SOIL MOUNDS AND PATTERNED GROUND OF THE LAWRENCE MEMORIAL GRASSLAND PRESERVE

by

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A RESEARCH PAPER

submitted to

THE DEPARTMENT OF GEOGRAPHY

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

DECEMBER 1982

Directed by
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ACKNOWLEDGEMENTS

For his inspiration, support, and aid during all phases of this research, my deepest appreciation goes to my husband, Reid. My parents and family also deserve thanks for life-long encouragement and interest in my academic pursuits.

Many thanks also go to Mary Kay, the soils laboratory technician, who patiently guided me through the soil tests.

I would like to thank Dr. Rosenfeld for suggesting this project, advice along the way, and the major role he played in obtaining the aerial photographs.

The Pacific Northwest Chapter of The Nature Conservancy manages the Lawrence Memorial Grassland Preserve and generously gave permission to use this area for research. They also provided a much appreciated environment of financial and moral support.

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ABSTRACT: The Lawrence Memorial Grassland Preserve, located in Wasco County, Oregon, exhibits a wide variety of soil mounds and patterned ground features. The size, shape, and distribution of several elements of this peculiar landscape were analyzed with a detailed map, field observations, and statistical procedures. Common soil mound shapes are circular, polygonal, and elongated. These mounds display a great diversity in size as well. Patterned ground features such as sorted stripes and nets, are also widely distributed and varied. Many geomorphic processes and environmental conditions, including frost sorting, geologic setting, soils, erosion (both wind and water), and biologic activity, may contribute to the formation of these features.

INTRODUCTION

The focus of most studies of mounds and patterned ground is related to the genesis of these phenomena. Although general descriptions of the size, shape, and distribution of these features are common in the literature, there are frequent discrepancies, few detailed maps, and little attempt to integrate and analyze the factors that influence those characteristics.

This research primarily examined the physical attributes of this unique landscape and the environmental conditions that affect it. Basic information was compiled from approximately 40 acres of the 380 acre

Lawrence Memorial Grassland Preserve.

Comparison of similar features in different regions is often hampered by the abundance of terms used to describe them in the literature. For example, twenty-six words have been employed as synonyms for stone rings and stone nets.[1] Some of the terms denote varieties of a structure while others serve no recognizable purpose. The definition of terms such as solifluction and periglacial have become more general than when they first appeared in the literature. In this study, a conscious effort was made to use simple, established terms wherever applicable. However, in one instance no appropriate term was available, so a descriptive name, rock net depression, is used in this report.

LITERATURE

One of the earliest descriptions of the "hog wallows" or "prairie mounds" of central Oregon was by Joseph LeConte in 1877. He noted that the shapes grade from "circular mounds, through elliptic, long elliptic, to erosoin furrows and ridges". LeConte cited previous hypotheses for origin and suggested that erosion of a finer, more movable material from above a coarser, less moveable material was the mechanism of formation.[2]

By 1929, when Waters and Flagler wrote their article, the controversy over mound genesis had greatly increased. They outlined thirteen hypothesis including glacial action; deposits around water, gas, oil, or mud springs; wind action; deposits formed by burrowing animals; fish nests; human agency; and residuals from weathering. From their observations and measurements of mounds in Oregon, Washington, and Idaho they agreed with LeConte's hypothesis for mounds on the Columbia River Plateau.

They also concluded that 1) mounds in general are polygenetic 2) mounds do not develop on absolutely flat surfaces 3) mounds are invariably elongated in the direction of slope 4) the amount of elongation is a function of the steepness of slope 5) local irregularities in slope are expressed as irregularly shaped mounds 6) maximum height of mounds is generally accordant with adjacent undissected parts of the "ash blanket" 7) mounds do not develop where the soil thickness is greater than seven feet 8) intermound areas form "a definitely integrated, minutely adjusted drainage system" 9) this drainage system may be influenced by columnar jointing.[3]

Although many of their observations were remarkably accurate and insightful, they also dismissed the aberrations they observed as local or unimportant. For example, the data presented for slopes and average amount of elongations for the Maupin, Oregon group (the closest data site comparable to my research area) does not seem to warrant the conclusion that "elongation reaches a maximum on steeper slopes." In the Maupin study, three uniform slopes of 1°-2° were shown to have average elongations of 2.2 ft., 6.1 ft., and 10.3 ft.[4] A uniform slope of 4° had an average elongation of 10.8 ft.[4] The elongation observed on the 4° slope in not significantly different from the 10.3 ft. elongation found on a 1°-2° slope.

Kaatz noted the failure of patterned ground in central Washington to exhibit a consistent relation to slope. This appears to dispute the hypothesis that water erosion was the primary agency of origin. Instead, frost action and solifluction under a former periglacial climate were suggested as the dominate formational processes. Running water and polygonal joints in the underlying basalt were judged to be secondary pattern shaping factors.[5]

Such discrepancies in observation and interpretation exemplifies the multitude of literature that either adds support to, or refutes a particular hypothesis. In addition it demonstrates the historical, overriding concern of researchers to explain how this particular landscape developed.

Because of an abundance of literature that describes mounds and patterned ground, authors frequently compare the features and conditions existing in different regions. Knechtel employed this technique for his work on the "pimpled plains" of eastern Oklahoma. Although the mounds in Oklahoma are similar in pattern and spacing to the ice wedge networks of tundra regions, they bear an equally close resemblance to the dessication fissures of arid areas.[6]

In-depth research pertaining to a single attribute, such as the vegetation, soil, or stone stripes, are also common sources of information. Examples of this are the studies by Winward and Youtie, Paeth, Fosberg, and Pyrch.

Winward and Youtie inventoried the relatively luxuriant vegetation of the soil mounds, the sparser vegetation of the intermound areas, and non-patterned ground portions of the Lawrence Memorial Grassland Preserve of north-central Oregon.

Paeth examined the mineralogic composition and profile of patterned ground soils in the Puget Lowlands of Washington. Similar work was done by Fosberg for the Snake River Plain of Idaho.

Pyrch researched the characteristics of the stone stripes in the vicinity of the Lawrence Memorial Grassland Preserve and elsewhere on the Deschutes Umatilla Plateau.

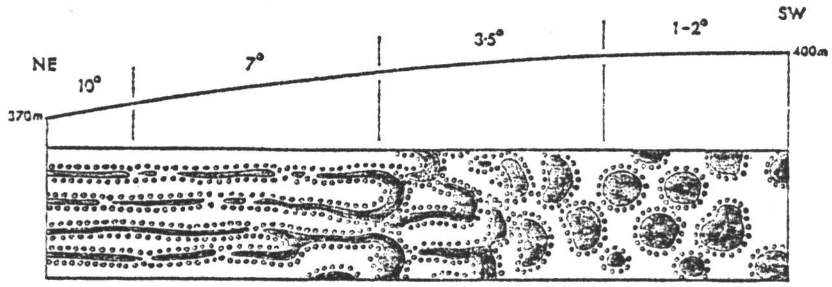
Reports of experiments performed in both the laboratory and the field represent a significant part of patterned ground literature.

One of the most extensive laboratory investigations was that of Taber about the mechanics of frost heaving. He concluded that the growth of segregated ice bodies required slow freezing of a frost-susceptible soil, continued input of water, and removal of the latent heat of crystallization, which is produced by the ice-water phase change, at a sufficient rate.[7] Laboratory and field observations by Soons and Greenland were in agreement with these conclusions. From their field studies they also found that these conditions were most likely to occur on a clear night that allows maximum surface radiation.[8]

These works are important because many researchers believe that frost action, under a periglacial regime, was primarily responsible for the sorting and downslope movement of particles that results in the patterned ground landscape of today. Periglacial processes are cited as the probable mode of formation for patterned ground in the Wind River Mountains of Wyoming, various localities in the Appalachian Mountains of Pennsylvania, Virginia, and West Virginia, and for the western Snake River Plain of Idaho.[9,10,11]

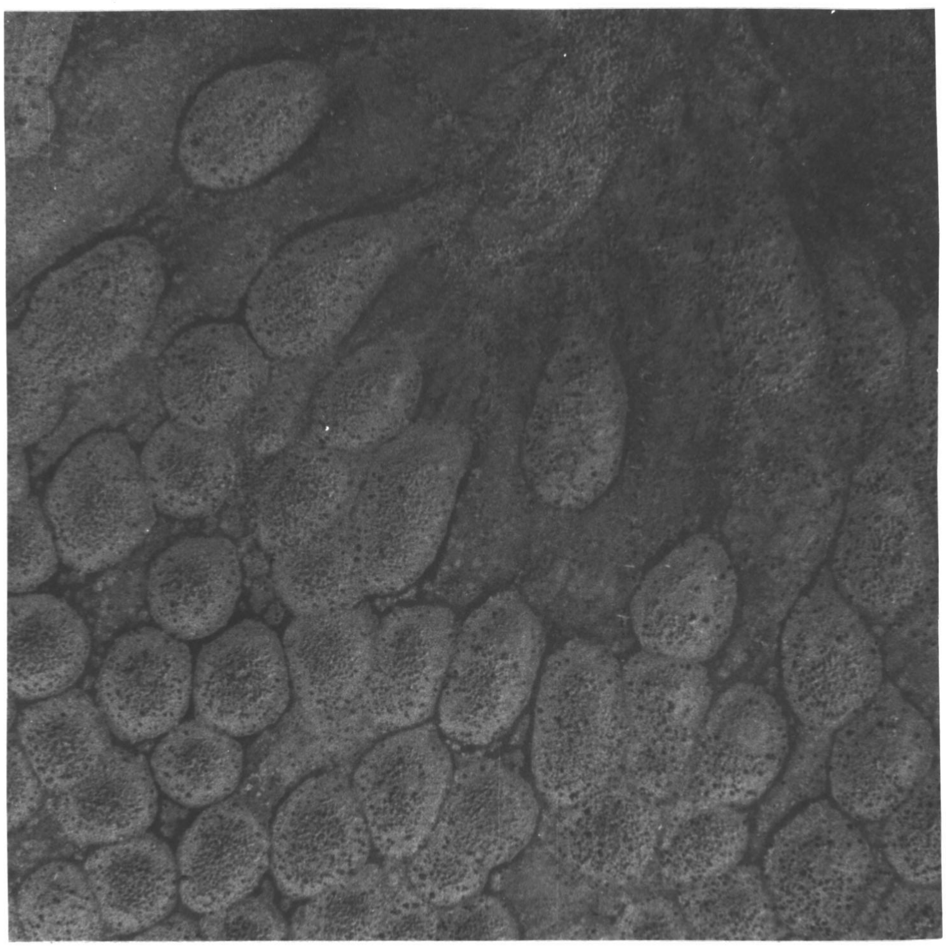
Washburn classified types of patterned ground in terms of shape and sorting. Thus, patterned ground features may be categorized as sorted or non-sorted circles, polygons, nets, steps, or stripes.[12] However, many of the sorted forms are gradational (Fig. 1). Some of the periglacial processes, proposed by Washburn and others, which contribute to the formation of these structures are:

1) formation of vertical shrinkage cracks by the contraction



Sorted stone circles changing to sorted stone stripes on a smooth, northeasterly, convex slope in Spitsbergen (after Büdel, 1960). Note that in this case the intermediate stone 'garlands' are open-ended downslope.

Diagram of patterned ground gradation. (From Davies, 1969)



Change of forms at the Lawrence Memorial Grassland Preserve

Figure 1. Gradational forms of sorted patterned ground

of soils at low temperatures

2) refreezing of water in shrinkage cracks

3) doming of the intercrack areas by growth of needle ice

4) differential freezing and thawing caused by variable heat capacity and conductivity in a heterogeneous soil mass[13]

AREAL SETTING

Physiography

The Lawrence Memorial Grassland Preserve is near the southern border of the Deschutes-Umatilla Plateau in north-central Oregon (Fig. 2). This is a part of the Columbia Basin Subprovince, which in turn is one of four subdivisions that constitute the Columbia Intermontane Physiographic Province (Fig. 3).[14]

The Deshutes-Umatilla plateau is approximately 250 km. (155 mi.) wide along its northern border, the Columbia River. Its north-south dimensions range from 15 to 115 km. (9-71 mi.) on the eastern and western margins, respectively. A steep escarpment marks the southern boundary as it abuts the northern slopes of the Blue Mountains. The plateau is the southern flank of an asymmetric syncline characterized by stratigraphic units that dip northward from 0.5° to 3°. Surface elevations range from a low of approximately 100 meters (3608 ft.) along the Columbia River to over 1100 meters (3608 ft.) in the vicinity of the Lawrence Memorial Grassland Preserve.[15] Streams are deeply entrenched and there is little or no dissection of the broad, interfluvial areas.[16]

Geology

The Columbia River Basalt Group is the dominant rock type of the Deschutes-Umatilla Plateau. Numerous fissure eruptions of basaltic lava

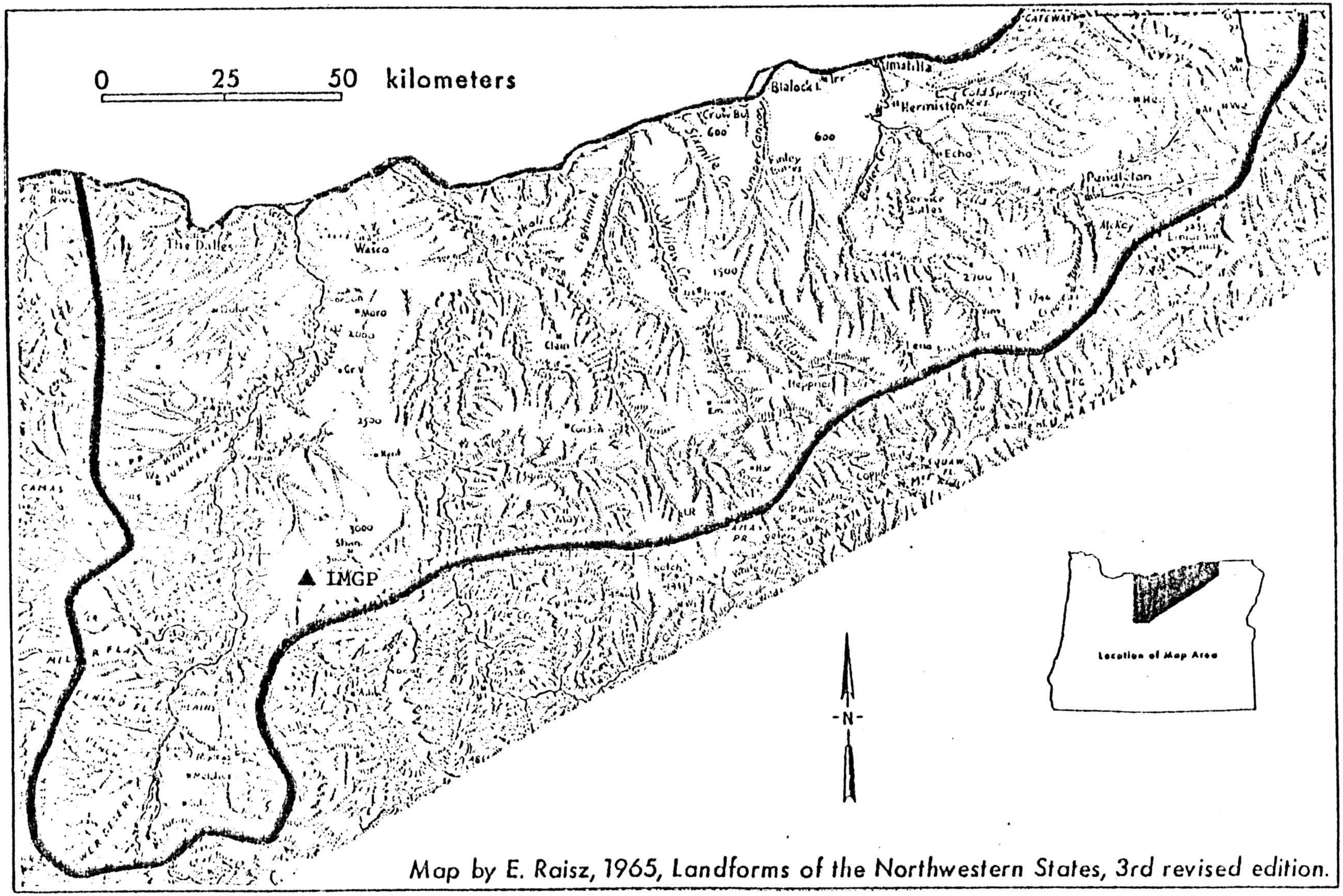


Figure 2. Generalized relief map of the Deschutes-Umatilla Plateau.

(From Pyrch, 1973)

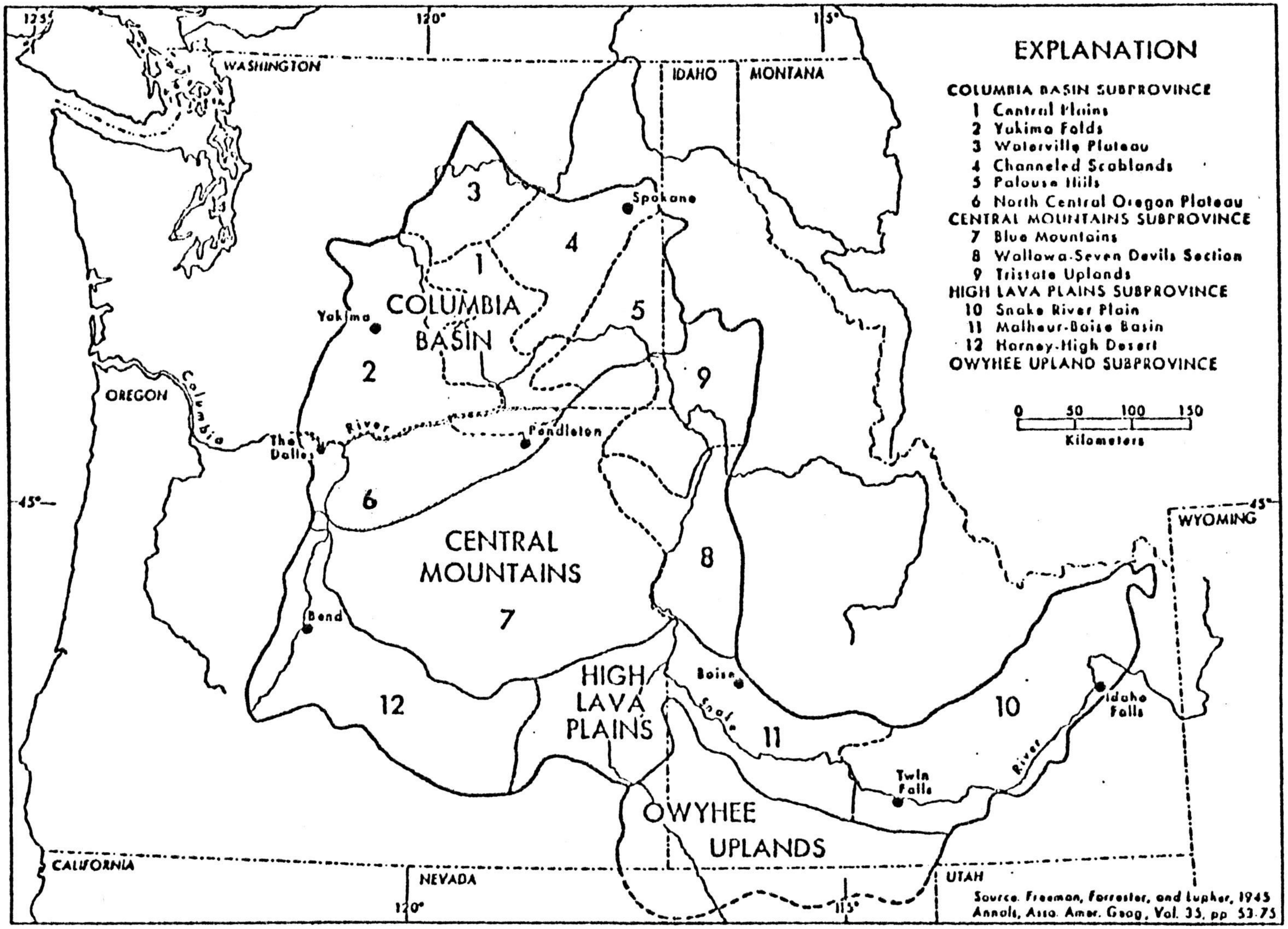


Figure 3. Geomorphic subdivisions of the Columbia Intermontane Physiographic Province. (From Pyrch, 1973)

during the Miocene and early Pliocene epochs resulted in a vertical sequence of flows that has an aggregate thickness of over 900 meters (2953 ft.) in this region.[17] The average thickness of the Columbia River Basalt Group is about 600 meters (1968 ft.) and is thinnest along the southern parts of the plateau. Thus, older rock units, such as the Clarno and John Day Formations that underly the basalt, are exposed in some areas.

Individual flows range in thickness from about 1 meter to 60 meters (3 to 197 ft.). The massive portion of a flow is commonly fine-grained and dark gray, whereas the upper margins are scoriaceous (a rough, blistered appearance) and are red or brown in color due to oxidation and weathering. Some tuffs are interbedded with basalt units on the upper surface of the Columbia River Group.

Columnar joints, formed when the lava cooled, are generally small features. Their lengths are typically between 0.5 to 1 meter (1.6-3.3 ft.), though some may be several meters long.[18] Structural joint systems result from tectonic episodes and have a more regional expression. Lineament studies to the northeast and southeast of the Lawrence Memorial Grassland Preserve reveal a predominant N 30° W orientation of compression-related fractures.[19]

Soils

The soils mantling the Deschutes-Umatilla Plateau developed from loessial material under grasses or shrub-grassland vegetation. These soils vary across the plateau from north to south, with thinner, finer soils near the southern margin. In addition, there are regional differences related to climatic variation. Soils become darker, more leached, and to some extent particle sizes are smaller as precipitation increases and temperatures decrease.[20] Among the areas where this occurs are the higher elevations along the southern, eastern, and western margins.

The soils of the Lawrence Memorial Grassland Preserve are classified as thin-loess mantled. The soil is highly variable, with depths ranging from moderately deep (40 to 100 cm.; 16 to 39 in.), to very shallow (less than 40 cm., 16 in.). The deeper soils belong to the Condon series and are dark colored, relatively stone-free, and with a medium silt loam texture. Poorer soils are members of the Bakeoven series, and are characterized by many stones, a lighter color, and a silty to clayey loam texture.[21] The Condon and Bakeoven soils tend to be found together on the mound and intermound topography, locally known as biscuit-scabland. However, these soils are not exclusive to this topography. When the soil types occur together, the Condon series form the mounds and the Bakeoven series occupy the intermound areas. Most soil in the research area belongs to the Bakeoven-Condon Complex, defined as being 50-80 percent Bakeoven very cobbly loam and 10-35 percent Condon silt loam.[22] South and west exposures tend to have a somewhat greater percentage of the Bakeoven series, while north and east exposures have more of the Condon component.[23] This is probably related to the direction of the prevailing wind that deposited these soil types.

Climate

The climate of the Lawrence Memorial Grassland Preserve can be characterized by its seasonal variability. Average annual precipitation is 220 to 400 mm. (9-16 in.) and only 9 percent of the total occurs in summer.

Temperatures may be extremely hot during summer days and cool at night. Typical diurnal fluctuations are from 10° to 16° (18° to $29^{\circ}F$).[24]

Freezing may occur throughout the year, though the summer months are normally frost free.

Vegetation

Five plant communities and several community fragments, comprising 150 species, have been identified within the Lawrence Memorial Grassland Preserve.

Idaho fescue (*Festuca idahoensis*) and bluebunch wheatgrass (*Agropyron spicatum*) are the most abundant grass varieties on the mounds and in the drainage heads.[25] A number of shrubs, such as the mountain snowberry (*Symphoricarpos oreophilus*) also occur on the north facing mound slopes along with the grasses.

Intermound areas are dominated by scabland sagebrush (*Artemisia rigida*), Sandberg's bluegrass (*Poa sandbergii*), and cous bisquit-root (*Lomatium cous*).

In general, the greatest plant diversity exists within the ravines.

Research Area

Approximately 40 acres of the Lawence Memorial Grassland Preserve were chosen as the study area for this project (Fig. 4). It is located along a portion of the southeast boundary, slopes generally northward, and has a local relief of approximately 20 meters (66 ft.). Critera used in selecting this study area were:

1) a diversity of mounds and patterned ground in terms of size, shape, and distribution
2) small drainages on the east and west sides provide a variety of slopes and slope aspects
3) fences that trend generally north-south and east-west form an easily recognizable landmark for aerial photography

TOPOGRAPHY OF THE LAWRENCE MEMORIAL GRASSLAND PRESERVE AND VICINITY

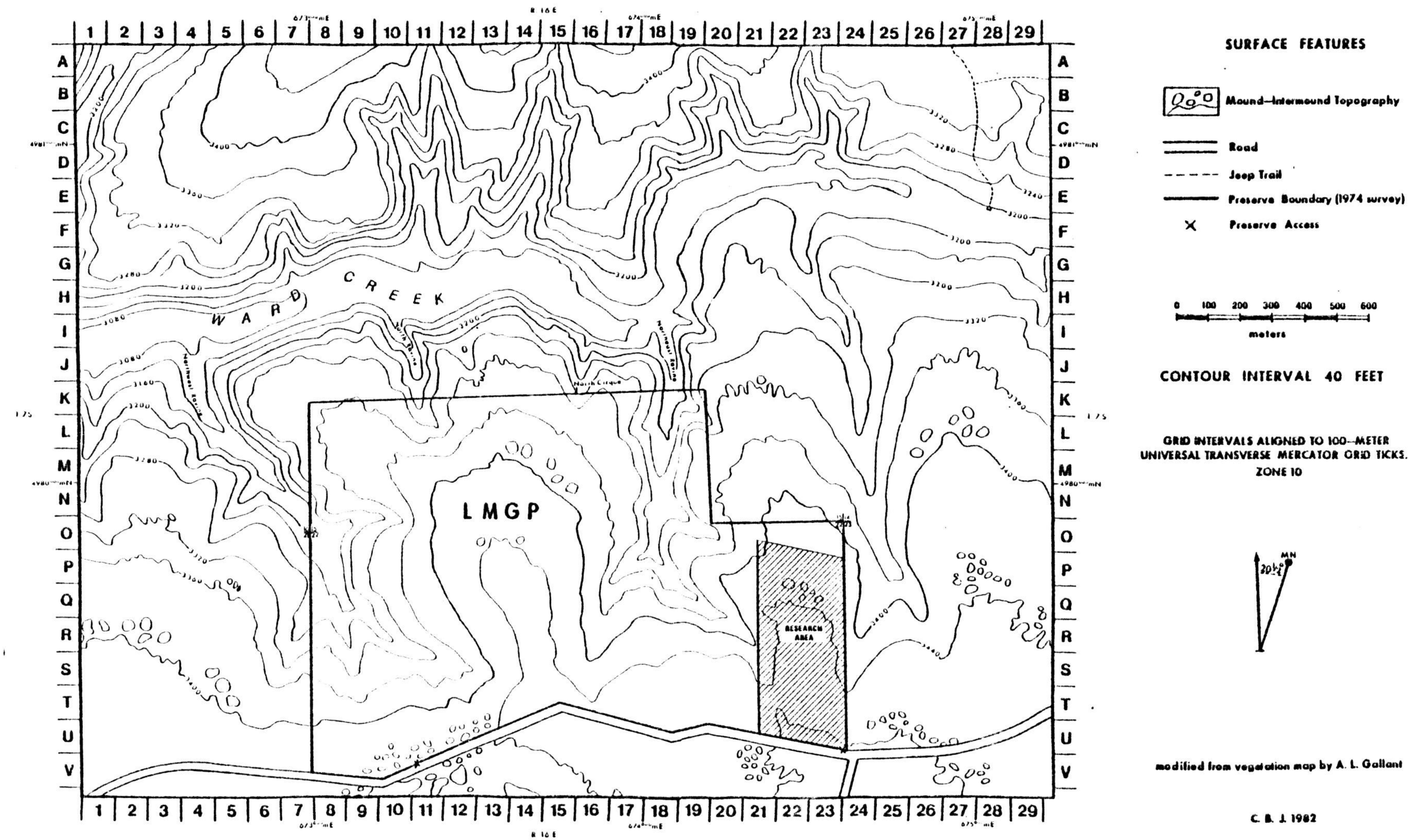


Figure 4. Research area and vicinity

4) accessibility for field operations

METHODS

Field Mapping

A point at the southeast corner of the Lawrence Memorial Grassland Preserve was designated as the base point. The boundary of the research area was delineated with a transit and stadia rod and marked with flagged, wooden stakes. This boundary forms a parallelogram 274 meters (900 ft.) at its north and south limits and 594 meters (1950 ft.) along its east and west margins. The property fences that extend from the southeast corner of the Lawrence Memorial Grassland Preserve also served as the southern and eastern borders of the study area.

Height, position, and shape of about 50 individual mounds were mapped from the datum point and subsequent base stations using standard surveying techniques. This data served as a reference for later photogrammetry. Intermound elevations from points scattered across the entire area were also determined by this technique. Contour lines were plotted on a base map from these known elevations.

Aerial Photography

Complete, low altitude photographic coverage of the research area was obtained from air photography missions flown in October, 1981 and August, 1982. The scale of the photographs was calculated by the formula R.F.=f/H where R.F. is a representative fraction, f is the lens focal length, and H is the effective height above the ground datum.[26]

A zoom transfer scope was used to magnify the photographs and to transfer the relevant data onto a base map (Appendix). It also aided in reconciliation of distortions between sequencial photographs in a flight line and between photographs of adjacent flight lines. Variations in aircraft altitude, pitch, and yaw may be a source of distortion in the aerial photographs. Optical properties of the camera, enlarging equipment, and zoom transfer scope may also induce some degree of distortion.

All photographs used in compiling the base map were taken on the same day. This was important because the ability to delineate the mounds and patterned ground features from the intermound areas depended largely upon the ability to discern its characteristic vegetation. Therefore, any perceived differences in mound sizes, resulting from the seasonal variation in vegetation density, were eliminated.

Mounds that appear to coalesce were mapped as separate units only if most of the area between the mounds exhibited a change of vegetation or a rock net boundary. In some instances, this intermound area appeared to be a vague line, so the placement of a boundary between mounds was subject to personal interpretation. After the features visible in the aerial photographs were plotted, the photographs were re-examined to confirm the original interpretations and to make refinements where necessary. In addition, several features that could not be identified with adequate certainty were field checked, particularly the mounds that appeared to merge. Often, the area between these mound tops was distinctly lower in elevation, though not as low as the surrounding intermound regions, and exhibited no change in vegetation or soil composition. These areas were mapped as mound saddles.

The completed base map is comprised of both the physical features interpreted from the aerial photographs and the contour lines determined from surveyed points.

Statistics

Area and perimeter measurements were made from the base map with an electronic measuring device for each of the 203 mounds within the research area. To minimize operational error, the area measurements were repeated three times and the values averaged. Each perimeter was measured twice and, as before, the mean value was found. The numbers obtained for area (A) and perimeter (p) were used in the equation $R_c=4\pi A/p^2$ to determine circularity ratios (R_c).[27] As values of this morphometric index approach 1.0, the structure it describes more closely approximates a circle. Circularity ratios were an important element in subsequent statistical procedures. The mean circularity ratio value (.89), standard deviation (.12), and coefficient of variation (13 percent) were computed with the statistical functions of a hand-held calculator. Mounds having circularity ratios equal to or less than the mean of .89 were considered elongated. The geographic distribution of elongated mounds was evaluated by correlating circularity ratios with nine predetermined divisions of the research area (Fig. 5). These subdivisions are of equal area and roughly correspond to natural physiographic differences, particulary slopes. Information compiled for each section included number of mounds, circularity ratios of these mounds (classified in groups R_c greater than .89, .70-.89, .50-.69, and less than .50), average circularity ratio and average slope (Table 1).

Linear regression analyses of mound morphometry versus slope were performed for this data and that obtained by three linear surveys (Fig. 6). The independant variable was assumed to be the slope value, with the circularity ratio as the dependant variable. Results of the linear regression analysis for transects A-A', B-B', and C-C' were plotted

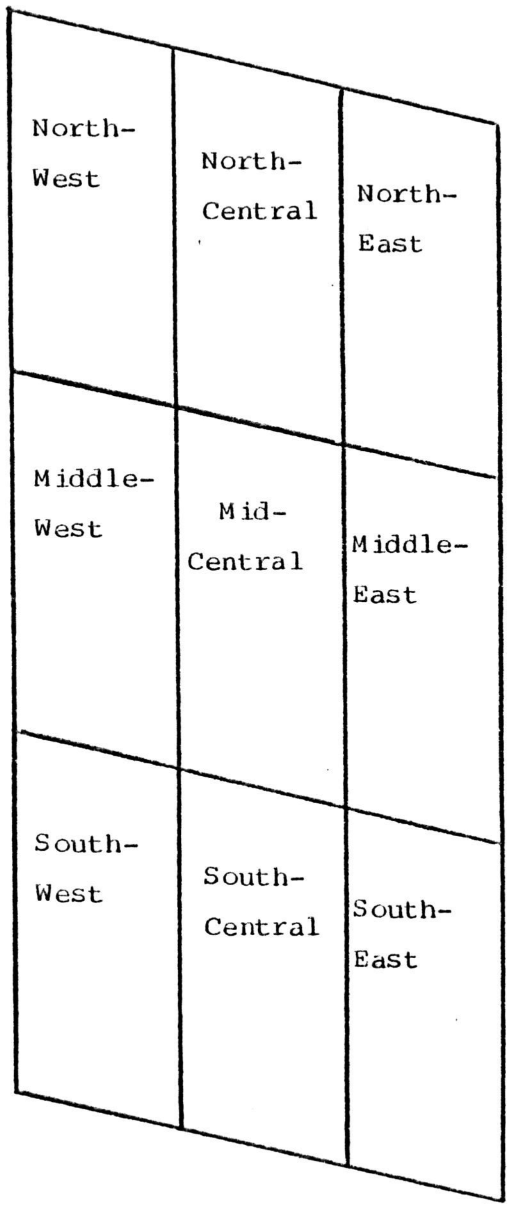


Figure 5. Research area subdivisions

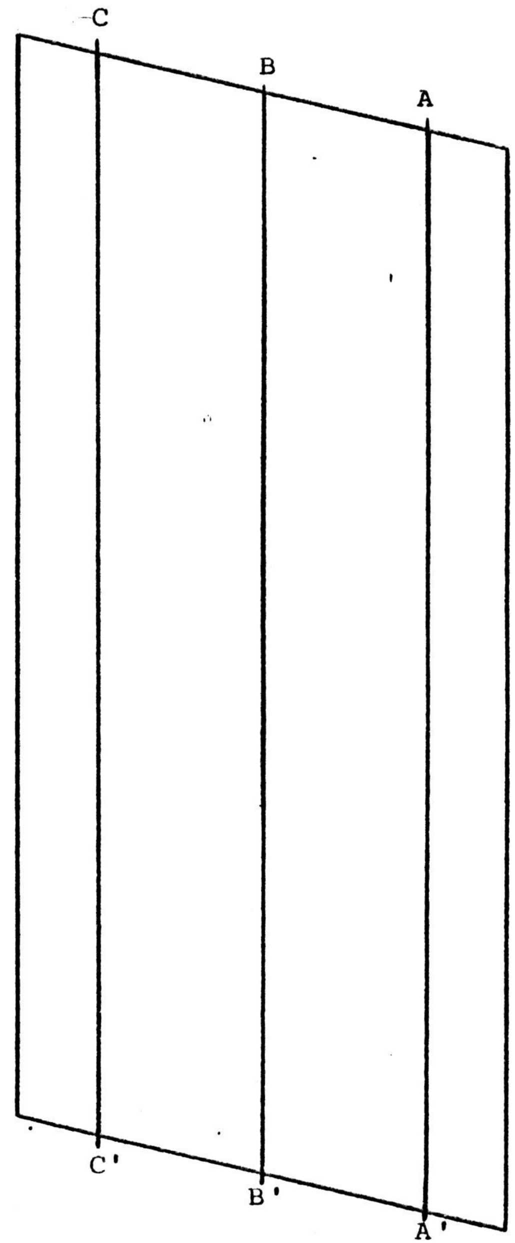


Figure 6. Position of three linear surveys

	Number of Mounds	General Slope (%)	Mean Circularity Ratio	Elongated Mounds (%)	Elongated Mounds		
					.70-.89	.50-.69	less than .50
North-East	28	6	.88	46	12	1	0
North-Central	25	7	.94	16	3	1	0
North-West	11	6	.92	36	2	2	0
Middle-East	8	10	.86	50	4	0	0
Mid-Central	14	5	.91	14	1	1	0
Middle-West	12	13	.87	50	5	0	1
South-East	31	12	.89	52	14	2	0
South-Central	25	4	.93	21	6	0	0
South-West	23	10	.85	52	8	3	1

Table 1. Data of the Nine Subdivisions

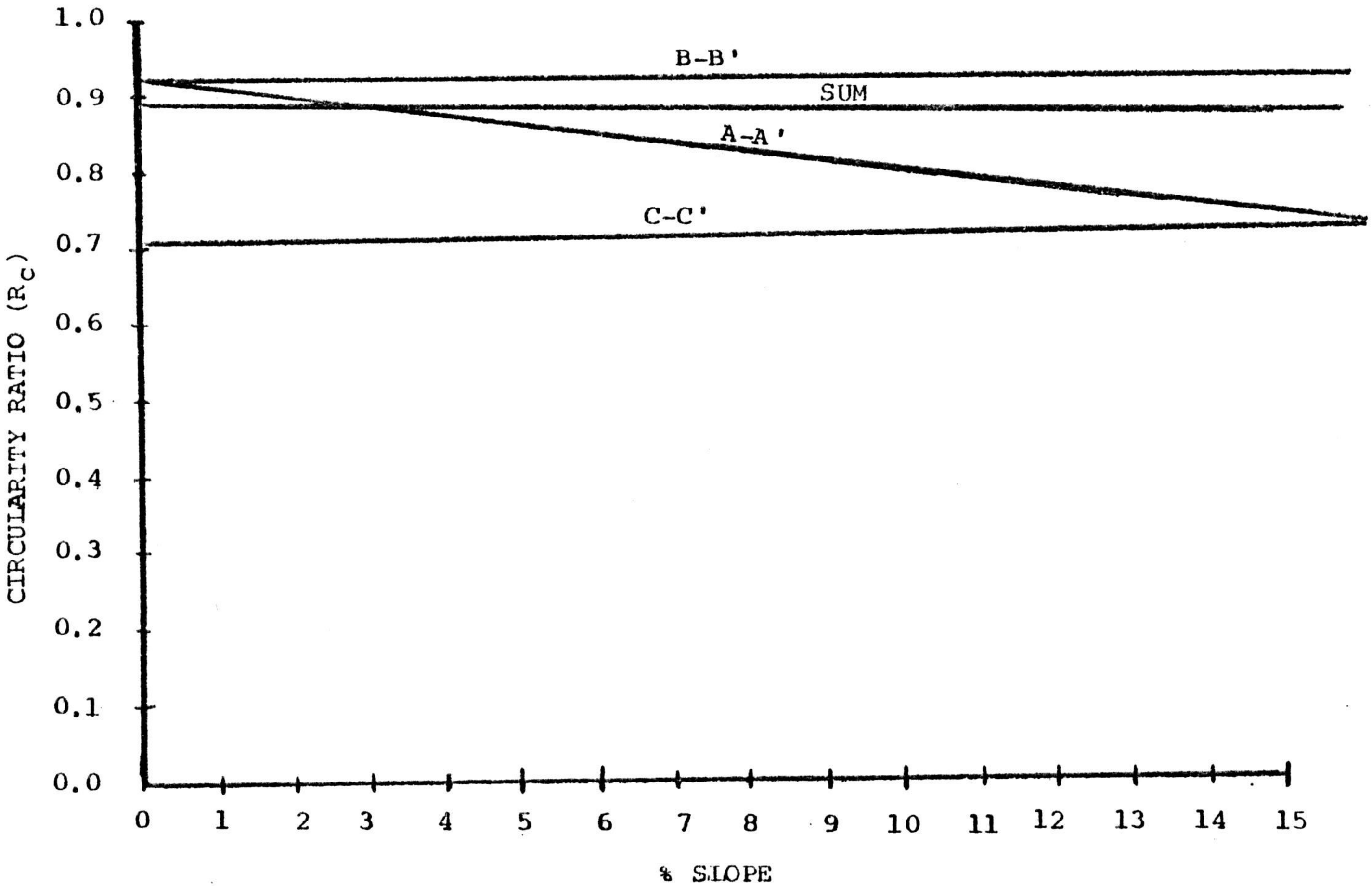


Figure 7. Linear regression analysis

graphically (Fig. 7).

Similar statistical methods were employed for soil sample data.

Soil Tests

Fourteen core samples were taken from mound and intermound areas across the entire research area. The length of each core sample was an indication of the relative soil thickness, but because large stones may have been encountered within the soil mass, it is not a reliable measure of the true soil thickness.

Standard laboratory tests were employed for the soil texture and moisture retention analyses. Sieving and washing procedures were used to determine the percentage of gravel in each air-dried sample.

Sand, silt, and clay fractions were determined by performing hydrometer tests on 50 gram subsamples of the sifted soil. This test involves chemical and mechanical dispersion of soil aggregates and measurement of the percentage of particles in suspension at specific time intervals. Sample weights and particle size percentages were corrected for soil water weight. The terms loam, very fine loam, or silt loam were applied in accordance with a standard, triangular, texture classification system.[28]

Linear regression analysis correlated slope, again as the independant variable, to sample sand or gravel contents.

Although not all samples were large enough to permit moisture retention testing, the six samples used helped to characterize the soils of the Lawrence Memorial Grassland Preserve. Moisture retention tests at 15 bars of atmospheric pressure, define the amount of water held in the soil at the permanent wilting point of plants. This is the point at which the addition of water will not induce a recovery. For this test, small samples are soaked, pressurized, oven-dried, weighed and compared to a standard soil sample (Table 2).

Orientation Analyses

Two long-axis orientation analyses were performed in order to determine directional variances that may be produced by geomorphic processes. The first, a field technique, resembled till fabric analysis in its design. Three uniform slopes were selected, and the general downslope orientation of each was found with a Brunton pocket transit (Fig. 8). The long (a) and intermediate (b) axes of fifty intermound rocks of various sizes were measured on each of the slopes. Again, the Brunton compass was used to find the bearing of the long axis. The ratio of "a" axis to "b" axis was plotted in relation to long-axis direction on a stereographic (Wulff) net.[29] Rose diagrams portrayed the long-axis orientation data (Fig 9).

The second orientation analysis was a map technique. Elongated mounds on the northeast portion of the research area seemed to be much more prevalent and uniformly oriented than ones on the corresponding western side, even though the slopes of each side were approximately equal. A 360° compass and a grid were used to find the directional trend of the long axes of fifteen mounds in each area (Fig. 10). The results were plotted on rose diagrams (Fig. 11).

DISCUSSION

The number and complexity of mound and patterned ground features on the Lawrence Memorial Grassland Preserve seem to preclude simple explanations for their size, shape, and distribution. No single process or environmental condition adequately satisfies the questions that

Sample	Mound or Intermound	Slope %	Depth (inches)	Total Sample	50 gram Subsample			Classification	Moisture Retention Average*
				% Gravel	% Sand	%Silt	% Clay		
A	Mound	1	15.0	10.9	28.3	45.4	26.3	fine loam	7.5
B	Intermound	1	9.0	19.9	39.9**	40.2**	19.9**	fine loam	---
C	Mound (u)***	9	11.0	6.1	32.9	41.0	26.5	fine loam	---
D	Mound (d)***	9	17.5	13.9	35.5	41.9	22.6	fine loam	10.2
E	Intermound	9	5.5	17.4	46.4**	37.7**	15.9**	loam	---
F	Mound	3	10.0	15.8	31.5	47.9	20.6	fine/silty loam	---
G	Intermound	3	6.0	5.3	24.5**	53.0**	22.5**	silt loam	---
H	Mound	3	18.5	13.6	27.2	52.0	20.8	silt loam	10.0
I	Intermound	3	5.5	23.0	36.7	44.9	18.4	loam/ coarse loam	---
J	Mound (u)***	6	16.0	5.7	30.0	46.0	24.0	fine/silty loam	9.2
K	Mound (d)***	6	20.5	4.8	32.6	43.7	23.7	loam	13.3
L	Intermound	6	7.0	12.3	42.8	39.1	18.1	loam/ coarse loam	8.1
M	Mound (u)***	3	15.5	6.9	27.0	50.0	23.0	loam/ silty loam	---
N	Mound (d)***	3	12.5	11.4	36.9	43.0	20.1	loam/ coarse loam	---

*standard moisture retention=11.1 **subsample less than 50 grams ***u=upslope, d=downslope

TABLE 2. SOIL SAMPLE SUMMARY

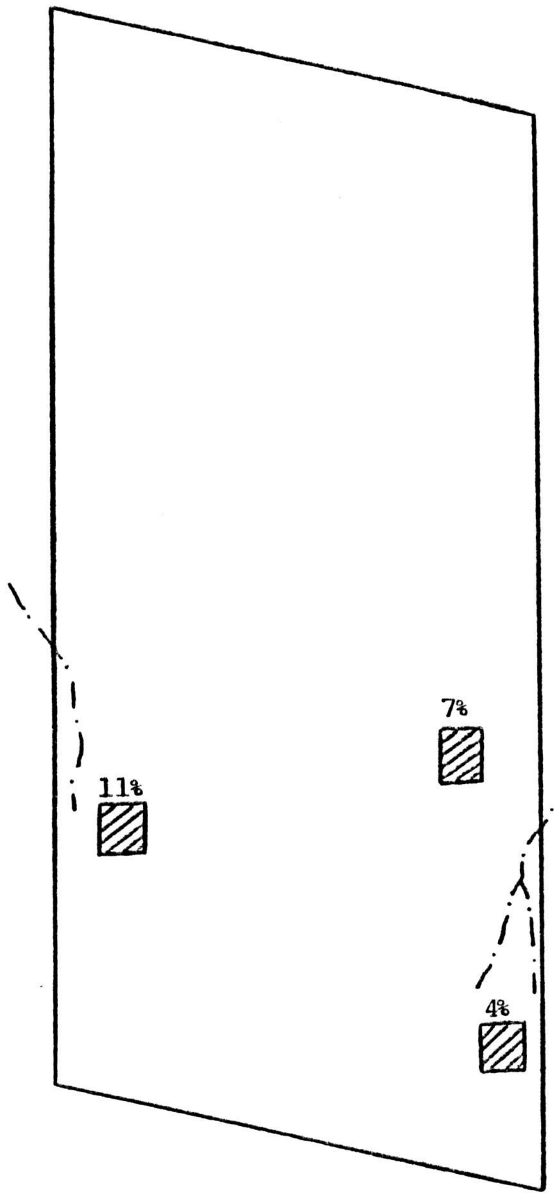


Figure 8. Rock orientation study areas

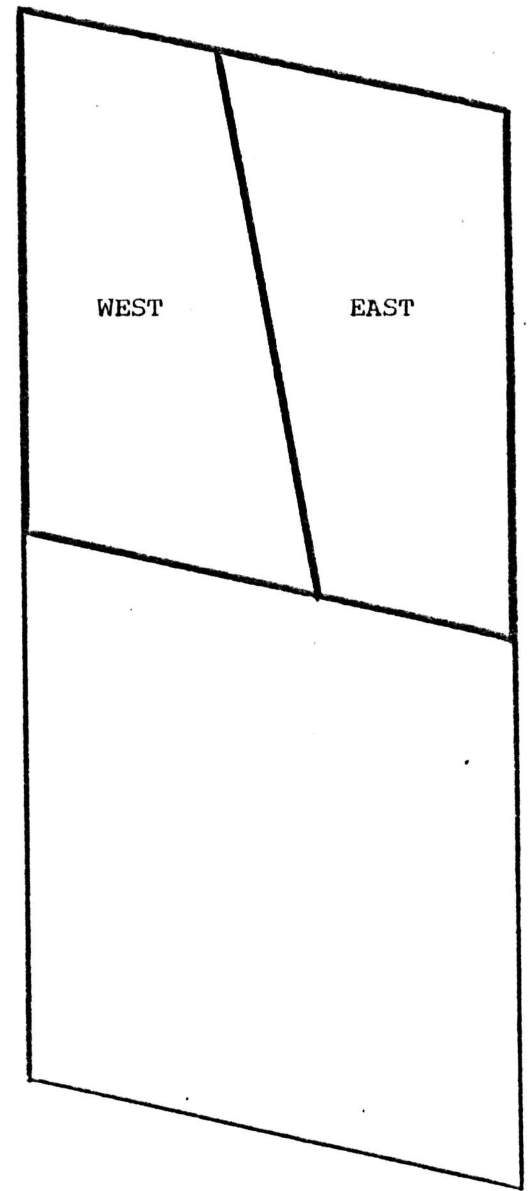
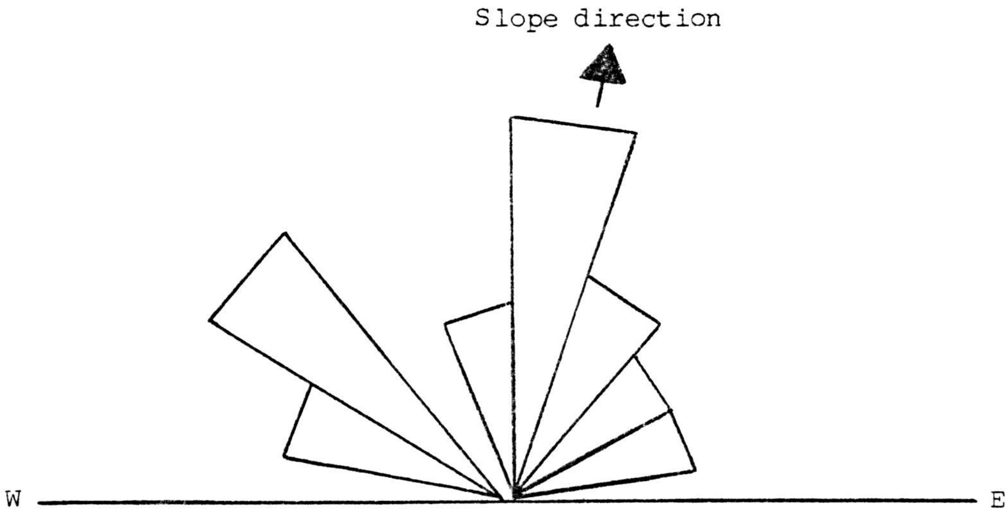
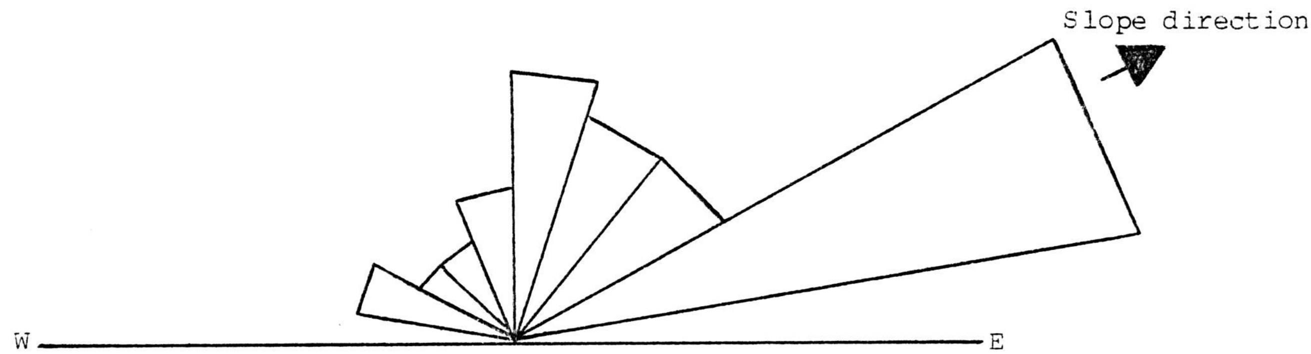


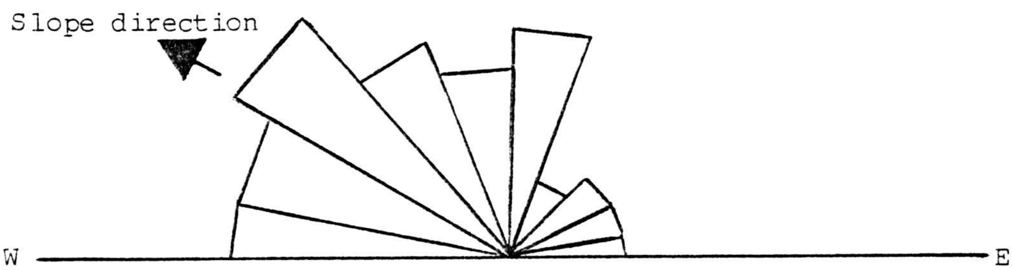
Figure 10. Mound orientation study areas



Group 1. Slope approximately 4%. 20% of the rocks parallel to slope, 18% perpendicular to slope.



Group 2. Slope approximately 7%. 30% of the rocks parallel to slope, 8% perpendicular to slope.



Group 3. Slope approximately 11%. 16% of the rocks parallel to slope, 6% perpendicular to slope.

Figure 9. Long-axis rock orientation

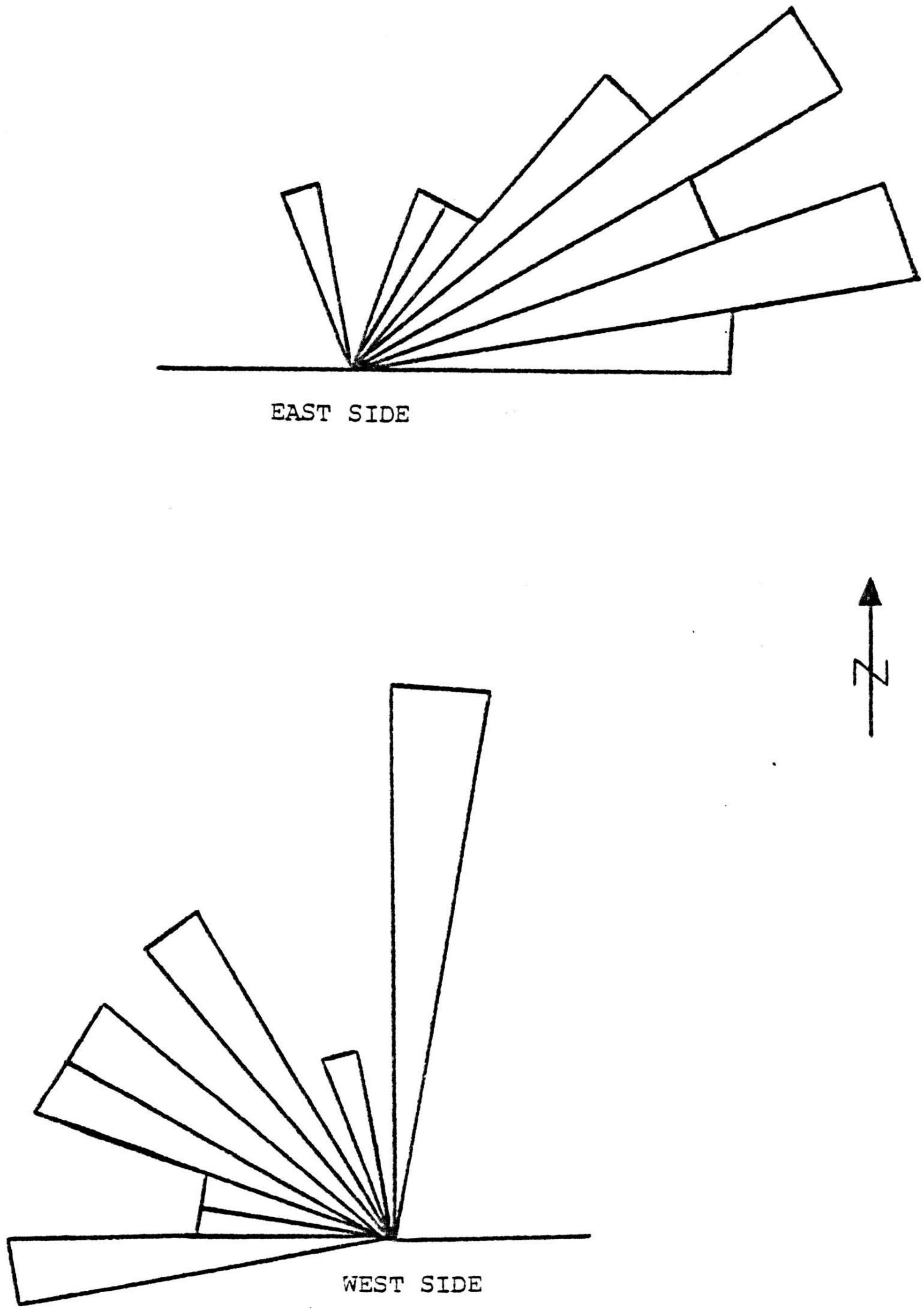


Figure 11. Orientation of elongated mounds

arise when the patterned ground landscape is examined. Does the location of the soil mounds affect their size and shape? Why are there well developed stone rings or nets in some areas and not others? What factors influence the formation and position of debris islands, stone stripes, and terraces?

Perhaps it is not reasonable to seek a common answer for those and many other questions. It should be remembered that:

1) Surface features may reflect 3-dimensional variances in the soil mass and the underlying geology

2) The effects of geomorphic processes are both horizontal and vertical

3) Different processes may work in concert or in opposition to one another

4) Conditions and processes change through time

With these principles in mind, the physical features of the Lawrence Memorial Grassland Preserve were examined.

<u>Mounds and Patterned Ground</u>

Soil mounds are tremendously variable in size, shape, and distribution, though to some extent these entities influence each other. They range in area from 32 square meters (346 sq. ft.) to 1402 square meters (15,092 sq. ft.). Circular mounds measure from 5 to 35 meters (15-115 ft.) in diameter. Although the great majority of mound heights are close to the mean height of approximately 1 meter (3 ft.), there are some that are barely distinguishable from the intermound level and others that reach a height of nearly 1.8 meters (6 ft.). Minimum heights usually occur on small circular mounds and on the downslope end of extremely elongated mounds. Mounds that are circular, with significantly steeper banks on the downslope side, and exist on relatively gentle slopes are those that attain the maximum heights.

Circular mounds viewed in cross-section, when the cross-section is parallel to slope direction, would appear asymmetrical, domed, or flat-topped. A cross-section perpendicular to the slope direction would reveal little asymmetry. There are many factors, which singularly or in combination with others, could produce these mound configurations. Among the possible causes are mass wasting, soil compaction, water erosion, and biologic influences. However, these factors are so numerous and their interrelationships so complex, that definitive conclusions are difficult to make.

In general, mounds are elongated downslope, but the amount of elongation could not be correlated to the percent slope for the 40 acres encompassed by this study. Linear regression analysis of the transects A-A', B-B', C-C', and the sum of all three produced gently sloping to nearly horizontal lines when plotted on a graph (Fig. 7). This indicated little relationship between percent of slope and circularity ratios.

Data collected from each of the nine sub-sections previously described was also subjected to linear regression analysis. As with the transect data, slope was related to mound circularity ratio. In addition, linear regression was used to find the relationship of amount of slope and the number of mounds per area (density). These too produced poor correspondence. The Pearsons product-moment coefficient of linear correlation (r) for slope versus the number of mounds was -0.17. Negative values indicate that the dependant variable (number of mounds) decreases as the independant variable (slope) increases. The small fraction indicates an extremely poor covariance of the elements involved.[30]

The linear correlation coefficient for the relationship of average slope to mean circularity ratio of each section was -.67. Although this figure does not represent a close correlation, it indicates better correlation than the result obtained from the transect data. This disparity is likely caused by the averaging process and the few data pairs in the section sample. The purpose of the analysis of the 9 areas was to identify trends in the entire research area and should not be considered as accurate or meaningful as the results of the transect analysis. Because little correlation was found to exist between slope and mound shape, other factors must be responsible for the varied mound configurations.

The extremely long mounds (R_c less than .50) have a common general orientation of about N 28° W. A very similar trend (N 30° W) in regional joint patterns suggests that the shape of these mounds are genetically related to the joints in the underlying basalt.

The shape of mounds surrounded by sorted stones may be related to the frost sorting process. Though some sorting occurs presently, the process was most active during a periglacial regime, characterized by many freeze-thaw cycles and sufficient water for frost action. Under these conditions a heterogeneous soil mass is sorted, and mounds are formed by the following process:[31]

1) Ice forms around or at the base of stones because of their greater heat conductivity.
2) Soil water is preferentially drawn to the freezing area. This causes accretions of ice and increased frost action.
3) Stones are ejected radially from the freezing nuclei.
4) The sorting process concentrates fine material in the center

of the nuclei and stones at the border.

5) The accumulation of stones serves as a sub-surface drainage.

6) Through time, erosion lowers the ground surface in stone areas, surface drainages form, and high centered mounds of soil are left as remnants of the original surface.

Sorted circles form where the sorting process operates in isolation from other sorting centers. Conversely, when many sorting nuclei impinge upon each other, the forms are polygonal. Examples of each of these distributions exist on the Lawrence Memorial Grassland Preserve. A number of large, widely-spaced, and relatively circular mounds, (some with well developed stone rings encircling them), occupy the gently sloping divide between the drainages. Polygonal patterns are found in parts of the south-central and southeastern sections of the research area. Though not perfectly formed, the stone polygons and nets are reminiscent of densely packed hexagons.

The frost sorting process fails to explain mounds that have no associated rock patterns. Perhaps the rings existed at one time but subsequent mass-wasting or other erosion obliterated them. Another explanation is that the rings may have been covered by vegetation, lichens, and soil infillings during long inactivity. However, the apparent stability of rings around adjacent mounds suggests that stone rings never formed around these mounds.

A number of processes have been suggested as producing non-sorted structures. Washburn classified these processes in two major categories.[32] In one, cracking of the surface layer is essential to the formation of the non-sorted features. In the other, surface cracking is not necessary (Table 3). Seasonal frost cracking and frost action along bed-

Genetic classification of patterned ground

PATTERNS		PROCESSES												
		CRACKING ESSENTIAL						CRACKING NON-ESSENTIAL						
				THERMAL CRACKING										
					FROST CRACKING									
		DESICCATION CRACKING	DILATION CRACKING	SALT CRACKING	SEASONAL FROST CRACKING	PERMAFROST CRACKING	FROST ACTION ALONG BEDROCK JOINTS	PRIMARY FROST SORTING	MASS DISPLACEMENT	DIFFERENTIAL FROST HEAVING	SALT HEAVING	DIFFERENTIAL THAWING AND ELUVIATION	DIFFERENTIAL MASS-WASTING	RILLWORK
CIRCLES	NONSORTED								Mass-displacement N circles	Frost-heave N circles	Salt-heave N circles			
	SORTED						Joint-crack S circles (at crack inter-sections)	Primary frost-sorted circles, incl.? debris islands	Mass-displacement S circles, incl. debris islands	Frost-heave S circles	Salt-heave S circles			
POLYGONS	NONSORTED	Desiccation N polygons	Dilation N polygons	Salt-crack N polygons	Seasonal frost-crack N polygons	Permafrost-crack N polygons (incl. ice-wedge, permafrost soil-wedge polygons)	Joint-crack N polygons		Mass-displacement N polygons?	Frost-heave N polygons?	Salt-heave N polygons?			
	SORTED	Desiccation S polygons	Dilation S polygons	Salt-crack S polygons	Seasonal frost-crack S polygons	Permafrost-crack S polygons	Joint-crack S polygons	Primary frost-sorted polygons?	Mass-displacement S polygons?	Frost-heave S polygons?	Salt-heave S polygons?	Thaw S polygons?		
NETS	NONSORTED	Desiccation N nets incl? Earth hummocks	Dilation N nets		Seasonal frost-crack N nets, incl.? Earth hummocks	Permafrost-crack N nets (ice-wedge and ? permafrost soil-wedge nets)			Mass-displacement N nets, incl.? Earth hummocks	Frost-heave N nets, incl. Earth hummocks	Salt-heave N nets			
	SORTED	Desiccation S nets	Dilation S nets		Seasonal frost-crack S nets	Permafrost-crack S nets?		Primary frost-sorted nets	Mass-displacement S nets	Frost-heave S nets	Salt-heave S nets	Thaw S nets		
STEPS	NONSORTED								Mass-displacement N steps	Frost-heave N steps?	Salt-heave N steps?		Mass-wasting N steps	
	SORTED							Primary frost-sorted steps?	Mass-displacement S steps	Frost-heave S steps	Salt-heave S steps	Thaw S steps?	Mass-wasting S steps	
STRIPES	NONSORTED	Desiccation N stripes	Dilation N stripes?		Seasonal frost-crack-N stripes?	Permafrost-crack N stripes	Joint-crack N stripes?		Mass-displacement N stripes	Frost-heave N stripes	Salt-heave N stripes		Mass-wasting-N stripes?	Rillwork N stripes?
	SORTED	Desiccation S stripes	Dilation S stripes		Seasonal frost-crack S stripes?	Permafrost-crack S stripes	Joint-crack S stripes	Primary frost-sorted stripes?	Mass-displacement S stripes	Frost-heave S stripes	Salt-heave S stripes	Thaw S stripes?	Mass-wasting S stripes	Rillwork S stripes

Table 3. Washburn's genetic classification of patterned ground (1973)

rock joints are examples of processes which cause surface cracking. Mass displacement and differential frost heaving create non-sorted polygons and nets without cracking. Though some processes are more probable than others for the features on the Lawrence Memorial Grassland Preserve, it is difficult to determine genesis on the basis of form because, as Washburn stated: 1) patterned ground is polygenetic 2) similar forms may result from different processes 3) the same processes may produce different forms 4) there are more processes than currently recognized.[33]

It is likely that more than one process is active at a time, and that other factors influence their function. For example, the orientation and predominance of elongated mounds and patterned ground features on the east side of the drainage might be interpreted as a reflection of the dominant orientation of periglacial processes.[34]

Orientation analysis of these mounds confirms the greater uniformity of elongation direction than on the western side (Fig. 11).

A ground surface subject to solifluction, typically associated with a periglacial regime, commonly contains a prevalence of rocks with their long-axes oriented parallel to the slope direction. Particles tend to turn at right angles to the direction of flow when the movement is arrested.[35] Both orientations were evident from the long-axis analyses of three slopes within the research area. However, the tendancy for rocks to be perpendicular to the slope direction is only well developed in the area of relatively gentle slopes (Fig. 9). The majority of rocks are oriented with their long axis parallel to slope for all three areas. Intermediate slopes had the greatest tendancy for downslope alignment and the rocks in the high slope group were, in general, less homogeneous in directional bearing. The rate of erosion on the steeper slopes probably is an important determinant for erratic long-axis orientation.

Thus, the two orientation analyses demonstrate that periglacial processes are likely the primary cause of the distribution and bearing of elongated mounds in this area, although other processes and environmental controls may be involved. For example, the deeper, coarser Condon soil has a tendancy to be concentrated on the north and east-facing hillslopes. Frost susceptibility, moisture retention, and other inherent properties could enhance frost processes and be expressed in the distribution of mounds. The prevailing westerly wind also has a directional affect on the landscape. Snow is piled on the lee slopes, thus producing dissimilar amounts of snowmelt during the spring, while the winward slope is exposed to greater desiccation year-round. The flora and fauna indiginous to the Lawrence Memorial Grassland Preserve also interact with and modify the size and shape of mounds. Denser vegetation on southern exposures insolates and stabilizes the soil more than the sparser vegetation on north-facing slopes.[36] Though animal influence is mostly localized, the excavation of soil makes it prone to wind transport. In addition, abandoned tunnels may collapse and act as a catchment for water runoff.

<u>Other sorted forms</u>

Though sorted stripes occupy similar positions and gradients (approximately 12 percent) along the eastern and western drainages, other sorted forms are concentrated on the downslope side of mounds and on the east-facing slope. The force of gravity in conjunction with mass wasting and erosion effect an accumulation of rocks downslope. However, the greater density of stripes, garlands, and stone-banked terraces on the eastern hillside is not so easily explained. In fact, one might expect that the western side, because of its steeper slopes, would exhibit a greater propensity to accumulate rubble. Other factors must be responsible for the large number of stone features on the east side.

Again, the orientation of periglacial sorting processes is likely an important part of this phenomena. To fully understand the surface features, however, it is helpful to examine the underlying geologic structure. Because the layers of Columbia River Basalt are nearly horizontal, more area of a specific basalt layer would be exposed on a gentle slope than on a steeper one. If this geologic unit is also particularly susceptible to frost-wedging, frost shattering because of extensive joint systems, or a scoriaceous texture, then the resultant angular rubble will be more prevalent on the gentler slope. The low slope angle also influences the rate of downslope movement of the material.

The geologic character of the region appears to have considerable influence upon the position of terraces and debris islands found on the Lawrence Memorial Grassland Preserve.

Stone-banked terraces seem to be formed by large stones or boulders moving downslope more rapidly than finer materials. The mass moves downslope under the influence of frost-induced creep and is stopped by a decrease in slope, by vegetation, or by increasing mutual contact.[37] The large terrace, near the middle of the eastern slope, has a riser scarp of approximately 1.8 meters (5.8 ft.) and its length, though somewhat discontinuous, is about 13.2 meters (43.3 ft.). The coarse material at the scarp grades to finer particles at the inner edge of the tread (Fig. 12). Corresponding to this decrease in texture is an increased amount of vegetation. These terraces move downslope and impinge upon the one below.

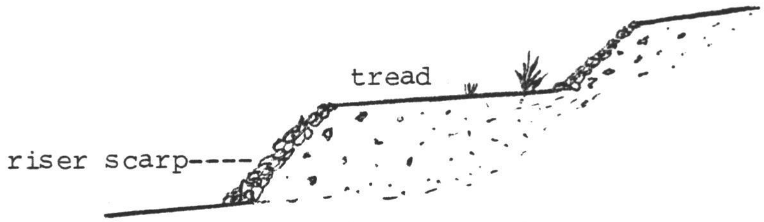
Other terraces expand by undercutting the one above. Benches are formed by the erosion of rocks along sub-horizontal planes of weakness. Variation in susceptibility to frost weathering along the scarp, assists the erosion process and results in the retreat of the embankment. Because rocks accumulate along the scarp, it is difficult to distinguish these rock-cut terraces from the stone banked ones.

Although no terraces that were clearly of the rock-cut category were identified within the research area, they probably exist on other parts of the Lawrence Memorial Grassland Preserve, as well as the stone-banked varieties.

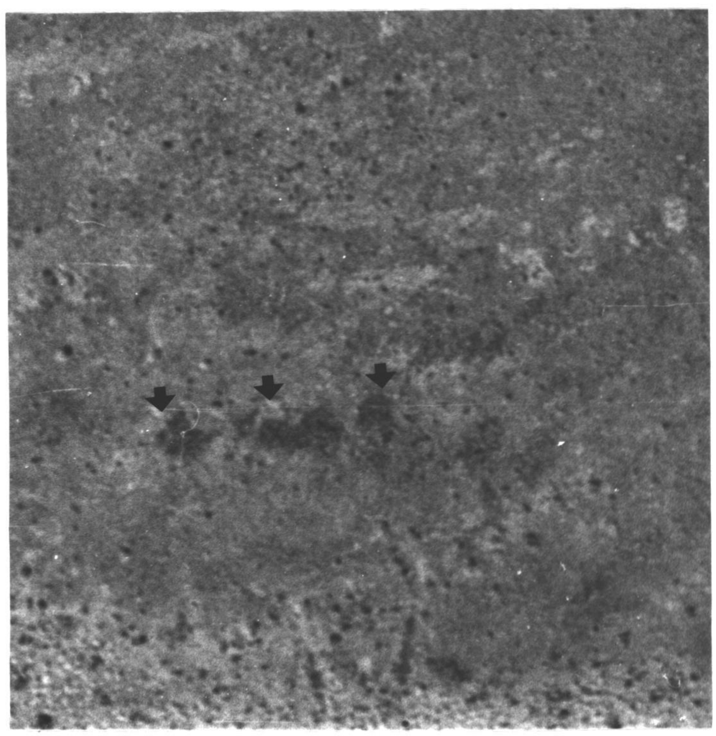
Debris islands are small, flat, irregularly shaped and sorted features that are generally associated with stone rings or stone pavement of intermound regions.

They are formed by an alternate freezing and thawing process. The growth of segregated ice causes larger particles to be displaced while smaller particles are extruded above the surface. Upon subsequent thawing, the fine material is deposited.[38]

One linear group of debris islands trends downslope (though at a significant angle from the general slope direction) away from its associated rock net (Fig. 13). This unusual feature occurs near the upper end of the East Drainage. As with the extremely long mounds on the west side, this line of debris islands has an orientation similar to the ravines in the area. Therefore, a geologic control, such as a regional joint system, is probably involved.



Cross-sectional sketch of stone-banked terrace



Aerial photograph of stone-banked terrace

Figure 12. Stone-banked terraces

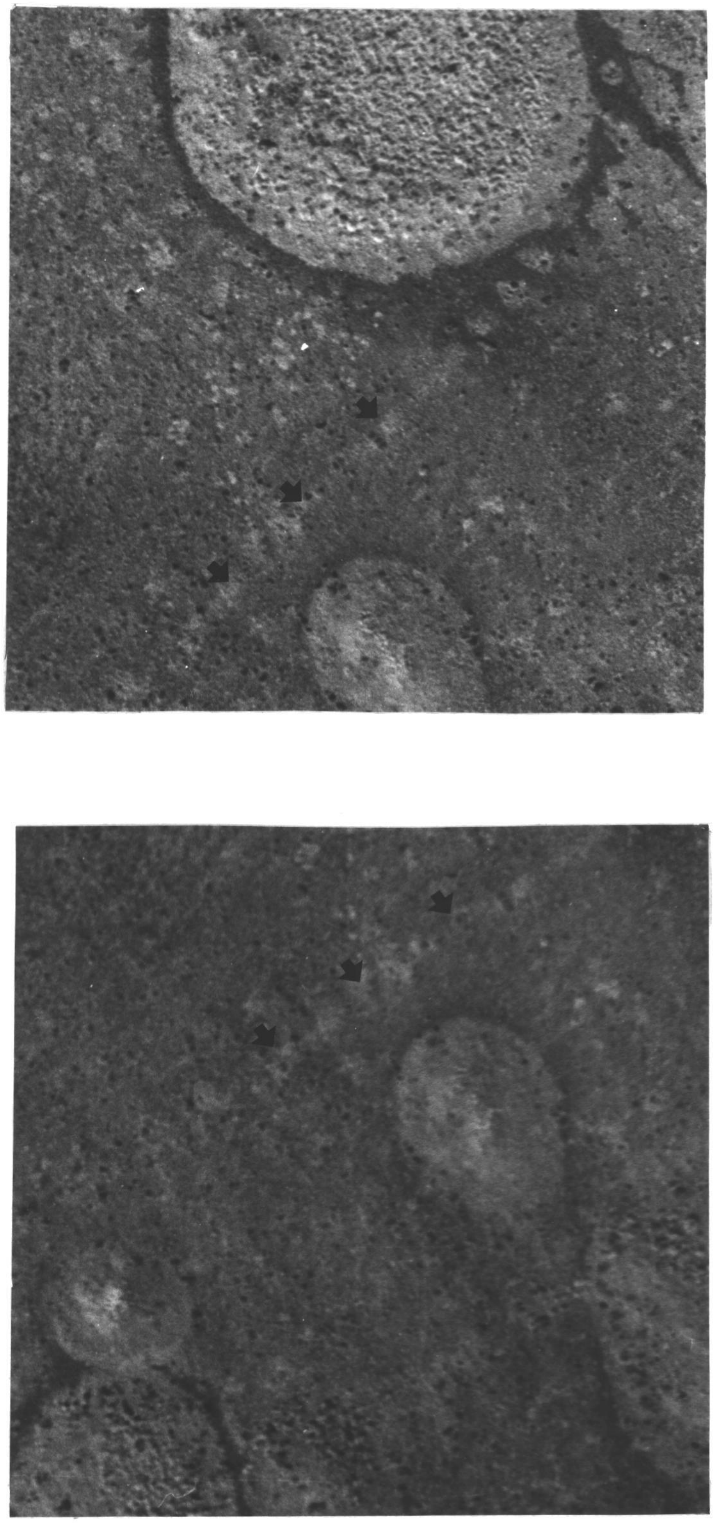


Figure 13. Linear group of debris islands

The present-day process of segregated ice growth may be enhanced by the position of bedrock joints and by sorted forms already in existence. Specific water supply conditions, the removal of latent heat of crystallization, and a slow freezing process are requisites for the formation of segregated ice. A joint system covered by a veneer of soil may be particularly conducive to the action of ice segregation because the conductivity of the rock allows slow cooling of the soil above and may act as a reservoir for moisture. The same principle applies to the association of debris islands with existing mounds and stone pavement. Water held in the thicker mound soils and the thermal properties of the surrounding rocks act as a nucleus for the development of the smaller forms.

Another ice related feature observed on the Lawrence Memorial Grassland Preserve are symmetrical depressions or "wells" among the rocks of the stone rings. No mention of this phenomenon was found in the literature, so the descriptive term "rock net depression" was utilized. Their appearance, upon first observation, resemble holes that an animal, such as a badger or coyote, might dig. However, a closer inspection reveals that the disturbed rocks, of the well developed depressions, are scattered uniformly around a steep-sided, symmetrical depression. The depth of large depressions is about equal to that of the rock net. A series of these depressions occured among the rocks at the mound-stone ring border. Because they were only observed on an extremely cold day, they are probably transitory forms like the frost boils that were also prevalent thet day. The growth of segregated ice is presumably the primary force for overturning and ejecting material from these depressions. Ice was visible at the bottom of some depressions. Their distribution along established mound-rock borders lends support to the concept that smaller forms are associated with larger structures because some of the conditions necessary for segregated ice growth are fulfilled.

Soil Testing Results

Soil samples of mounds were found to contain approximately six percent less sand and gravel than corresponding intermound areas. Paired samples from the upslope and downslope portions of individual elongated mounds revealled a tendancy for the downslope sample to have a higher percentage of sand. However, the amount of sand or gravel did not exhibit a close association to the percent of slope in linear regression analysis. Figures obtained for the Pearsons product-moment coefficient of linear correlation were -0.2 for percent slope versus percent gravel and 0.4 for percent slope versus percent sand. The correlation seems to be somewhat closer when mound and intermound values are calculated separately, but because the data pairs are so few, it is not a reliable indicator of the relationship.

It appears that the force of gravity, which concentrates particles downslope, is counteracted by the natural distribution of soils and by wind transport of finer material.

With one exception, the moisture retention values for soil samples of the Lawrence Memorial Grassland Preserve were less than that of the local standard, a Chehalis silt loam.

Texture and moisture retention capabilities of soil are important properties in terms of erosion and frost susceptibility. When dry, silt is prone to wind erosion, but compacts when wet.[39] Thus, a thin film of water surrounding the silt particles and an absence of large air-filled pores makes the frost heaving of silt soil faster, with more volume and uniformity, than finer material. The growth of segregated ice causes sand and gravel to heave as well, but because of their greater permeability, the rate of heave may be restricted by pore spaces and water flow. In addition, the ice that forms is readily thawed by infiltrating water. Soil saturated with water moves slowly downslope by solifluction.

CONCLUSIONS

Although the data and descriptions for soil mounds and patterned ground features in this research apply only to part of the Lawrence Memorial Grassland Preserve, it appears that the inter-disciplinary approach used was successful in explaining its complexities. A single hypothesis of origin generally fails to wholly explain the great variety of sizes, shapes, and distribution. However, a number of frost related processes, both past and present, seem to manifest themselves in the landscape. Among the elements examined were slope, slope aspect, geology, soil properties, vegetation, biologic activity, and geomorphic processes.

A study of mound attributes revealed that 63 percent of the 203 mounds have circularity ratios above the mean of 0.89. The average mound area is 284 square meters (3061 sq. ft.), and the mean perimeter is 61 meters (201 ft.). Standard deviation of mound circularity ratios is 0.12 and coefficient of variation is 13 percent. Extremely long mounds have a common orientation that appears to be related to regional joint systems in the underlying Columbia River Basalt.

The amount of elongation in mounds does not correlate well to slope percentages in linear regression analyses. Graphical portrayals of percent slope, as the independant variable, and the morphologic index (R_C), as the dependant variable, revealled nearly horizontal lines. This indicates that the variables have little correspondence. Similar regression analysis for percentage slope versus number of mounds per area produced equally poor correlation.

Mounds exhibit a variety of distributions ranging from large, widely-spaced circles, to smaller, close-packed polygons.

Soil mounds and patterned ground are more prevalent on the east-facing hill slope. This distribution may be related to the orientation of frost processes, the existence of deeper, less clayey soil, geologic features, and the effects of a prevailing west wind.

Secondary features such as debris islands, frost boils, and rock net depressions seem to be associated with larger, established forms because the components required for their formation are more likely to be present.

An analysis of soil samples showed a general increase in particle sizes on the downslope side of elongated mounds. However, the percent of sand or gravel does not seem to correlate to the percent slope.

SUMMARY OF PROCESSES

The major forces of geomorphic activity, currently observed or reflected in the physical properties of the Lawrence Memorial Grassland Preserve, are related to frost, water, and wind. These are not mutually exclusive processes, rather each may influence the function of another.

For example, the formation of frost may be enhanced by the presence of water or diminshed by wind-related dehydration.

Because of a prior colder climate and the present day environmental conditions, evidence of frost processes are most prevalent. Intense frost sorting, differential frost heaving, and gelifluction are largely responsible for such obvious forms as sorted nets, polygons, steps or garlands, and stripes. The susceptibility of geologic structures to frost processes, in conjunction with the force of gravity, create and concentrate the stone rubble of terraces and talus slopes. Frost boils and rock net depressions confirm that frost processes are presently active to some degree. In addition, widespread frost cover, needle ice, and ice among the rock borders of mounds, similar to those in active periglacial areas, were observed in the research area.

When the ice melts or precipitation falls, the affect of liquid water upon the landscape is apparent. Downslope runoff at or near the surface is common because infiltration may be impeded by frozen ground, shallow soil, and bedrock. Sinuous drainage tributaries, hillslope rills, and mound saddles portray the dissection of the shallow loessial soil by running water.

Because the soil mantle of the Lawrence Memorial Grassland Preserve is primarily wind-borne, some soil properties, such as texture and thickness, manifest the paleo-influence of wind as a geomorphic process. The concentration of deeper, coarser soils on north and east facing slopes suggests that the wind direction and source of material was from the northeast. Current wind activity includes the transport of loose soil and snow. Therefore, all geomorphic processes operate upon variable amounts of material through time.

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