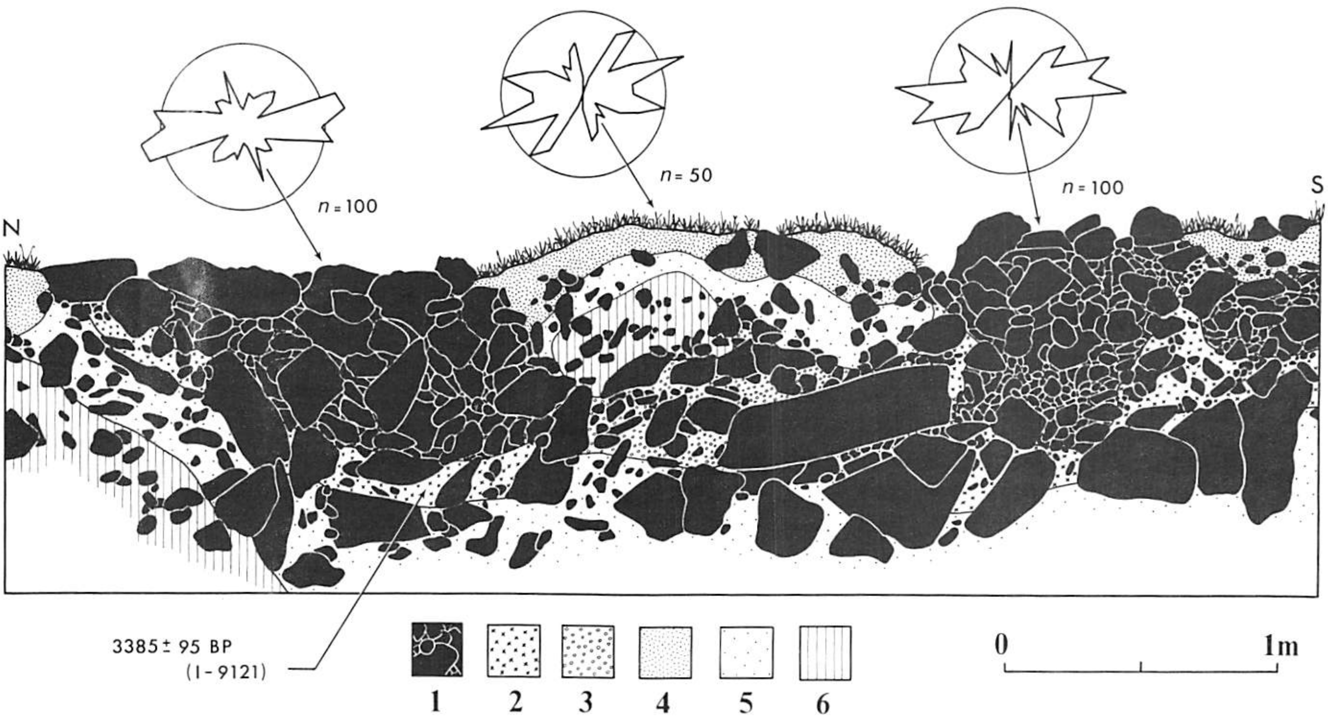


Figure 7. Cross-section of a large sorted net west of the former D-7 weather station. Rose diagrams show long-axis orientations of cobbles and boulders.

1. Openwork rubble.
2. Very dark brown (10YR 2/2m) humus-rich, stony, gravelly sandy loam.
3. Dark yellowish brown (10YR 4/4m) stony, gravelly loamy sand, extensively tunneled by small mammals.
4. Black (10YR 1/1m) sandy loam A horizon, developed beneath Kobresia myosuroides meadow vegetation.
5. Very dark grayish brown (10YR 3/2-3/3m) gravelly sandy loam A/C horizon. Weak platy structure.
6. Dark yellowish brown (10YR 4/4m) gravelly sandy loam Cox horizon. Structureless to weakly blocky.

80 cm deep (Figure 7). Clast size decreased with depth within the borders; the long axes of stones were oriented predominantly parallel to the ground surface, which sloped to the northwest at 5-10°. Coatings of an unidentified white precipitate, thought to have formed by evaporation of mineralized groundwater, occurred on stones in openwork rubble abutting areas of fine-textured earth. Small-mammal droppings and nesting materials were abundant in the rocky borders of the sorted net, which provide a protected habitat for mice and voles. Interstices between rocks in the lower parts of the borders were filled with very dark brown sediment thought to consist largely of soil humus eroded from higher on the slope and redeposited by wind and water. A radiocarbon date of 3385 $\pm$ 95 BP (I-9121) for the NaOH-insoluble fraction of this material applies to a period of slope stability and soil formation, and cannot be interpreted as either a minimum or a maximum age for development of the sorted net.

Stone content increased with depth in the center of the net; distinctions between borders and center were no longer visible below 80 cm, suggesting that this was the lower limit of effective frost sorting. A well-defined A-A/C-Cox soil profile was developed in the fine-textured center of the pattern, beneath a cover of Kobresia myosuroides. Differences in A-horizon thickness indicate that plant colonization began at the edges of the center and proceeded inward, or that the developing turf zone was periodically disrupted by frost heaving and lateral surface movements. The curiously "perched" character of the center (Figure 7) suggests that the surface expression of the pattern has moved downslope relative to the center of upwelling.

Sorted nets in shallow ponds

Two active sorted nets were excavated in areas of seasonal submergence. The first was at an altitude of 3160 m on the south slope of Niwot Ridge (Figure 3, Locality 11), about 75 cm below the modern high-water level of an ephemeral kettle lake in the subalpine forest. The borders of the net were shallow, extending to a maximum depth of about 20 cm (Figure 8a). The long-axis orientations of elongate sand grains, measured in thin sections impregnated with plastic resin (Benedict, 1969), are consistent with lateral spreading of fines from beneath the rocky borders, and with upwelling in the fine-textured center. The water table lay at a depth of 45 cm on 10 October 1965, a few weeks prior to the beginning of seasonal freeze at this altitude.

A second profile (Figure 8b) was obtained from the patterned floor of a small pond on a Niwot Ridge turf-banked terrace, 3475 m a.s.l. (Figure 3, Locality 9). The borders of the net were about 28 cm deep, and rested in sediment stained very dark grayish brown by organic matter that had filtered downward through the openwork debris. Stones in the borders of the feature were derived from a layer 45 to 55 cm thick. The lack of vertical sorting below this depth is attributed to shallow freezing beneath an insulative cover of winter snow. Differences between these patterns and the large sorted net illustrated in Figure 7 are largely a consequence of differences in depth of freezing, initial differences in the rockiness of the subsoil, and differences in vegetation growth and pedogenic processes.

Sorted stripes on a snowbank floor

Active sorted stripes were trenched and described on the northeast-sloping (12°) floor of a late-lying snowbank at 3490 m altitude on Niwot Ridge (Figure 3, Locality 3). Stripes of cobble- and boulder-sized material stood higher than adjacent fines, and had a maximum depth of about 25 cm (Figure 8c). Tabular stones lay with their flat sides parallel to the ground surface or slightly imbricated, and their long axes aligned in the direction of slope. Fine-textured sediment between the rocky stripes was dark yellowish brown in color, its upper few centimeters stained dark brown by detrital organic matter deposited with the snow in winter and released onto the snowbank floor by melting. Sediment immediately beneath the rocky stripes was coarser and less cohesive than sediment at comparable depth between the stripes. Microfabric data are consistent with circulatory overturn; fines are thought to have moved downward and outward from beneath the stripes of rock, and to have risen toward the surface in the stripes of fine material. Groundwater was encountered at 45-cm depth on 8 October 1964, when the stripes were excavated; in many years the water table is shallower than this at the beginning of freeze.

Relationship of diameter to depth

During the course of the study I excavated the borders of nine sorted nets and four small secondary polygons to determine their depths. Border depth increased with increasing pattern diameter (Figure 9); both dimensions are influenced by the thickness of the active layer. For primary sorted nets, the ratio of diameter to depth varied from 9.2 to 3.6. Ratios were highest where stones were least numerous (Figure 9).

Modern activity

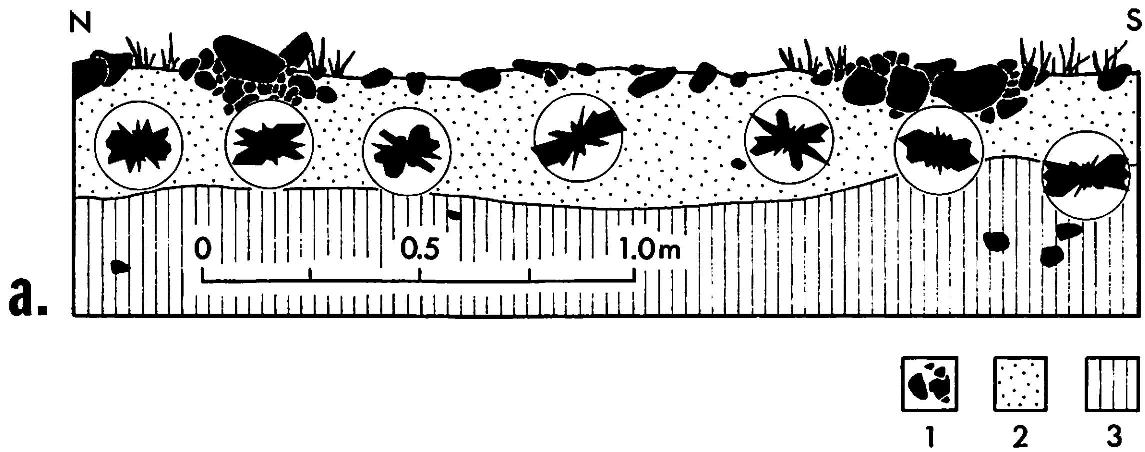
To determine the kinds of environments in which sorted nets are currently active, I painted lines across the junctions between stones in their borders at 18 localities. The percentage of lines offset during an annual freeze-thaw cycle was taken as a measure of the activity of the pattern; results are summarized for five environments in Table 1.

Displacement was greatest (64% of 163 marked junctions) in the borders of sorted nets on the floors of shallow ponds whose sediments were saturated, but not submerged, at the beginning of the autumn freeze. Lichens were absent in the borders of these patterns, due either to frost disturbance or to the physiological effects of immersion. Centers were largely free of vegetation. But at two localities (one illustrated in Figure 5b), eroded remnants of a 15-cm-thick turf layer suggest that the patterns have been partially reactivated following a period of stability and vegetation growth. Additional evidence for episodic patterned-ground activity is discussed later in the paper.

Displacement was least (3% of 108 marked junctions) in the borders of sorted nets on well-drained, windswept tundra knolls and ridgecrests (Table 1). Even this small amount of disturbance is likely to have been caused by factors other than frost: for example, by animals walking across the patterns. The centers of the nets were fully vegetated and displayed well-developed soil profiles. Rocks in their borders showed strong differential weathering and

Figure 8 (facing). Cross sections of active sorted nets and stripes, Niwot Ridge. Rose diagrams show long-axis orientations of cobbles and boulders (white) and elongate sand grains (black).

a. Sorted net in the floor of an ephemeral kettle lake on a Pinedale-age lateral moraine on the south flank of Niwot Ridge.
   1. Openwork rubble.
   2. Dark brown (10YR 3/3m) structureless gravelly loamy sand with surface lag gravel and stone layer. Grades into very dark brown (10YR 2/2m) humus-rich sandy loam beneath borders.
   3. Dark yellowish brown (10YR 4/6m) sandy loam. No visible sedimentary layering. Weak medium blocky structure.
b. Sorted net in a pond on a turf-banked terrace north of Tree Limit Van.
   1. Openwork rubble.
   2. Very dark grayish brown (10YR 3/2m) humus-rich sandy loam. Weak medium blocky structure.
   3. Dark yellowish brown (10YR 3/4m) stone-free gravelly sandy loam. Structureless.
   4. Dark yellowish brown (10YR 4/4m) very stony, gravelly sandy loam. Moderate medium blocky structure.
c. Sorted stripes on the floor of a late-lying snowbank northwest of the former D-7 weather station.
   1. Openwork rubble.
   2. Dark brown (10YR 3/3m) sandy loam with surface lag gravel and stone layer. Moderate medium blocky structure.
   3. Dark yellowish brown (10YR 3/4m) sandy loam. Weak fine to medium blocky structure. Grades to a structureless loamy sand beneath stripes of coarse debris.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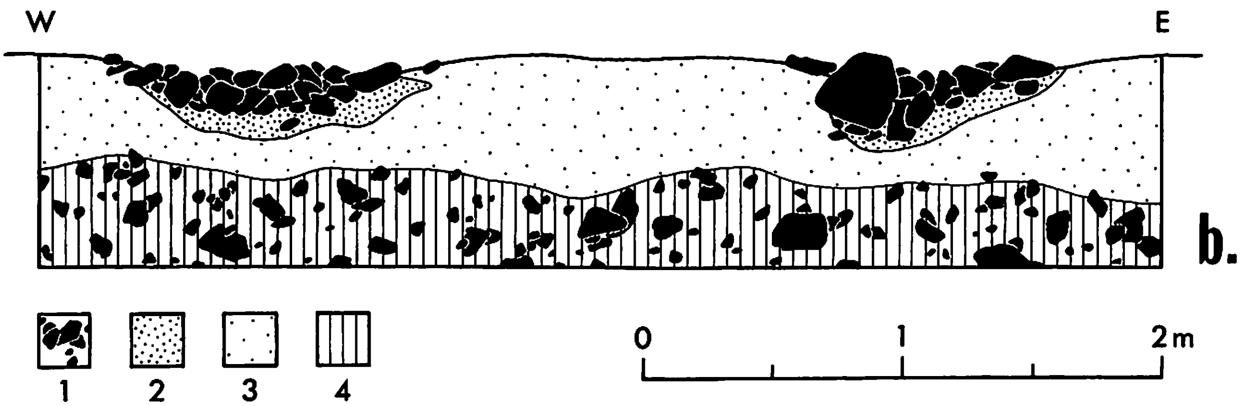
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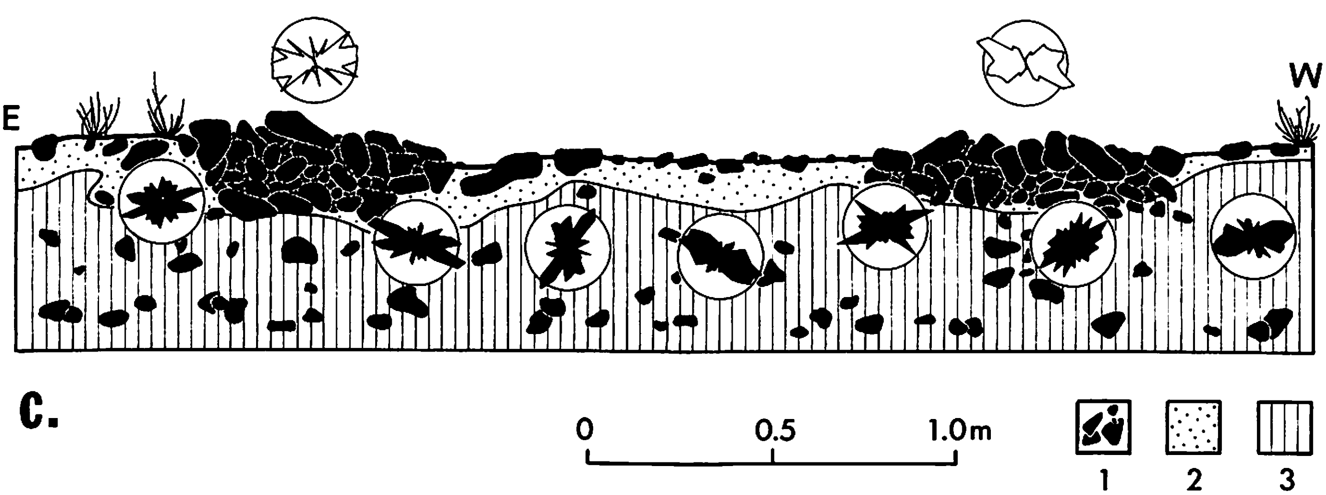
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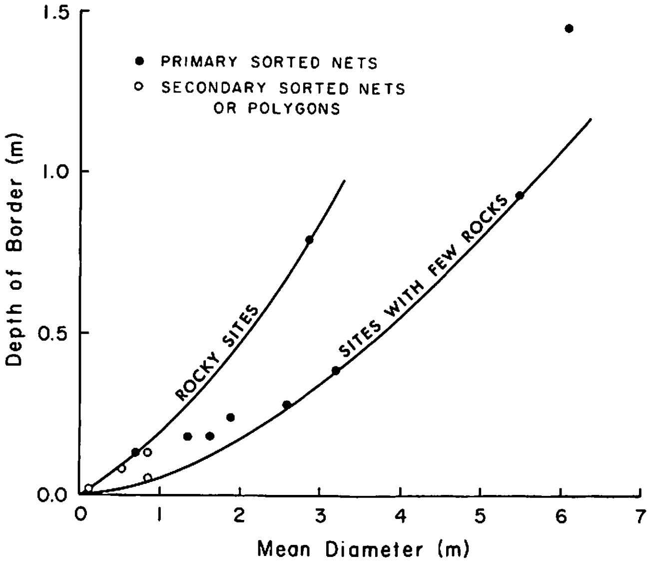


Figure 9. Graph showing depths of pattern borders (n = 13) as a function of diameter. Lines indicate trends for the rockiest and least-rocky sites.

mature lichen covers; foliose lichen thalli bridged the contacts between many stones. Maximum Rhizocarpon subgenus Rhizocarpon diameters of 113 to 170 mm suggest that the borders of sorted nets on windswept knolls have been inactive for at least 3200 yr, and in some cases for more than 5000 yr.

Measurements in sorted stripes gave similar results. Displacement was greatest (82% of 66 marked junctions) in saturated areas that receive meltwater seepage from late-lying snowbanks. Disturbance was least (4% of 113 marked junctions) on slopes that become snow-free by mid summer and are dry by the beginning of the autumn freeze.

In a study reported in greater detail elsewhere (Benedict, 1970a: 202-203), I measured downslope movement at two sorted-stripe localities with comparable slope angles but different soil-moisture regimes. The positions of painted stones at each site were determined with reference to a plumb bob suspended against a horizontal wire stretched between two cased benchmarks. Stripes at 3570 m altitude on a 12°, southeast-facing slope that is relatively dry in autumn (Figure 3, Locality 2) moved downslope at an average rate of 0.3 mm yr^{-1} between 1964 and 1967. During the same three-year period, stripes at 3490 m altitude on a saturated, 12-13°, northeast-facing solifluction slope (Figure 3, Locality 3) moved downslope at an average rate of 22.1 mm yr^{-1}, almost two orders of magnitude faster than at the drier site; displacement was greatest in bands of fine-textured earth, and least in bands of cobbles and small boulders.

SITE NO.	TYPE OF SITE	ELEV. (m)	AUTUMN MOISTURE	DIAMETER OF NET (m)	MEAN DIAMETER OF STONES IN BORDERS (cm)	TEXTURE OF CENTER (30cm)			NO. LINES	PERIOD	STONES DISPLACED (%)
						SAND (%)	SILT (%)	CLAY (%)			
13	POND	3,525	SATURATED	1.8	20	56	29	15	35	1963-64	89
11	"	"	"	"	"	"	"	"	30	"	87
12	"	"	"	"	"	"	"	"	29	"	66
38	"	3,160	"	0.8	25	78	16	6	24	1966-67	46
41	"	3,425	"	1.7	20	52	41	7	20	"	45
42	"	3,475	"	2.4	30	67	21	12	25	"	32
32	DRAINAGE AREA BELOW GLACIER	3,785	SATURATED	6.1	30	42	37	21	25	1964-65	28
30	POORLY DRAINED SADDLE	3,720	VERY MOIST	6.9	30	37	43	20	22	1964-65	36
26	TURF-BANKED TERRACE	3,610	MOIST	6.9	40	45	35	20	33	1963-64	18
36	"	3,635	↑	5.9	35	53	33	14	20	1966-67	30
35	"	3,650			5.9	30	53	41	6	26	"	0
34	"	3,675	↓	7.0	35	56	33	11	20	"	0
33	"	3,695	DRY	6.0	35	60	35	5	21	"	0
27	KNOLL	3,535	DRY	2.6	25	52	37	11	26	1963-64	8
28	"	3,400	"	2.5	35	61	22	17	21	"	5
24	"	3,745	"	3.5	25	47	46	7	21	"	0
39	"	3,485	"	1.9	30	44	40	16	20	1966-67	0
37	"	3,610	"	1.9	30	44	48	8	20	"	0

Table 1. Physical characteristics of sorted nets in the Niwot Ridge area, with data on annual displacement of stones in their borders.

Origin

The hypothesis of origin outlined in this paper is not original -- its basic aspects were developed by Alfred Jahn more than 40 yr ago (Jahn, 1948). Neither does the hypothesis explain all large-scale sorted nets and stripes in the Colorado Rocky Mountains -- some have formed by other processes (accumulation of stones in dilation-crack networks, grussification of isolated boulders in blockfields, etc.). But it is the most plausible explanation for most sorted nets and stripes in the region. It is consistent with (1) their surface morphologies and internal structures, (2) their more-or-less regular spacing, (3) their frequent lateral gradation into blockfields and stone pavements, (4) fabric and microfabric data that suggest circulatory overturn, (5) the inferred ages of the patterns and paleoenvironmental history of the region, and (6) the results of small-scale laboratory experiments. The hypothesis involves an initial stone-pavement phase, development of a metastable density profile due to melting of icy fine-textured sediments beneath the pavement, and reestablishment of a stable (i.e., patterned) system, possibly in response to an applied shock.

Excavations show that the rocky surface layers of blockfields and stone pavements in the Front Range are underlain by fines from which most stones have been ejected by vertical frost sorting. The development of such layered profiles is described by Czeppe (1960). The thickness of the surface rubble unit depends on the thickness and initial rockiness of the active layer, and on the intensity and duration of vertical frost sorting. Because coarse rubble is inherently denser than fines (Washburn, 1969), profiles with surface accumulations of stones are potentially unstable; density differences are accentuated when ice lenses melt from the fines, creating water-filled voids that persist until excess water can drain from the profile.

According to this hypothesis, sorted nets and stripes develop as a result of mass movements set into motion when such metastable systems are disturbed. Plugs of mobile, low-density fine material rise upward into the high-density rubble layer. Where the rubble is not excessively thick, they emerge at the surface. Stones move laterally from the up-domed centers, accumulating in the depressions between them. Where centers are closely spaced, the stones become concentrated in well-defined bordering troughs, producing sorted nets, elongate nets, or stripes, depending upon angle of slope. Where relatively few plugs of fine material emerge at the surface, debris islands are the dominant pattern.

No other explanation satisfactorily accounts for the widespread occurrence of sorted nets on Front Range knolls and ridgecrests that are blown free of snow in winter and receive no snowmelt seepage (Figure 10). Massive freezing, rather than ice segregation, characterizes the well-drained soils of these localities today. But as the permafrost table rose during cooling phases of the Pleistocene, downward-percolating meteoric water accumulated at the surface of the relatively impermeable frozen subsoil. Large volumes of clear ice may have accreted in this manner, while at the same time vertical frost sorting produced a layered profile with a surface pavement of stones. When conditions became warmer, as they did about 15,000 to 14,000 yr BP in the Front Range, melting of ice-enriched permafrost further reduced the stability of the system.

What caused these metastable, layered profiles to collapse and patterned ground to form? The answer is by no means clear. In experiments described in the following section of the paper, jarring was required to cause patterning. But under natural conditions this may not have been necessary, and in the case of some patterns (such as sorted nets that have formed on the floors of ponds during the past century) it seems highly unlikely. If jarring was required, earth tremors of tectonic or landslide origin are possible sources. The tendency of Front Range valley walls to expand, and often to collapse, in response to glacial unloading at the close of the Pleistocene is recorded by sackung features and by massive rock-glacier aprons and landslide deposits. A lightning strike, or even the struggles of a mired animal, might have been sufficient to trigger liquefaction.

Once the basic ground pattern had developed, sorted nets and stripes in autumn-saturated environments continued to evolve slowly by a combination of differential frost heaving and mass displacement. Formation of segregated ice lenses in the fine-textured centers of the patterns caused upfreezing of coarse clasts; during periods of thaw the clasts moved laterally along local gradients into pattern borders. Just as transport of sediment from

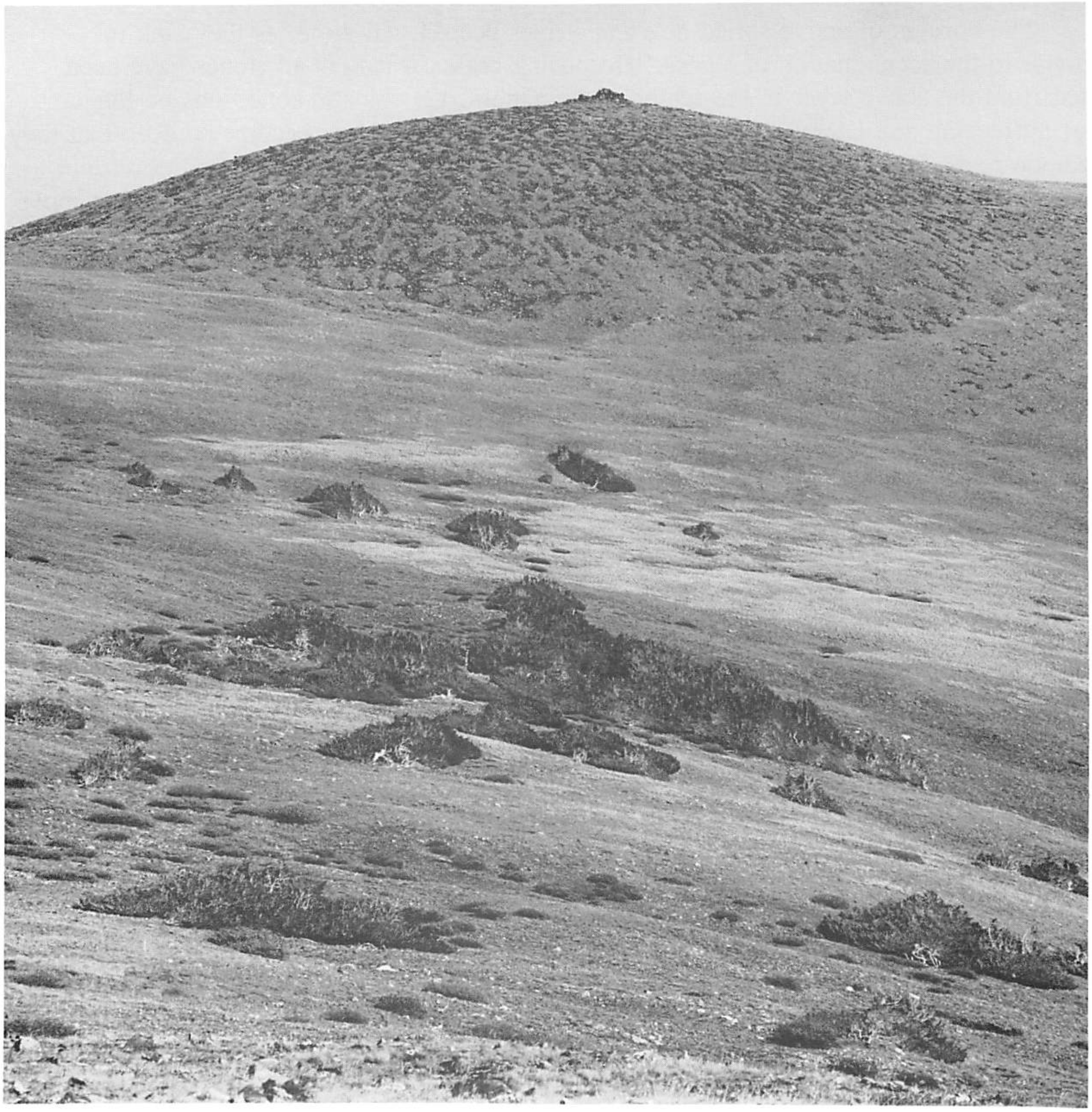


Figure 10. Inactive sorted nets on a well-drained, windswept tundra knoll (summit altitude 3523 m) near the east end of Niwot Ridge (Figure 3). Any general theory of sorted-net origin must be able to account for pattern formation in such xeric environments. Photo 1 October 1992.

upland regions to the continental shelf creates isostatic imbalances that are relieved by flow within the mantle, lateral movement of surface sediment from the updomed centers of sorted nets to their borders created imbalances that were relieved by flow within the mobile soil at depth. The borders sank beneath the weight of added material, and underlying fine-textured earth was displaced inward toward the centers of the patterns. Microfabric studies (Figures 8a, 8c) and the trajectories of artifacts and charcoal at an archeological site where Early Archaic occupation was followed by reactivation of sorted nets (Benedict and Olson, 1978: 40-41) support the concept of circulatory overturn. Additional supporting evidence is given by Rydquist (1960) and Wassén (1965).

The borders of active sorted nets and stripes deepen with time, as they sink in response to the accumulation of stones. Deepening ceases when (1) all stones have been sorted from the active layer in the center of the pattern, (2) climatic conditions no longer favor upfreezing and lateral movement of stones, or (3) the borders become so deep that they rest upon rocks in the nonsorted subsoil. In the latter case, raised borders will develop, increasing in height until there is no longer a seasonal gradient along which stones can move laterally; further ejection of stones will produce sorted nets with stony centers that are only slightly finer-textured than their encircling borders.

Laboratory studies of pattern origin and size

Miniature patterns that resemble natural sorted nets and stripes in all respects except for their small mesh diameters were produced in a series of experiments modeled after studies in Polish laboratories (Dżułyński, 1963; Jahn and Czerwiński, 1965; Ankatell et al., 1970; Cełga and Dżułyński, 1970). The tests were conducted in circular aluminum pans, 25 cm in diameter and 10 cm deep. The pans were filled with a suspension of clay and water, which was allowed to settle until the clay had become dense enough to support a thin layer of sand sieved uniformly upon its surface. The sand was analogous to the surface debris layer of a stone pavement; the clay had an open, unpacked structure analogous to that of sediment from which ice lenses have recently melted. Liquefaction and patterning were induced by dropping the pans a distance of about 1 cm onto a concrete slab. An example of sorted nets produced by this procedure is illustrated in Figure 11. The tests were designed to evaluate the effects of five independent variables upon pattern diameter.

In 12 of the tests all variables were held constant except clay-layer thickness. Pattern dimensions increased with increasing thickness of the clay (Figure 12a), suggesting that under natural conditions the diameters of sorted nets produced by mass displacement will increase with the thickness of the low-density layer that underlies the surface pavement of stones.

Eight tests were conducted to evaluate the effect of sand-layer thickness. Pattern dimensions increased with increasing thickness of the sand (Figure 12b). But as the sand became thicker, more impacts were needed to cause patterning: the number increased from 4 (at a sand-layer thickness of 0.06 cm) to 30 (at a thickness of 0.57 cm), suggesting that sorted nets may be unable to develop in blockfields with very thick rubble layers. The common lateral gradation from (1) well-developed sorted nets, to (2) blockfields with

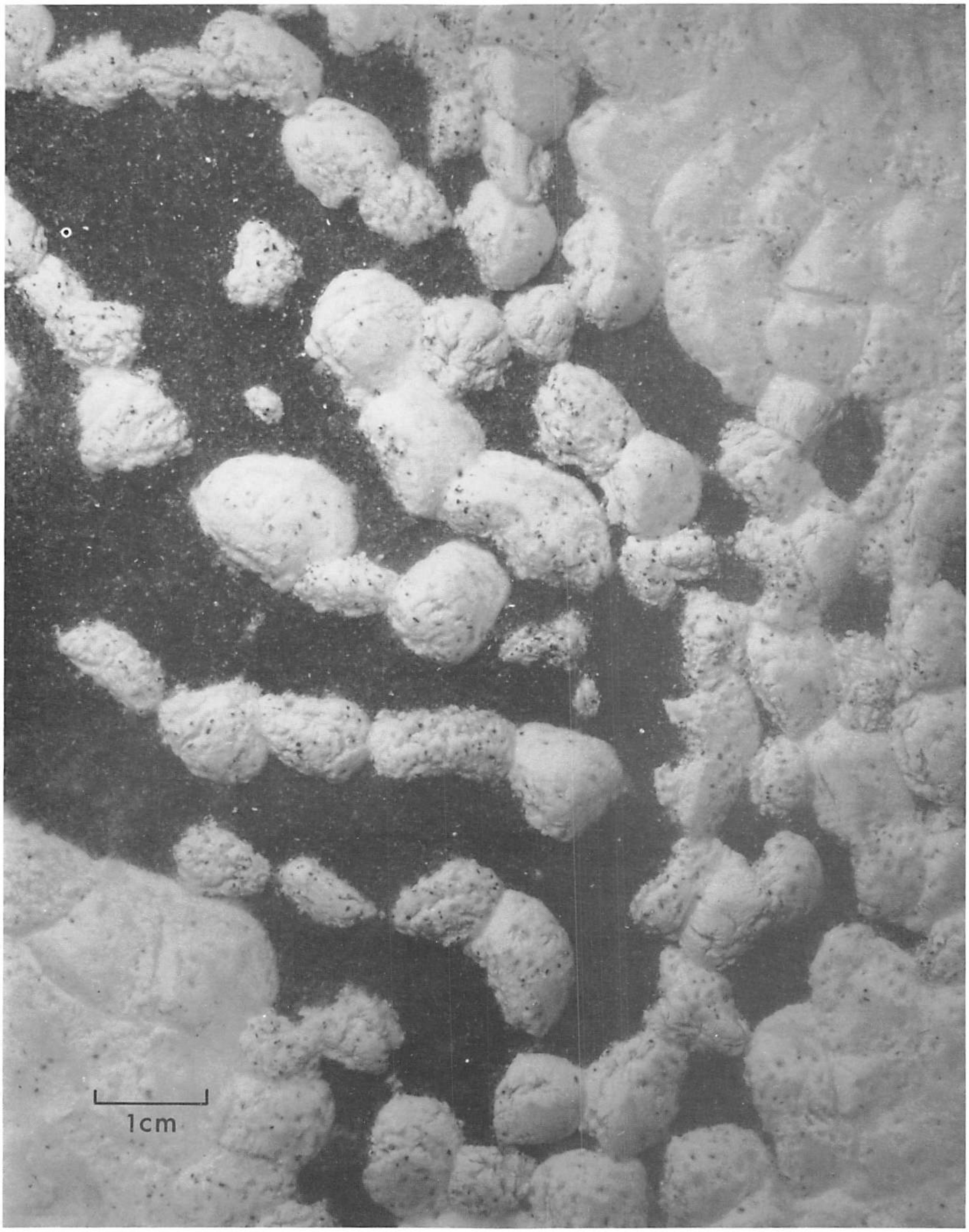


Figure 11. Miniature sorted nets produced by jarring a container of clay, settled from an aqueous suspension, and covered with a thin surface layer of sand.

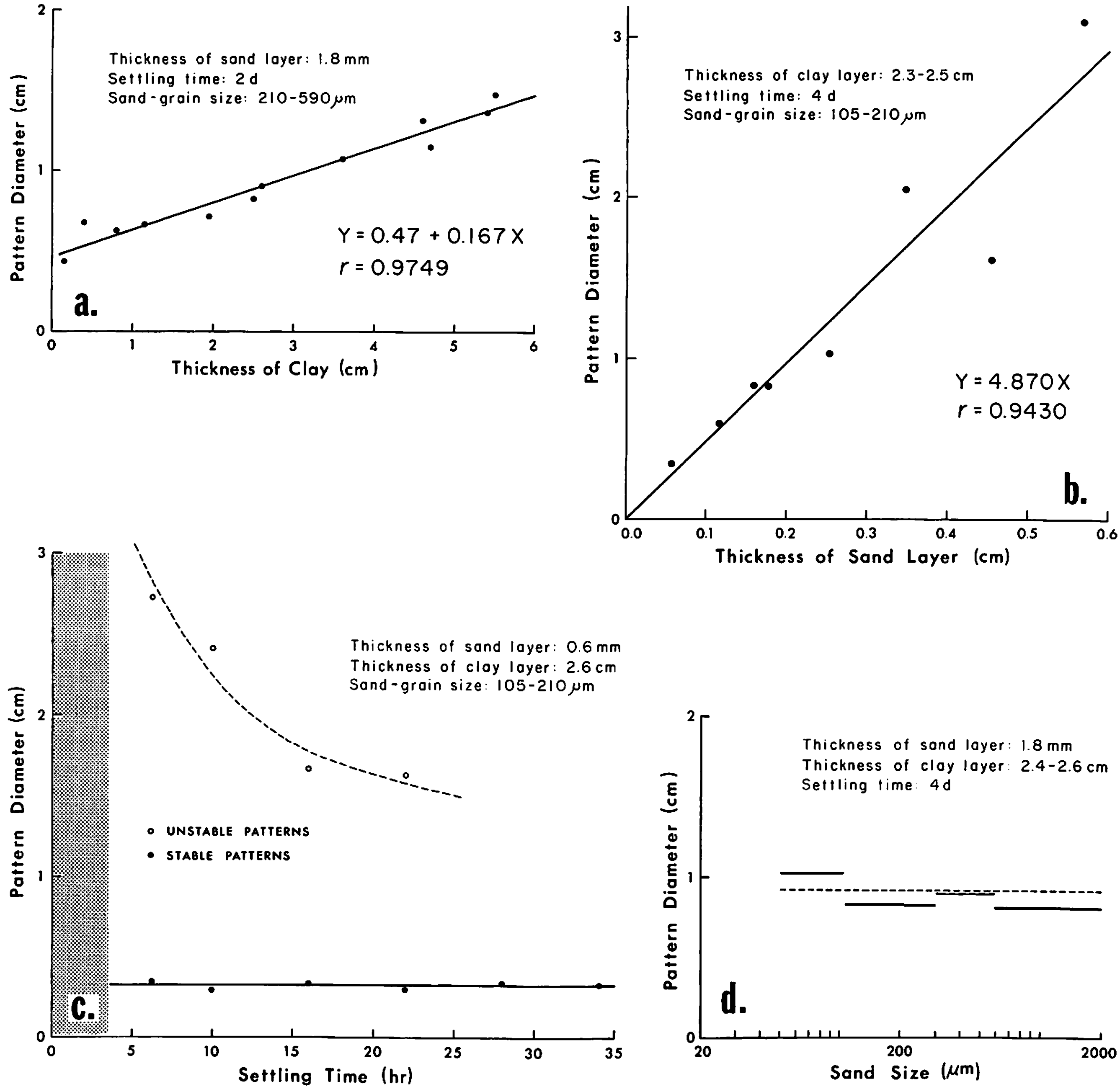


Figure 12. Results of experiments to determine the factors that control the diameters of miniature sorted nets. Mesh diameter is determined by the thickness of the clay and sand layers (a, b), and is unaffected by settling time, sand size, and sorting (c, d). The shaded area (c) indicates that clay densities were insufficient to support sand. The dashed line (d) shows the mesh diameter obtained using an equal mixture of all five sand separates.

scattered debris islands, to (3) unpatterned blockfields with plugs of fine-textured earth visible only in profile (Benedict and Olson, 1978: Fig. 21), may reflect increasing initial thickness of the surface debris layer.

Clay-layer density -- a function of settling time -- was the independent variable in seven tests (Figure 12c). At settling times shorter than 3.5 h, the clay was too weak to support a layer of sand. At longer settling times, jarring produced two sets of patterns. The first consisted of relatively large, sand-covered mounds separated by shallow troughs; slight additional jarring caused the troughs to become deeper and the patterns to collapse, setting off a chain reaction of collapses elsewhere in the pan, and causing homogenization of the sediments. As settling times increased, these transient patterns became smaller, more stable, and less conspicuous; in fully settled clay they were no longer visible. The second set of patterns consisted of small circles of clay arranged in networks on the sandy crests of the larger mounds. These were similar in size to the patterns produced in other experiments. Their diameters remained constant regardless of differences in clay-layer density (Figure 12c).

Figure 12d shows the results of five tests in which sand-grain diameter was the only independent variable. The separates used in this experiment ranged from very fine to very coarse sand. A sixth test was conducted using equal parts of each sand separate (dashed line). Mean pattern diameters were unaffected by differences in grain size and sorting within the sand layer, consistent with the field observation that the borders of large sorted nets can consist either of fine or of coarse material, or be a mixture of many sizes.

It can be argued that small-scale model studies should not be extrapolated to natural systems: the water molecule, for example, cannot be reduced in size in the same way that sand grains can be substituted for boulders. Laboratory studies, however, can generate hypotheses to be tested by large-scale field experiments and observations. Hypotheses resulting from the present study are (1) that the diameters of sorted nets formed by mass displacement will be determined by the thickness of the surface rubble layer, the thickness of the layer of mobile fines from which rubble has been ejected, and the depth of thaw at the moment of spontaneous liquefaction; (2) that diameters will be unaffected by the size and sorting of stones in the surface debris layer, the density of the underlying fine-textured sediment, and the intensity of the shock that triggers liquefaction; and (3) that patterned ground will be unable to form where the shock is inadequate, the thickness of the debris layer prevents fines from reaching the surface, or the density of the fine-textured sediment is so low that a shock to the system produces total collapse and homogenization. Field experiments on a much larger scale would help bridge the gap between these small-scale studies and field observations.

Age and paleoenvironmental significance

Most large sorted nets in the Front Range are thought to have formed during the late Pleistocene. Some, however, are younger, as indicated by their occurrence on Holocene moraines and rock glaciers, and on the floors of glaciated valleys (Benedict, 1985: Fig. 17). The youngest have developed during the past century. Crude sorted nets 1.2 to 2.4 m in diameter occur at the crest of the innermost Little Ice Age moraine of Arapaho Glacier; mechanical sorting during differential melting of the moraine's ice core (Corte, 1959) may have contributed to their formation. Well-defined sorted nets occur in tailings of the Oliver Twist Mine, in the Mosquito Range, south of the study area; the gently sloping surface of the tailings pile is irrigated by snowmelt water. Sorted nets 2.2 to 4.5 m in diameter have formed on the floor of Sandbeach Lake, an irrigation reservoir at 3135 m altitude in Rocky Mountain National Park; they occupy the seasonally submerged surface of a delta-like bench built of sediments that have washed into the reservoir from its wave-eroded modern shoreline, and must post-date construction of the Sandbeach Lake Dam between AD 1910 and 1912.

Figure 13 shows the average diameters of sorted nets at 44 localities in the Indian Peaks region of the Front Range. Although many factors can prevent sorted nets from attaining their theoretical maximum dimensions, the concentration of large patterns at an altitude of 3600 to 3800 m suggests that this was the optimum altitude for deep and effective frost sorting during the late Pleistocene. The decrease in average diameter at lower altitudes can be attributed to decreasing depth of vertical frost sorting. The decrease in diameter at higher altitudes may reflect shallow summer thawing, but could also be due to shallow bedrock; thick diamictons rarely occur above 3800 m in the Indian Peaks region.

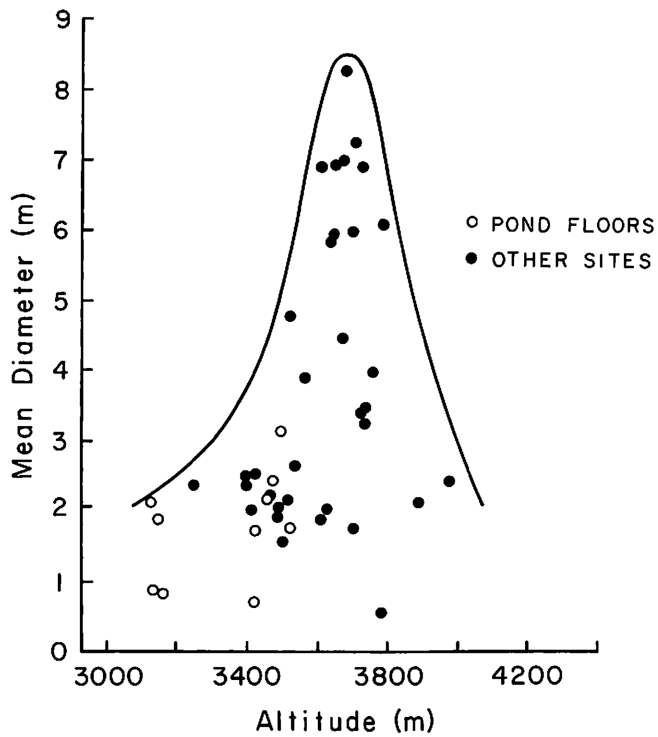


Figure 13. Mean diameters of sorted nets at 44 localities in the Niwot Ridge area, plotted as a function of altitude. Patterns on the floors of ponds (circles) extend to lower altitudes than patterns in drier environments (dots). The heavy line is an estimate of the mean diameter to be expected under optimum conditions; many factors can prevent sorted nets from achieving this diameter.

The presence of sorted nets on well-drained ridgetops at altitudes as low as 3245 m (Figure 13) indicates that icy permafrost was widespread during the late Pleistocene, occurring as much as 100 m below modern timberline. Permafrost is not required in order for sorted nets to form in saturated environments, as indicated by patterned-ground development during the past 80 years in Sandbeach Lake. Sorted nets with histories of alternate stabilization and reactivation provide evidence of paleoenvironmental change; a radiocarbon-dated example is discussed by Benedict and Olson (1978).

EARTH HUMMOCKS AND FROST BOILS

Description

Earth hummocks (thúfur) in the Front Range (Figure 14) are irregularly circular in ground plan, becoming elongated downslope where the gradient exceeds about 4°. Individual hummocks vary from 0.3 to 2.0 m in diameter and are generally 0.5 m or less in height. Large, composite forms, caused by the merger of several closely spaced hummocks, may be 5 m or more in maximum horizontal dimension. The flanks of many hummocks are undercut by small-mammal burrows and runways. Stones locally protrude through the turf; a reddish-brown surface stain and absence of lichens suggests that some stones have emerged at the surface within recent decades. Environmental factors common to all earth-hummock localities on Niwot Ridge are (1) level to gently sloping terrain, (2) a dense turf cover dominated by sedges, grasses, and willows, (3) running or standing surface water in spring and early summer, and (4) shallow but persistent winter snow accumulation.

Frost boils (nonsorted circles) are irregularly circular in shape, and are 1.5 m or less in diameter (Figure 15). Where frost boils merge, large areas may be stripped clear of vegetation and churned by frost disturbance. On gentle slopes, the surfaces of frost boils remain roughly horizontal, their fine-textured centers prevented from spreading downslope by rims of vegetation that enclose their lower margins. Environmental factors common to all frost-boil localities on Niwot Ridge are (1) a relative scarcity of stones, (2) level to gently sloping ground, (3) a cover of vegetation, (4) abundant moisture, and (5) negligible winter snow cover.

Because the centers of frost boils lack insulating vegetation, they are loci of intense ice segregation, and develop bulging, convex surfaces in winter. Tension cracks bisect the centers of many frost boils, trending in the direction of elongation; the cracks open in winter due to differential frost heaving, and close in summer, gradually filling with stones that slump inward from their sides. Small sorted stripes can develop by this mechanism.

The surfaces of many frost boils are patterned with polygonal networks of frost-desiccation cracks that develop during periods of closed-system diurnal freezing in a shallow active layer above seasonally frozen ground. The cracks fill with pebbles during periods of thaw, forming miniature sorted polygons, or Zellenboden. Cracking is accompanied by precipitation of white salt crusts on stones, pebbles, and coarse sand grains; salts from a Niwot Ridge frost boil were identified as gypsum by Peter W. Birkeland (1968), using

Figure 14. Earth hummocks in a tundra wetland south of Sundance Mountain, Rocky Mountain National Park, altitude 3630 m. Photo . October 1992.

Figure 15. Frost boils in the Albion-Kiowa saddle, altitude 3650 m. The rock hammer is 32 cm long. Arikaree Peak (4008 m) is on the skyline at upper right. Photo August, 1961.

emission spectrometry. Zellenboden are conspicuous only during periods of frequent, shallow freeze-thaw alternation (Figure 1). They form in autumn (after the seasonal freeze has begun and an impermeable substratum is present), and gradually disappear in winter, becoming prominent again during the spring thaw. By midsummer they are no longer visible, and the centers of the frost boils have lost much of their convexity. No cracking or gypsum precipitation occur during periods of summer drought, when open-system conditions prevail, and the soil remains moist due to capillary flow from below.

Profile studies

Hummocks and frost boils in a wet saddle

Profiles from the floor of a broad saddle at 3510 to 3520 m altitude on Niwot Ridge (Figure 3, Locality 4) illustrate the transition from earth hummock to frost boil that occurs when the top of a hummock is eroded by wind, exposing the mineral subsoil to intensified freezing and thawing (Figure 16). Profiles A and B are from uneroded hummocks. Their surface organic layers are intruded by plugs of mineral soil, which have caused updoming of the features and thickening of peat on their downslope (left) sides. Profile C shows a degraded hummock, and profile D a hummock that has completed its transformation into a frost boil. Irregular tongues of buried organic matter, representing former surface horizons overridden by laterally spreading mineral soil, were visible in all of the profiles. Except for localized concentrations of stones, textural differences beneath the surface peat layer were minor: units were differentiated by differences in consistence, organic-matter content, and the oxidation state of iron oxides.

Microfabric data (Benedict, 1969: Figs. 1-2) suggest that the mineral cores of earth hummocks have been displaced upward, toward the ground surface, as well as in a downslope direction. The vertical component of movement intensifies when desiccation and wind erosion destroy the insulating peat, permitting deeper frost penetration and more-frequent freeze-thaw cycles.

Concentrations of stones beneath inter-hummock depressions (Figure 16) are interpreted as the borders of relict sorted nets, formerly active on the floor of the saddle. Just east of the hummock area, where peat development is inhibited by drier conditions, the borders of the nets are visible at the surface as shallow, sod-covered troughs, and their junctions as rubble-filled depressions or "stone pits," vegetated only by lichens and mosses. These patterns grade upslope into sorted nets with exposed, rocky borders, such as are illustrated in Figures 5a and 7.

Frost boil in a turf-banked lobe

Four profile drawings were made at different distances from the center of a frost boil in a turf-banked lobe at 3500 m altitude on Niwot Ridge (Figure 3, Locality 8). Profile complexity increased from margin to center (Figure 17). Near the margin of the frost boil the profiles reflected the influence of frost creep and solifluction in the upper 40-50 cm of soil. Near the center, vertical movements predominated, and oxidation/reduction effects were more conspicuous. The upper 5-10 cm of bare mineral soil in the center of the frost boil was vesicular, with a frothy appearance similar to that of scoria; the vesicles are thought to mark the locations of air bubbles liberated during thaw and trapped in the drying soil. Tongues of strongly gleyed earth, very sticky and cohesive, were associated with buried humus layers at depth. A humus layer approximately 1 m below ground surface in another frost boil on the same lobe was dated by Fahey (1975) at 10,400 ± 400 BP (GaK-3823); the layer was thought to be older than formation of the patterned ground.

Winter profile studies

An earth hummock on a Niwot Ridge turf-banked lobe (Figure 3, Locality 10) was trenched with explosives on 3 May 1966, shortly before the beginning of thaw. No profile could be drawn due to a miscalculation in the amount of blasting powder needed. Enough of the feature remained, however, to determine the nature of its frozen interior. Mineral soil beneath the ice-poor surface peat layer was rich in ice, which occurred as (1) finely disseminated crystals in soil pores, (2) thin, transparent lenses of segregation ice, 25 mm or less in length and 0.1-1.0 mm thick, spaced at vertical intervals of 1-4 mm and oriented roughly parallel to the hummock surface, and (3) sheaths of clear ice surrounding the lower parts of large pebbles, cobbles, and small boulders. The thickest sheaths were associated with the largest clasts; ice was thin or absent at the tops of the stones, but formed pedestals as thick as 10-11 mm directly beneath them. Ice pedestals beneath stones reflect freezing of water in cavities formed when the stones are pulled upward by heaving of the surface frozen layer to which their tops have become bonded.

Winter excavations in an area of frost-disturbed bare earth near Locality 8 (Figure 3) revealed the same three kinds of ice. Also present in the upper 20 cm of sediment were relatively continuous layers of cloudy, white ice, several millimeters thick, spaced at intervals of 2-6 cm and oriented parallel to the ground surface (Benedict 1970a, Figs. 33, 34). These are thought to have formed during pauses in the downward progression of autumn freezing, when -- for periods of hours, or perhaps days -- heat flow to the surface was balanced by latent-heat production at the freezing front.

Modern activity

No evidence was found to suggest that new frost boils or earth hummocks are presently developing on Niwot Ridge. In 1962 I marked all existing ground patterns on the moist tread of a large turf-banked terrace (Figure 3, Locality 8) using wire stakes. No new frost boils or earth hummocks appeared during 6 years of observation. Comparison of repeat photographs taken annually between 1962 and 1965, and again in 1975, 1983, and 1987, showed no changes in the appearances of earth hummocks and no enlargement of degraded hummocks or frost boils. Instead, at many localities the tendency during this 25-yr period was for colonization of frost-disturbed bare earth by plants.

Although present conditions on Niwot Ridge do not favor development of new frost boils or earth hummocks where none previously existed, repeat photographs show that pebbles and small cobbles in the centers of frost boils in wet sites are displaced each year.

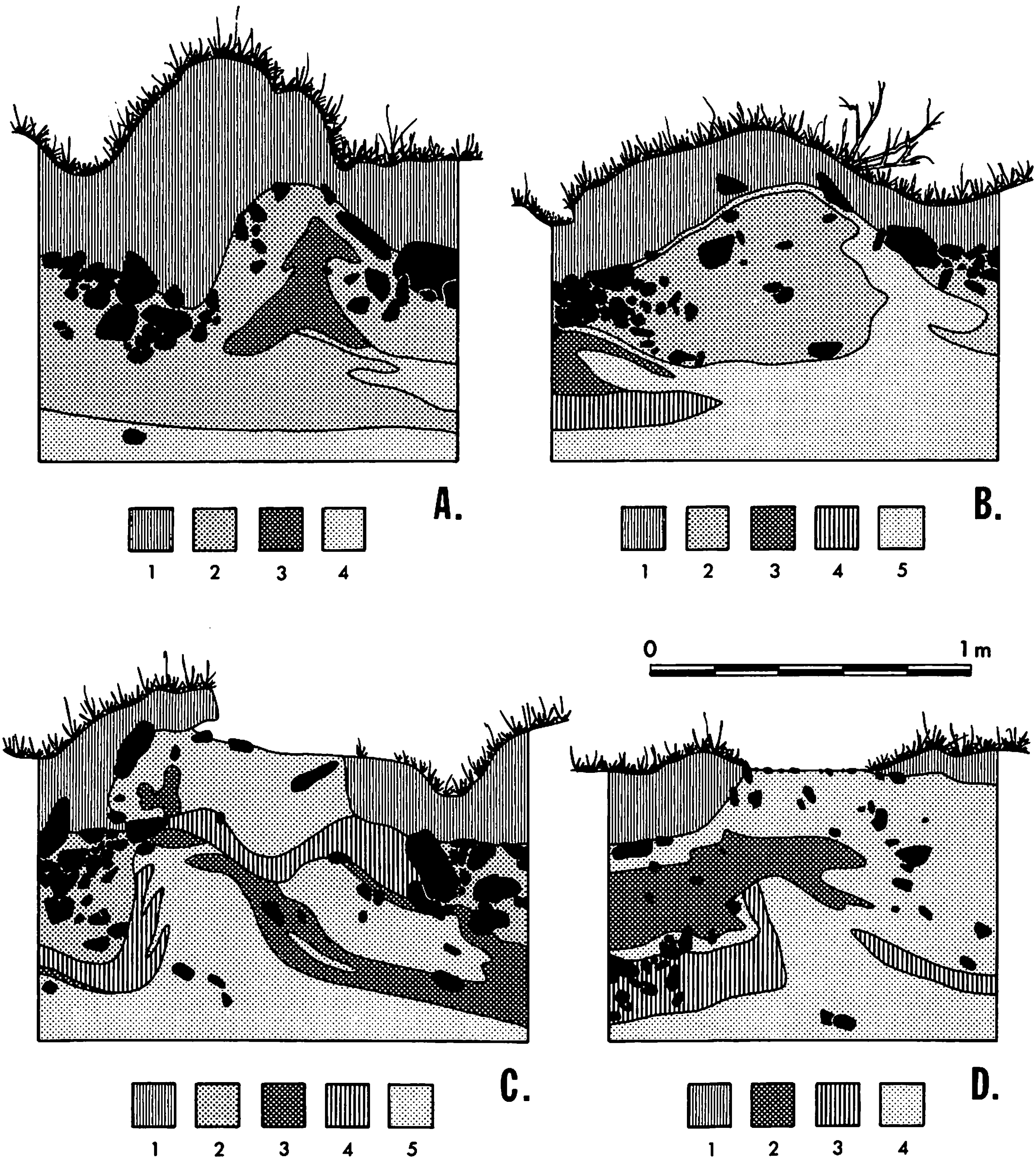
Figure 16 (facing). Cross sections of earth hummocks and degraded hummocks in the saddle on Niwot Ridge. Slope is from south to north (right to left) in all profiles. Stone concentrations beneath peat in interhummock depressions are thought to represent the borders of relict sorted nets.

A. Earth hummock.
   1. Very dark brown (7.5YR 2/2m) mucky sedge peat, thickest on downslope side of hummock.
   2. Very dark brown to dark brown (7.5YR 2/2-3/2m) humus-rich sandy loam.
   3. Very dark brown (10YR 2/2m) humus-rich sandy loam, mottled olive gray. Sticky, with odor of H_2S.
   4. Dark yellowish brown (10YR 4/4m) sandy loam.

B. Earth hummock.
   1. Dark brown (7.5YR 3/2m) mucky sedge peat, thickest on downslope side of hummock.
   2. Dark brown (10YR 3/3m) humus-rich gravelly sandy loam.
   3. live gray (5Y 4/2m) sandy loam, mottled dark yellowish brown and very dark grayish brown. Firm and sticky.
   4. Dark brown (10YR 3/3m) humus-rich sandy loam. Firm.
   5. Dark yellowish brown (10YR 4/4m) gravelly sandy loam to loam.

C. Degraded hummock.
   1. Very dark brown (7.5YR 2/2m) mucky sedge peat.
   2. Dark yellowish brown (10YR 3/4m) loam.
   3. Dark gray (5Y 3/1m) sandy loam to loam. Firm and sticky.
   4. Very dark grayish brown (10YR 3/2m) humus-rich sandy loam, mottled dark brown and dark yellowish brown. Firm.
   5. Dark yellowish brown (10YR 4/4m) sandy loam, mottled very dark gray and very dark grayish brown.

D. Frost boil with raised peat rim.
   1. Very dark brown (7.5YR 2/2m) mucky sedge peat.
   2. Very dark gray (5Y 3/1m) loam.
   3. Dark brown (10YR 3/3m) humus-rich gravelly sandy loam, mottled dark yellowish brown.
   4. Dark gray (5Y 4/1m) gravelly sandy loam, coarsely mottled brown (7.5YR 4/4m).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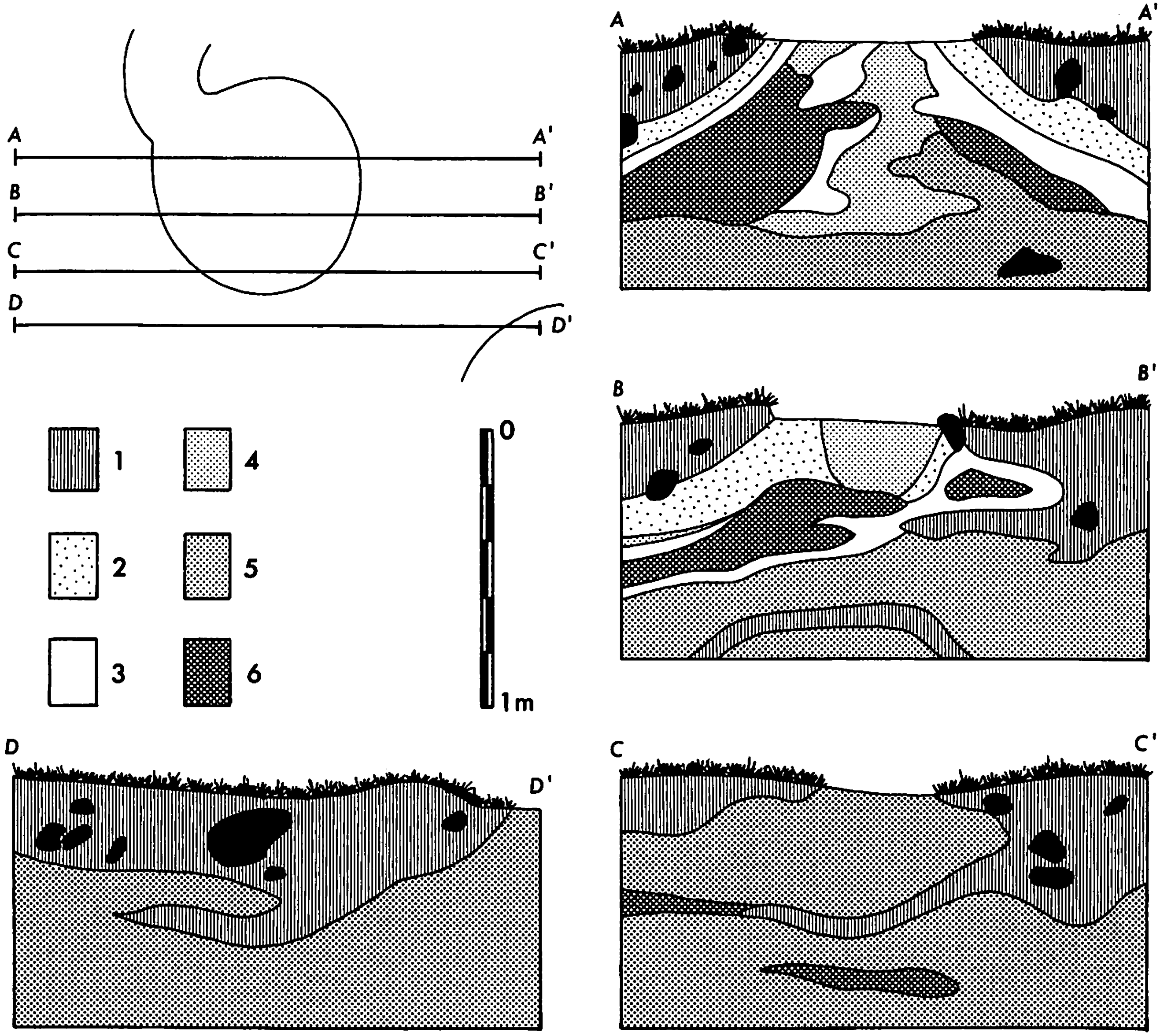

Figure 17. Cross sections of a frost boil near the front of a turf-banked lobe on Niwot Ridge. Slope is from north to south (left to right). All units beneath the surface turf layer have weak medium blocky structure.

1. Very dark brown (10YR 2/2m) humus-rich gravelly loamy sand, firm where deeply buried.
2. Dark yellowish brown (10YR 4/4m) to olive brown (2.5Y 4/4m) gravelly loamy sand. Weak medium blocky structure.
3. Strong brown (7.5YR 4/6m) sandy loam.
4. Dark grayish brown (2.5Y 4/2m) sandy loam.
5. Olive gray (5Y 4/2m) sandy loam.
6. Dark greenish gray (5GY 3/1m) loam, strongly gleyed. Very sticky and cohesive.

Field experiments support this conclusion. A 10-cm X 10-cm grid painted in 1962 in the center of a frost boil on a turf-banked terrace at 3490 m altitude (Figure 3, Locality 8) was disrupted after a single winter; only the largest cobbles remained in their original positions.

A grid of 51 dowel sticks was installed in a frost boil on the same terrace. The dowels were spaced at 10-cm intervals except where rocks prevented their insertion to a standard depth of 25 cm; they were reinserted to their original depths each summer. Three years of data are summarized in Figure 18. Upfreezing of dowels is attributed to shallow diurnal freezing and thawing of the soil in autumn and spring (see Figure 2), and to the annual freeze-thaw cycle in the upper 25 cm of soil. Upfreezing was greater in bare than in vegetated earth; centers of upfreezing shifted slightly from year to year (Figure 18). An increase in the magnitude of upfreezing during the course of the study coincided with a two-fold increase in springtime precipitation (Greenland, 1987), but was not necessarily related to this factor. Tilting of dowels showed that earth near the surface of the frost boil moved radially outward during the spring thaw along temporary gradients created by doming.

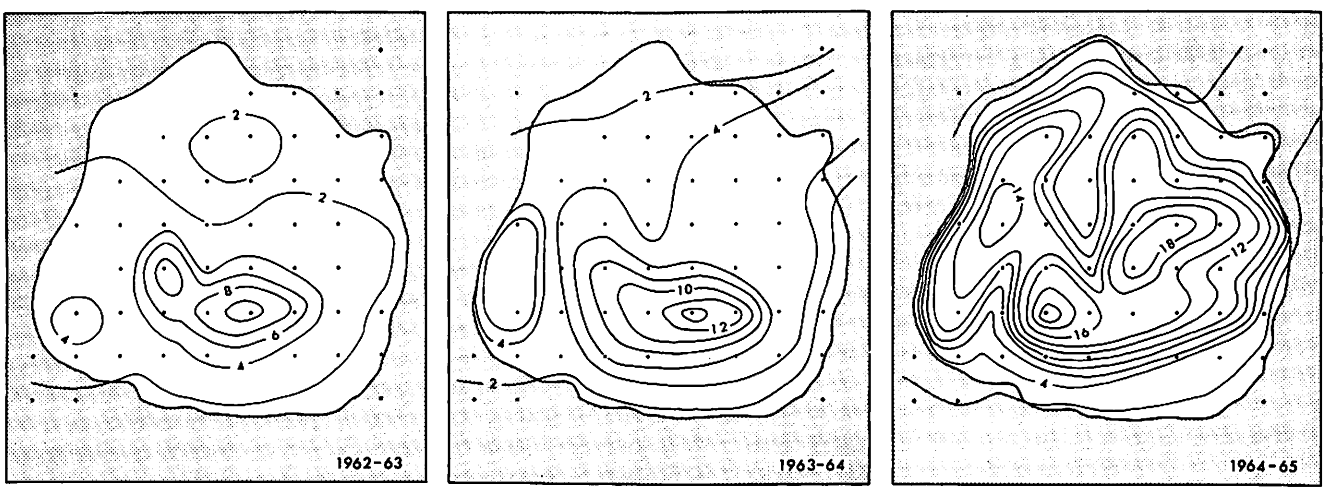

Figure 18. Maps showing annual upfreezing of 1/4 inch (6.4 mm) wooden dowels inserted to depths of 25 cm in an active frost boil on Niwot Ridge. Contour interval 2 cm. The dowels (shown with dots) were installed in a 10-cm X 10-cm grid. Vegetated areas are shaded. Seedlings are excluded from the frost-boil center by upfreezing of stones, centrifugal movement of surface soil, and large daily temperature fluctuations. No enlargement of the bare-soil area has occurred in the past 25 yr.

Origin

Most of the earth hummocks and frost boils examined on Niwot Ridge appear to have formed by mass-displacement processes: e.g., by the upward intrusion of fine-textured mineral soil into a vegetated surface layer. Hummocks are characteristic of sites where the turf cover is thick and cohesive, preventing fine sediment from emerging at the surface; frost boils develop where the turf is thinner and weaker, or where erosion destroys the protective turf cover of established earth hummocks (Figure 16). The mechanism is similar to that suggested for sorted nets and stripes, but lacks a stone-pavement phase. The requisite density imbalance is created when melting ice lenses produce more water than can be contained in available pore space. Slow drainage of water from the profile leaves a relatively dense, compacted surface layer supported by a less-dense slurry of supersaturated, thawing soil. If the metastable equilibrium of the system is disturbed by a sudden shock, or by other factors (Jahn and Czerwiński, 1965), plugs of low-density material will rise toward the surface.

Other hummocks in the region, particularly at lower altitudes, show evidence of having formed by different mechanisms. These include (1) differential frost heaving above pockets of fine-textured clastic material deposited in fens by snow avalanches, (2) doming caused by upfreezing of large subsurface boulders, and (3) locally accelerated plant growth, independent of frost action. Hummock windrows (parallel ridges of peat that lack mineral-soil cores and that extend across fens for tens of meters in the direction of the prevailing wind) appear to reflect the interaction of wind and vegetation growth. Some isolated frost boils have formed by the enlargement of bare-soil patches created by wind erosion in wet sites.

Age and paleoenvironmental significance

Earth hummocks, degraded hummocks, and frost boils were studied in a broad saddle on the crest of Niwot Ridge (Figure 3, Locality 4). Two belt transects were established across the hummocky area in 1966. The transects consisted of 34 individual quadrats, each measuring 5 m X 5 m (Figure 19). Vegetation in the hummocky area consisted mainly of sedges and scattered low willows; willows have subsequently become dominant, hiding the hummocks and frost boils from view. The following comments are based on conditions as they existed in the mid 1960s, and may no longer apply due to changes in patterns of winter snow accumulation caused by the increased shrub cover.

Snow normally begins to accumulate at the hummock locality in mid October, before the beginning of the annual freeze (Figure 20a). For a period of about 5 mo, including the most severe part of winter, strong westerly winds prevent the hummocks from becoming completely buried. The depressions between them are filled with wind-slabbed snow, but their crests are exposed to wind erosion, deep seasonal freezing, and large daily temperature variations. On warm winter days, the south-facing sides of hummock crests thaw to depths of several centimeters. In spring, decreased wind velocities allow a general blanket of snow to accumulate in the area. Maximum snow depths occur in April or May (Figure 20a). Melting begins shortly thereafter, and by mid June the entire area is free of snow; hummock

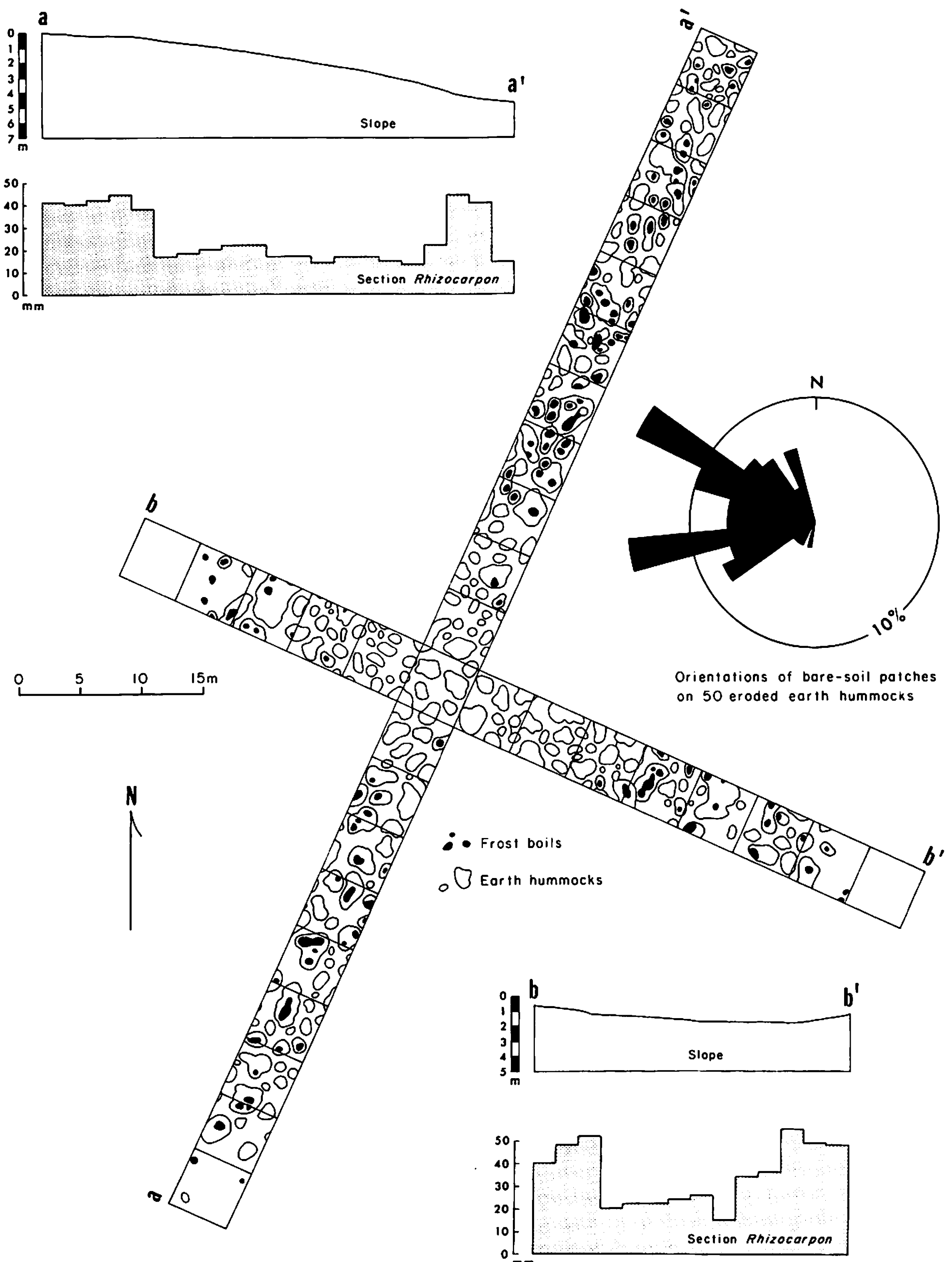

Figure 19. Map of earth hummocks, degraded hummocks, and frost boils along intersecting belt transects in the saddle on Niwot Ridge. Topographic profiles, maximum section-*Rhizocarpon* thallus diameters, and orientations of bare-soil patches on hummock crests are shown.

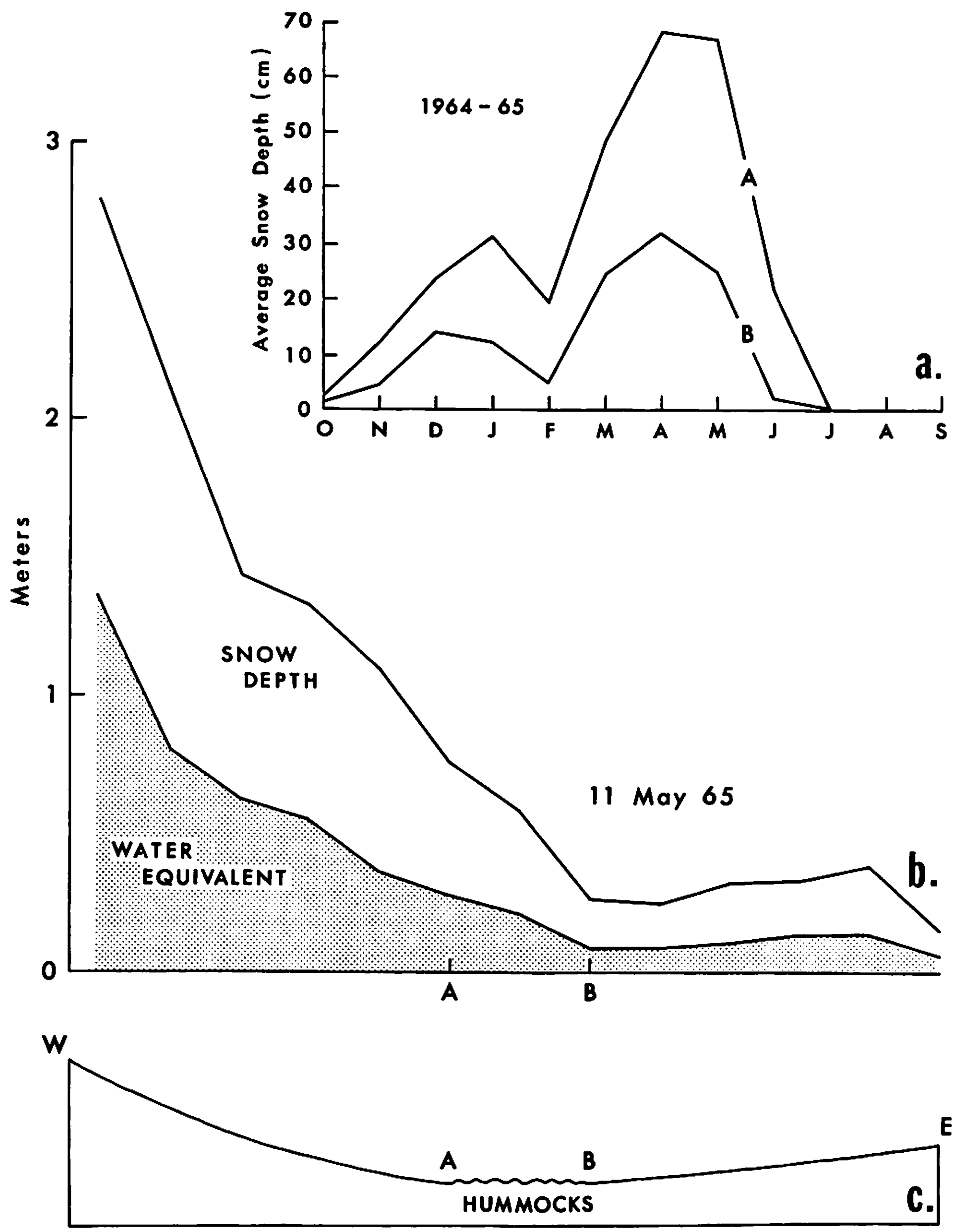

Figure 20. Snow-depth data for earth hummocks in the saddle on Niwot Ridge, winter of 1964-65. a, average monthly snow depths at the west (A) and east (B) margins of the hummocky area. b, results of a Mount Rose snow survey across the saddle under conditions of near-maximum accumulation. c, diagrammatic profile showing topographic setting of the hummocks.

relief, accentuated by differential winter heaving, is strikingly greater than in late summer. Meltwater from a snowbank on the slope west of the saddle (Figure 20b, 20c) irrigates the hummock locality in June and July, but by mid August standing water has ordinarily disappeared from inter-hummock depressions.

Earth hummocks can survive only as long as their turf covers remain intact. In the saddle on Niwot Ridge, erosion begins on the west-southwest and northwest slopes of the hummocks (Figure 19), suggesting that initial disruption of the turf is caused by winds that sweep around the north and south flanks of the knoll west of the site. Diurnal freeze-thaw cycles affect mainly the south sides of the features, so cannot have initiated erosion. Once the turf has been broken, however, increased frost disturbance enlarges the bare-soil area. As shown in Figure 19, only the wet, central portion of the hummocky meadow has escaped the effects of erosion.

At various times during the Holocene, the snowbank west of the saddle expanded and contracted in response to climatic change, causing the saddle to become alternately wetter and drier. Changes in soil moisture are reflected by the history of patterned-ground activity in the hummock area. Sorted nets underlying the hummocks (Figure 16) developed, or were reactivated, during a period of significantly increased soil moisture. This may have coincided with an interval of snowbank expansion and patterned-ground activity dated between 5300 $\pm$ 130 BP (I-4418) and 4010 $\pm$ 90 BP (I-9777) on nearby Mount Albion (Benedict and Olson, 1978). As conditions ameliorated, the sorted nets stabilized and became blanketed by 10-30 cm of peat (Figure 16). No dates are available for peat in the hummock area proper. But a date of 3475 $\pm$ 175 BP (GX-10,156) for buried soil humus at the south end of the saddle (Burns and Thorn, 1984) suggests a possible time for periglacial stability, as does a date of 3385 $\pm$ 95 BP (I-9121) for soil humus redeposited in the border of a sorted net southeast of the saddle (Figure 7).

Intrusion of the peat by plugs of mineral soil, forming earth hummocks, implies an abundance of autumn moisture derived from late-lasting seasonal or perennial snow. Increased snow cover was characteristic of the Audubon glacial interval, as indicated by lichen snowkill and accelerated downslope soil movement on the slope to the west (Benedict, 1970a); earth hummocks in the saddle are likely to have formed as a result. Snow accumulation decreased at the close of the Audubon interval, and by 1000 BP most parts of the slope had become snowfree for the requisite 10- or 12-wk annual period needed for lichen growth and survival (Benedict, 1990). Maximum section *Rhizocarpon* diameters measured in 1966 on exposed rocks in each of the 34 quadrats (Figure 19) suggest relative stability during the past 1000 yr except in the moist, central portion of the hummocky area, where upfreezing and overturn of stones was important during the Little Ice Age.

CONCLUSIONS

The patterns discussed in this paper are interrelated forms, commonly resulting from upward mass displacement of plugs of fine earth in response to density imbalances in the soil. Differences in appearance reflect differences in the nature of the restraining surface layer (stones vs. peat), its thickness and strength, and the local angle of slope. The patterns formed rapidly -- perhaps instantaneously -- during periods of melting ground ice, then continued to evolve at a much slower pace due to circulatory overturn driven by vertical frost heaving in their centers. Morphologically similar patterns can form by other mechanisms. Earth hummocks and frost boils have a particularly broad range of possible origins. In contrast, sorted nets on dry knolls and ridges are difficult to explain with alternative hypotheses.

The autumn soil moisture required for ice segregation and patterned-ground activity is derived, in the Front Range, almost entirely from melting snow. As a result, the modern distribution of active patterned ground closely mirrors the routes followed by meltwater drainage. Where soil-moisture conditions fluctuated during the Holocene due to snowbank contraction and expansion, patterned ground shows evidence of alternate stabilization and reactivation. Such areas are potential sources of paleoenvironmental information (Benedict and Olson 1978). The trend since 1962, when repeat photography was begun on Niwot Ridge, has been toward revegetation of patterned ground at many localities; it is not clear whether this is part of a continuing response to climatic amelioration following the Little Ice Age, or is a consequence of reduced grazing pressure by domestic livestock.

Large sorted nets and stripes on well-drained knolls and ridgecrests (Figure 10) imply the former existence of icy permafrost at altitudes as low as 3245 m; the ice is thought to have accreted during cooling phases of the late Pleistocene. Sorted nets on the floors of lakes and ponds and in areas of snowmelt seepage do not require permafrost, and can form under present conditions at altitudes as low as 3135 m. Most earth hummocks and frost boils in the region date from periods of late Holocene snowbank expansion, such as the Audubon interval and Little Ice Age, when autumn soil moisture was more-widely available than today.

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