AN ABSTRACT OF THE THESIS OF

ROBERT CARL PAETH for the M. S. in Soils
(Name) (Degree) (Major)

Date thesis is presented January 19, 1967

Title DEPOSITIONAL ORIGIN OF MIMA MOUNDS

Abstract approved Signature redacted for privacy.
(Major professor)

An investigation was conducted to determine the origin of Mima mounds in Jackson County, Oregon and Thurston County, Washington. Data on soil morphology, mineralogy, and particle size distribution were used to test the periglacial ice wedge hypothesis, the gopher hypothesis, the erosional hypothesis, and the loess hypothesis.

The results of this investigation show that these hypotheses do not satisfactorily explain the origin of Mima mounds.

The conditions of an acceptable hypothesis are given and a depositional theory on the origin of Mima mounds is suggested within the framework of these conditions.

DEPOSITIONAL ORIGIN OF MIMA MOUNDS

by

ROBERT CARL PAETH

A THESIS

submitted to

OREGON STATE UNIVERSITY

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1967

APPROVED:

Signature redacted for privacy.

Professor of Soils
In Charge of Major

Signature redacted for privacy.

Head of Soils Department

Signature redacted for privacy.

Dean of Graduate School

Date thesis is presented **January 19, 1967**

Typed by Donna Olson

ACKNOWLEDGEMENTS

The author is grateful to Dr. Ellis G. Knox for his assistance and encouragement during the course of this study and in the preparation of this manuscript.

Acknowledgements are also made to Dr. Harold E. Enlows for his assistance with petrographic analyses of grain mounts, and to Dr. Roger G. Petersen for his assistance with statistical analyses.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX TABLES

DEPOSITIONAL ORIGIN OF MIMA MOUNDS

INTRODUCTION

The remarkable mounds of the western United States have stirred the imagination of many people since they were first described by Wilkes (1845) in the Puget Lowlands of Washington. Mounds of this type occur most commonly on nearly level alluvial terraces, outwash plains, and mesas. They never occur on flood plains. Mount-bearing surfaces are commonly slightly higher than the surrounding drainage system and are not subject to erosion or deposition from present stream overflow. Level areas of mounds appear like open fields dotted with randomly spaced oblate hemispheroids convex upward. Mounds that occur on slopes are usually oriented in rows in the direction of the slope. The mounds range from 1 to 8 feet high and are from 10 to 150 feet in diameter. When viewed from above, they appear to be circular or slightly oval. They have no particular orientation except when they occur on slopes where their long axis is oriented in the direction of the slope.

The mounds consist of homogeneous loamy soil material that ranges from very gravelly to gravel free. Coarse fragments are usually concentrated in the surface few inches. The mounds rest abruptly on contrasting substrata. In some areas, cobbles and stones are concentrated in the intermound area. These mounds have been called by various names, the more common of which are Mima mounds, hog wallows, biscuit scabland, and patterned ground.

The mystery of the origin of Mima mounds has been the subject of much controversy for well over 100 years. Many people have suggested hypotheses in an effort to explain their origin, but few have tested any of those already in existence. The major objective of this study was to test four of these hypotheses. Those that were tested are: 1. the gopher hypothesis of Dalquist and Scheffer (1942), 2. the loess hypothesis of Barnes (1879), Shaw (1927), Olmsted (1963), and Freeman (1926, 1932), 3. the erosional hypothesis of Gibbs (1855), Le Conte (1877), Waters and Flagler (1929), Melton (1935), Holdredge and Woods (1947), Knechtel (1952), and Ritchie (1953) and 4. the periglacial ice wedge hypothesis of Eakin (1932), Newcomb (1940, 1952), Pewe (1948), Masson (1949), Kaatz (1959), Malde (1964), and Fosberg (1965). In addition to this, the conditions of an acceptable hypothesis were discussed and an appropriate hypothesis was suggested within the framework of these conditions.

LITERATURE REVIEW

Mima mounds were first described by Wilkes (1845) when he traveled through the Puget Lowlands of Washington. Gibbs (1855) described similar mounds below the "Des Chutes" River in the vicinity of The Dalles, Oregon. Since then, mounds of similar character have been reported in much of the western United States (Le Conte, 1877; Wallace, 1877; Barnes, 1879; Hilgard, 1884, 1905; Piper, 1905; Branner, 1905; Purdue, 1905; Campbell, 1906; Larrison, 1942; Dietz, 1945). According to Price (1949), mounds of this type occur in the Puget Sound Basin, Columbia Plateaus, Central Valley of California, Pacific border terraces, Rocky Mountains, Central Lowlands, Ozark-Ouachita Region, Ozark Plateau, Gulf Coastal Plains, and plateaus and high terraces at scattered locations in basin and range provinces.

Wilkes (1845) excavated several mounds in an effort to find evidence that might explain their origin. He found "no articles of any description" but suggested the mounds were formed "by scraping the surface earth together in a heap." Wilkes (1845) went on to say, "they certainly are not places of burial. They bear the marks of savage labour, and are such an undertaking as would have required the united efforts of a whole tribe." Gibbs (1855) suggested mounds near The Dalles were formed by "washing away the surrounding soil." Subsequent workers have suggested numerous hypotheses and novel theories in an attempt to solve the mystery of the origin of Mima mounds.

Wallace (1877) thought mounds were formed during the retreat of a broad foot of a glacier. Rogers (1893) suggested they were formed by flood water deposit of drift in depressions of an ice sheet. Upham (1904) attributed mound formation to terminal drift deposition.

Piper (1905) stated that mounds in eastern Washington occur only in areas where there has been running water. He suggested that water erosion formed mound microrelief on the surface of the basalt and the mounds resulted from "decay of the basalt".

Branner (1905) suggested that mounds were formed by transfer of minerals in solution and precipitation around nuclei at the present position of the mounds. Withdrawal of these minerals from the intervening areas caused the depressions around the mounds.

Hilgard (1905) attributed mound formantion to the work of ants.

Hill (1906) pointed out that mounds of the lower Mississippi Valley and Texas were formed in regions of "abundant periodic rainfall." When water fell on soil that was nearly level and had no well defined drainageways, it stood on the soil surface until it evaporated or was absorbed. Soils have different capacities for absorption, transmission, retention, and loss of water. This resulted in unequal settling of the ground to form mounds. Whitney (1948) had somewhat the same idea when he stated mounds were formed by uneven settling of considerable thicknesses of soft unconsolidated material that was "laid down hurriedly."

Dietz (1945) related mound formation on the Gulf coastal plain to accumulation of sand around clumps of marsh grass in shallow lagoons. Upon emergence, these small islets of sand appeared in relief as mounds.

Retzer (1945) studied mounds in the Stockton area, California and suggested that water confined under an impermeable clay oozed up through holes in the clay carrying mud to form mounds.

Krinitzsky (1949) maintained that mounds are mainly sandy and are the result of water and wind action in areas of alluvial origin. Kelley (1948) pointed out that mounds occur in a number of inland valleys in California that have narrow restricted drainage outlets. He suggested that mounds are giant ripple marks formed by deep water flowing slowly out of these valleys.

Masson (1949) said that mounding occurred from concentration of clay by freezing and thawing. Freezing caused the soil to expand placing clay particles in contact. These remained in contact after thawing to form mounds.

These hypotheses are obviously inadequate and will not be discussed further.

Dalquist and Scheffer (1942) introduced pocket gophers as builders of Mima mounds. They maintained that Mima mounds were formed by localized activity of gophers over long periods of time. Two conditions necessary for mound formation are: 1. gophers must be present, and 2. a prairie area with a thin layer of silt overlying a dense layer of gravel or some other substratum that is unfavorable to growth of plant roots. Under these conditions, pocket gophers remove earth from radiating burrows and transport it back into the central nesting area to form a mound. The removal of earth from the surrounding area accounts for the sunken intermound area. Intermound cobbles are exposed and concentrated in the intermound area by removal of finer soil material. Stallings (1948), Arkley (1948), Scheffer (1948, 1958), Koons (1948), Price (1950), Arkley and Brown (1954), and Larrison (1942) are in general agreement with this hypothesis.

Barnes (1879) suggested mounds in the San Diego area were formed by dust being captured by scattered clumps of vegetation. Natural erosion maintained the mound relief by constant lowering of the whole landscape. Somewhat the same view is held by Shaw (1927) and Olmsted (1963). Freeman (1926) stated that erosion of the channel scabland of Eastern Washington resulted in the formation of depressions in the surface of the basalt. These captured small pockets of loess. Vegetation became established and more loess accumulated to form the mounds. Freeman (1932) later suggested that erosion played a part in the formation of the intermound area.

Gibbs (1855), Le Conte (1877), Waters and Flagler (1929), Melton (1935), and Holdredge and Woods (1947) suggested that Mima mounds were formed by erosion of the soil mantle in intermound areas leaving the mounds standing in relief. Knechtel (1952) pointed out that erosion probably started in a system of polygonal cracks formed by shrinking and cracking of the soil mantle as it dried. Ritchie (1953) said during the Pleistocene the soil mantle contained a polygonal-fissure ice network. Water running in the network around the polygons removed the thawed soil material to form the mounds.

Because of the similarity of Mima mound microrelief to patterned ground described in the arctic (Neilson, 1960; Washburn, 1956), some periglacial phenomenon to explain their origin seems logical. Eakin (1932) was first to suggest that Mima mounds were formed by frost rearrangement of mixed alluvial material. Later workers (Newcomb, 1940, 1952), (Pewe, 1948), and (Kaatz, 1959) suggested that a polygonal system of ice wedges formed in the soil mantle during late Pleistocene. These ice wedges thickened year after year and forced the soil into blocks between the ice. When the ice melted, the soil slumped into mounds. Malde (1964) and Fosberg (1965) suggested that mass wasting of saturated soil in the intermound area played a part in mound formation.

METHODS AND MATERIALS

Sample Areas

The study area was limited to Jackson County, Oregon and Thurston County, Washington. Figure 1 is a map of the Jenny Creek sampling area in the southeast corner of Jackson County. Figure 2 is a map of areas sampled on Agate Desert and Upper and Lower Table Rocks near Medford. Figures 3, 4 and 5 respectively are maps of sample areas on Mima Prairie, Mound Prairie and Rocky Prairie in Thurston County, Washington.

The elevation of the Jenny Creek mound prairie is 3,400 feet. Agate Desert ranges in elevation from 1,600 feet on the eastern margin to 1,200 feet on the western margin south of Lower Table Rock. Both Upper and Lower Table Rocks rise abruptly 800 feet above the level of Agate Desert. Lower Table Rock has an elevation of 2,044 feet and Upper Table Rock has an elevation of 2,080 feet. Mima Prairie, Mound Prairie, and Rocky Prairie range in elevation from 120 feet to 250 feet.

These mound prairies are almost treeless, nearly level plains, that are dotted with regularly shaped, randomly spaced oblate hemispheroids convex upward. Mounds on these prairies range from 1 to 8 feet high and from 10 to 150 feet in diameter. The profile descriptions in the appendix show that the mounds sampled in this study

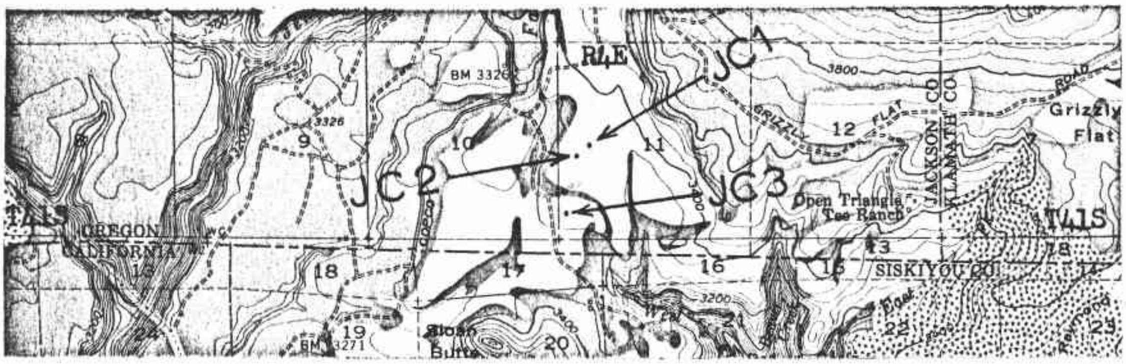

Figure 1. Map of sample sites in the Jenny Creek area, Jackson County, Oregon.

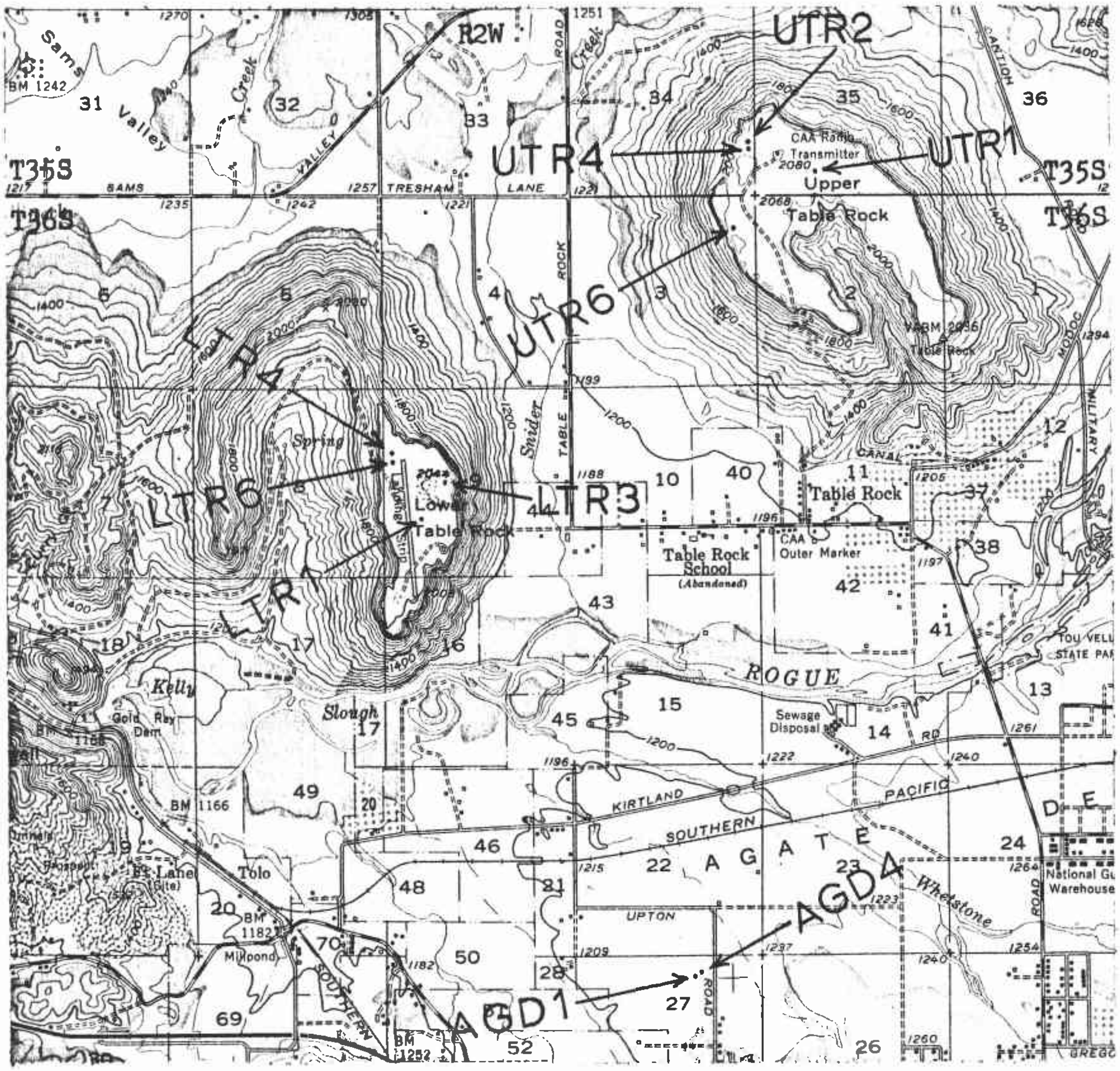

Figure 2. Map of sample sites on Upper and Lower Table Rocks and Agate Desert, Jackson County, Oregon.

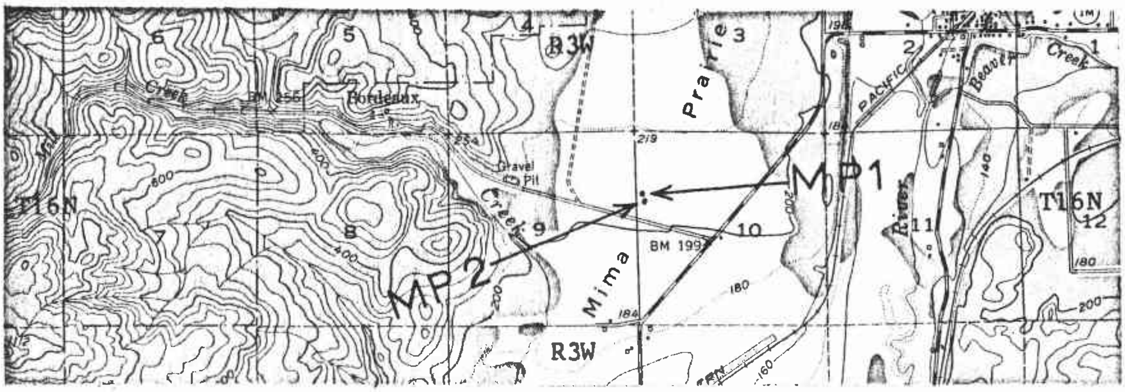

Figure 3. Map of sample sites on Mima Prairie, Puget Lowlands, Washington.

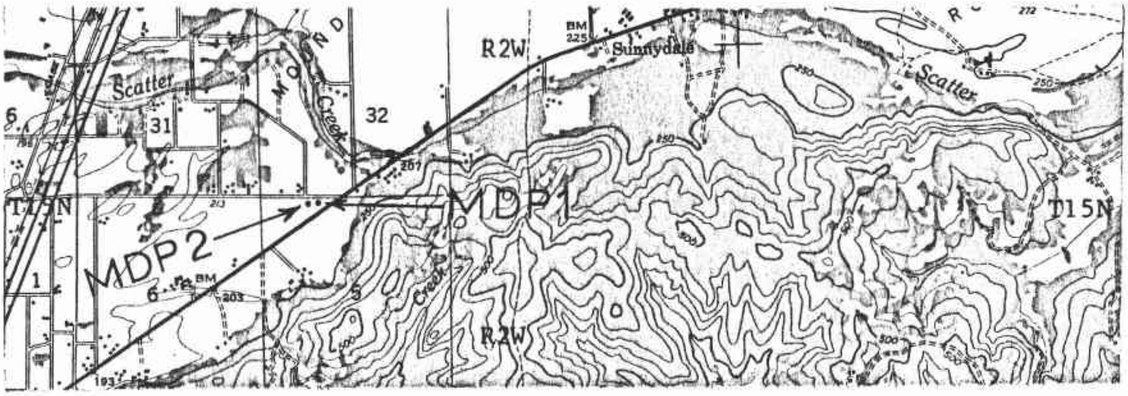

Figure 4. Map of sample sites on Mound Prairie, Puget Lowlands, Washington.

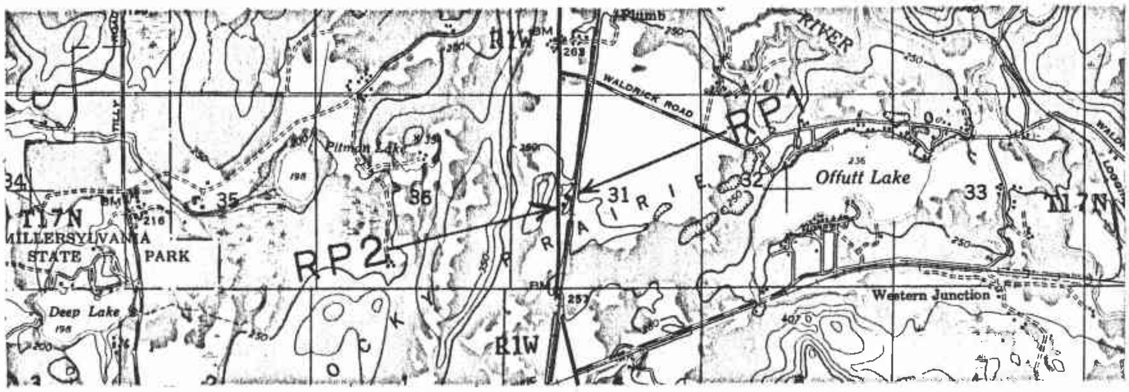

Figure 5. Map of sample sites on Rocky Prairie, Puget Lowlands, Washington.

range from 18 to 63 inches high. Thick mounds have steep side slopes and thin intermound soil profiles. Mounds occurring on Mima Prairie are examples of this type. Thin mounds have subdued relief with less sloping sides and relatively thick soil profiles in intermound areas. Mounds occurring on Mound Prairie are examples of this type. Some intermound areas contain rounded cobbles and stones. Intermound areas on Upper and Lower Table Rocks and in the Jenny Creek area contain angular stones and boulders of the same composition as the underlying basalt bedrock. These coarse fragments are commonly concentrated around the edge of the mound. In some cases, they overlie the toe of the mound. Malde (1964) referred to these as stone pavements and Washburn (1956) called them stone nets.

Mounds occurring on Mima Prairie, Rocky Prairie, and Mound Prairie consist of black, unstratified, gravelly loam high in organic matter. The outwash below these mounds consists of stratified dark yellowish brown, gravelly loamy sand almost free of organic matter. The contact between the mound and the underlying clean outwash is sharp. Mounds on Agate Desert rest abruptly on weakly cemented gravel. Mounds in the Jenny Creek area and on Upper and Lower Table Rocks rest abruptly on unweathered basalt bedrock.

Field Methods

Pairs of adjacent mounds were selected from Upper and Lower Table Rocks and Agate Desert. Two mounds selected in the Jenny Creek area were separated by about 400 feet. These mounds were chosen because they differed from each other in one or more morphological characteristics. Other mounds were selected from Lower Table Rock, Mima Prairie, Mound Prairie, and Rocky Prairie, the only restriction being that the adjacent intermound area contain a soil profile of sampling size. Pits were exposed in these mounds and adjacent intermound areas and the profiles were described in standard terminology of the U. S. Department of Agriculture (1951). Profile samples were collected, by horizon, from each pit. These samples were designated JC for Jenny Creek area, AGD for Agate Desert, LTR for Lower Table Rock, UTR for Upper Table Rock, MP for Mima Prairie, MDP for Mound Prairie, and RP for Rocky Prairie. Bedrock samples were collected from Upper and Lower Table Rocks for petrographic examination in thin section.

Laboratory Methods

Soil samples were air-dried, ground and passed through a 2 mm sieve. Gravel was saved and percent gravel was determined on a weight basis. pH determinations were made in the laboratory with a Beckman model N pH meter. Organic matter was determined by the Walkley-Black (1934) method. Particle size distribution was determined on LTR1, LTR2, UTR1, UTR3, UTR4, AGD1, AGD4, AGD5, MDP1, MDP2, MP1, MP2, RP1, and RP2 samples by the hydrometer method (Day, 1956) and sieving, using the USDA size classes. After completion of mechanical analyses, samples were wet-sieved and the 40 to 50 micron size fractions were saved from AGD1, AGD4, LTR1, LTR3, LTR4, LTR6, UTR1, UTR2, UTR4, and UTR6 profiles for grain analyses. Samples from JC1, JC2, and JC3 profiles were given the same treatment for organic matter removal, dispersion and segregation of the 40 to 50 micron size fraction. Subsamples were obtained by coning and quartering. Silt grains were mounted in Permount® on a petrographic slide and cured for 7 days at room temperature. This was followed by 7 days of curing in an oven at 75 degrees Celsius. Mineralogical data were obtained by a randomized count of 300 grains using a petrographic microscope. Thin sections were prepared in the standard manner (Brewer, 1964) except the cover glass was mounted with Permount®. Free iron was determined by using the method of the Soil Survey Laboratories of the U. S. Department of Agriculture except a 1.0 ml aliquot instead of a 0.1 ml aliquot was used to make the final 50 ml dilution.

Statistical Methods

The profile means of minerals were ranked and compared with the least significant difference at the 5 percent level as suggested in an oral communication from Dr. Roger G. Petersen, Professor of Statistics at Oregon State University.

RESULTS AND DISCUSSION

Refutation of Hypotheses

This section consists of the presentation and discussion of data in an attempt to refute four hypotheses on the origin of Mima Mounds. Each hypothesis will be considered separately. Some data and discussion will apply equally well to all four hypotheses. Consequently, the hypotheses will be considered in an order that will allow the most complete discussion of results with the first hypothesis. This is not intended in any way to imply importance or general acceptance of one hypothesis over another, but is done in an attempt to eliminate needless repetition in the discussion of results.

Periglacial Ice Wedge Hypothesis

If Mima mounds were formed in a thin continuous soil mantle by lateral thrusting of ice wedges, adjacent mounds, as well as other mounds on the same prairie, should be similar to each other. Figure 1 shows the location of JC1 and JC2 and Figure 2 shows the location of AGD1 and AGD4, LTR4 and LTR6, and UTR2 and UTR4. Soil profile descriptions and mineralogical data for these soil profiles are given in the appendix. Particle size distribution appears in Table 4. Evaluation of the mineralogical data appears in Tables 1, 2 and 3.

Table 1. Comparison of Ranked Means of Minerals From Profiles From Jenny Creek Mound Prairie (the vertical line connects profile means that are not significantly different)

	Iron Coated Feldspar	Total Feldspar	Biotite-Chlorite	Pyroxene	Amphibole	Quartz	Opaque Minerals	Glass
	JC3	JC1	JC3	JC2	JC3	JC1	JC2	JC1
	57.5	72.4	13.6	0.5	8.6	0.0	5.4	4.6
	JC2	JC2	JC2	JC1	JC1	JC2	JC3	JC2
	43.7	69.6	12.1	0.2	7.5	0.0	4.5	3.9
	JC1	JC3	JC1	JC3	JC2	JC3	JC1	JC3
	33.5	65.9	11.2	0.0	7.1	0.0	3.3	3.9
Least Significant Difference (5 percent)	2.5	3.0	2.1	0.4	1.4	0.0	1.9	1.8

Table 2. Comparison of Ranked Means of Minerals from Profiles on Agate Desert (the vertical line connects profile means that are not significantly different)

	Iron Coated Feldspar	Total Feldspar	Biotite-Chlorite	Pyroxene	Amphibole	Quartz	Opaque Minerals	Glass
	AGD4	AGD4	AGD4	AGD1	AGD1	AGD1	AGD4	AGD4
	58.9	77.8	3.1	0.6	8.1	7.8	1.6	2.3
	AGD1	AGD1	AGD1	AGD4	AGD4	AGD4	AGD1	AGD1
	46.7	76.7	2.3	0.6	7.4	3.6	0.7	0.8
Least Significant Difference (5 percent)	3.1	3.9	1.2	2.6	2.2	1.5	0.5	1.4

Table 3. Comparison of Ranked Means of Minerals for Profiles From Upper and Lower Table Rocks (the vertical line connects profile means that are not significantly different)

	Iron Coated Feldspar	Total Feldspar	Biotite-Chlorite	Pyroxene	Amphibole	Quartz	Opaque Minerals	Glass
	UTR1 52.9	LTR4 61.9	LTR3 18.0	LTR3 11.0	LTR6 17.1	UTR2 6.4	LTR1 5.8	UTR2 6.2
	LTR4 47.4	UTR1 61.3	UTR4 18.0	UTR6 5.3	UTR2 16.7	LTR1 5.8	LTR3 3.6	LTR3 4.2
	UTR6 45.1	UTR2 54.0	LTR1 16.7	LTR6 0.5	UTR4 15.8	UTR4 5.6	LTR6 3.6	UTR6 3.3
	LTR6 42.4	UTR6 53.6	UTR6 16.7	LTR1 0.3	LTR4 13.3	LTR4 1.8	UTR1 3.6	UTR4 3.0
	UTR4 37.3	LTR6 50.7	LTR6 14.9	LTR4 0.2	UTR1 12.4	UTR1 1.8	UTR4 2.9	LTR6 2.5
	LTR1 36.4	LTR1 50.2	UTR1 13.1	UTR1 0.2	LTR1 11.9	LTR6 1.4	LTR4 2.8	UTR1 2.5
	LTR3 34.6	UTR4 49.6	UTR2 13.0	UTR2 0.1	UTR6 9.5	UTR6 0.9	UTR6 2.4	LTR1 2.2
	UTR2 22.1	LTR3 49.4	LTR4 12.8	UTR4 0.1	LTR3 5.0	LTR3 0.1	UTR2 1.8	LTR4 2.1
Least Significant Difference (5 percent)	10.7	3.9	3.1	1.5	2.8	0.6	1.8	1.6

Comparison of soil profile descriptions shows that profiles from adjacent mounds have soil colors that differ by one hue. Petrographic examination shows that the 40 to 50 micron fractions of these profiles contain feldspar, biotite, chlorite, pyroxene, amphibole, quartz, opaque minerals, and glass. Many samples contain some zircon, garnet, sphene, and epidote in very small amounts. Samples from Jenny Creek contain small amounts of iddingsite. Two different kinds of feldspar are present in all samples. Some grains are glass-clear and unweathered. Others are weathered, eroded, and coated with free iron oxide. The proportion of these two types varies from one profile to another but is remarkably uniform between horizons within each profile. Profiles that have a high proportion of fresh feldspar are grayish and profiles that contain a high proportion of free iron oxide coated feldspar are reddish.

Table 1 shows that JC2 has 10.2 percent more feldspar coated with free iron oxide than JC1 and Table 2 shows that AGD4 has 12.2 percent more feldspar coated with free iron oxide than AGD1. Similarly, Table 3 shows differences between LTR6 and LTR4 and between UTR4 and UTR2 of 5.0 and 15.2 percent respectively. JC1-JC2, AGD1-AGD4, and UTR2-UTR4 test significantly different at the 5 percent level. LTR6 and LTR4 do not test significantly different at the 5 percent level.

According to Simonson (1959), "soil genesis can be viewed as consisting of two steps; viz, (a) the accumulation of parent material, and (b) the differentiation of horizons in the profile." Therefore, any difference in content of these two kinds of feldspars in adjacent profiles had to occur in one of these two steps. Either the soil profiles are derived from independent parent materials containing different amounts of these feldspars or these differences occur as the result of alteration.

Examination of the soil profile descriptions, in the appendix, shows that the profiles under consideration display very little horizonation. The profiles consist of a faint Al horizon and a relatively undifferentiated B horizon. Color values remain the same throughout the profiles and chromas increase with depth by one unit in 5 of the 16 profiles. The Al horizons were distinguished on the basis of structure and root content. Many separations within the B horizon were arbitrary separations for sampling purposes. All of the profiles lack clay films and grades of structure range from weak to moderate below the Al horizon. pH values change very little as a function of depth.

Table 4 shows that the particle size distribution is fairly uniform among horizons in each profile except for AGD1 and AGD4. The soil profile descriptions in the appendix show that these two profiles contain apparent discontinuities. Percent clay increases slightly with depth in AGD1 and AGD4 above these discontinuities and is nearly constant or decreases with depth in the remainder of the soil profiles. Eluviation of clay-sized particles to lower depths is suggested by progressive increases in ratios of clay to sand and clay to silt as a function of depth in AGD1 and AGD4 profiles. For example, the clay to sand ratio (Table 5) of AGD4 increases from 0.26 in the A1 horizon to 0.40 in the B21 horizon. Similarly, the clay to silt ratio increases from 0.36 in the A1 horizon to 0.56 in the B21 horizon. The sharp increase in very fine sand and corresponding decrease in coarse, medium, and fine sand in AGD1 suggests a profile discontinuity between the B1 horizon and the B21 horizon. Table 5 also shows that the clay to sand ratios for LTR1, UTR2, UTR4, MP1, MDP1, and RP1 profiles are almost constant or decrease slightly with depth. The corresponding clay to silt ratios either increase slightly or decrease slightly with depth. These ratios indicate that there might have been limited translocation of clay in AGD1 and AGD4 profiles but suggest that there has been no translocation of clay within the six remaining profiles.

Swenson and Riecken (1955) showed that the distribution of free iron oxide as a function of depth in weathered grassland soils is similar to that of clay. Free iron oxide usually increases with depth until a maximum is reached in the B2 horizon. Below the B2 horizon, there is a gradual decrease in free iron oxide with depth.

Free iron oxide content for several soil profiles appears in

Table 4. Particle Size Distribution (percent) of Mound Soil Profiles and Adjacent Intermound Soil Profiles.

				% less than 2 mm							
Profile	Depth (inches)	Horizon	Gravel (% of whole soil)	Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Silt	Clay	Textural class
UTR2 Mound	0-2	A1	1.7	0.4	0.5	0.9	3.1	6.2	64.8	24.2	silt loam
	5-12	B21	1.4	1.4	0.9	0.9	3.2	5.6	63.8	24.2	silt loam
	12-23	B22	2.4	1.1	1.0	1.2	3.4	6.1	61.3	26.0	silt loam
UTR3 Intermound	0-4	A1	0.3	0.2	0.6	0.8	3.5	5.7	58.3	30.8	silty clay loam
UTR4 Mound	0-7	A1	3.7	1.3	0.9	1.4	4.4	6.0	62.5	23.5	silt loam
	7-17	B21	1.4	1.5	0.9	0.7	2.4	5.9	66.9	21.8	silt loam
	17-24	B22	1.6	1.2	1.0	1.5	4.3	5.8	63.4	22.8	silt loam
AGD1 Mound	0-5	A1	26.0	5.6	9.7	8.5	9.9	7.2	47.3	11.8	loam
	5-12	B1	57.0	7.6	11.2	8.4	9.9	6.8	40.3	15.8	loam
	12-21	B21	13.4	7.2	3.2	1.5	6.9	13.3	47.8	20.1	loam
	21-23	IIB22	64.9	4.7	5.2	4.2	5.6	4.2	21.9	54.2	clay
AGD5 Intermound	0-5	A1	24.3	12.8	7.8	2.8	5.1	7.9	38.5	25.1	loam
	5-12	B21	4.8	1.8	7.4	9.6	9.6	6.5	29.1	36.0	clay loam
	12-17	B22	40.7	11.3	14.8	7.8	7.9	5.3	25.7	27.2	clay loam
AGD4 Mound	0-2	A1	26.5	10.8	15.0	8.4	9.1	6.7	36.8	13.1	sandy loam
	2-5	B1	20.8	7.8	11.2	8.8	9.6	7.1	39.7	15.8	loam
	5-12	B21	19.3	10.8	12.3	8.0	9.2	6.8	33.9	19.0	loam
	12-16	IIB22	40.9	12.5	9.2	5.4	6.0	4.5	20.1	42.3	clay
	16-23	IIB23	40.3	10.3	9.2	5.6	6.4	4.9	17.9	45.8	clay

Table 4. (continued)

				% less than 2 mm							
Profile	Depth (inches)	Horizon	Gravel (% of whole soil)	Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Silt	Clay	Textural class
LTR1	0-5	A1	4.3	2.3	4.5	2.9	4.7	6.6	55.0	23.9	silt loam
Mound	5-14	B21	8.4	6.9	5.2	1.2	2.3	5.6	56.8	21.9	silt loam
	14-24	B22	0.8	6.1	5.4	3.3	5.0	6.5	51.8	21.9	silt loam
	24-32	B23	9.9	6.2	6.0	2.6	4.4	6.2	51.6	23.0	silt loam
LTR2	0-2	A1	0.3	1.1	1.1	1.1	2.6	4.6	61.7	27.9	silty clay loam
Intermound	2-5	B2	1.3	3.1	3.1	2.3	4.7	6.3	53.6	27.0	silty clay loam
MP1	0-4	A11	59.8	12.9	11.8	9.0	7.8	3.0	47.6	7.9	loam
Mound	4-12	A12	66.4	11.6	12.6	9.7	8.1	2.7	48.5	6.8	loam
	12-24	A13	70.3	8.7	12.3	9.8	8.6	3.3	50.7	6.6	silt loam
	24-36	A14	60.7	8.5	13.0	10.0	8.7	3.2	50.1	6.5	silt loam
	36-50	A15	56.9	9.3	11.5	9.5	8.2	3.2	52.3	6.2	silt loam
	50-63	A16	56.5	8.7	11.2	9.6	8.5	3.3	53.7	5.0	silt loam
	63-70+	IIC	86.6	20.8	32.3	16.8	8.5	2.3	11.4	7.9	loamy sand
MP2 Intermound	0-5	A1	55.0	16.4	18.8	15.6	10.8	3.1	20.1	15.2	sandy loam

Table 4. (continued)

Profile	Depth (inches)	Horizon	Gravel (% of whole soil)	Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Silt	Clay	Textural class
				% less than 2 mm							
MDP1	0-6	A11	62.6	11.9	8.7	11.3	12.6	5.2	41.8	8.5	loam
Mound	6-12	A12	60.2	10.7	9.4	11.2	12.4	5.6	42.4	8.3	loam
	12-24	A13	59.3	9.5	8.3	11.8	13.6	5.7	44.2	6.9	loam
	24-36	A14	44.4	9.2	8.4	11.8	13.0	5.8	43.8	8.0	loam
	36-48+	IIC	75.3	15.5	12.7	19.1	17.7	5.6	23.5	5.8	sandy loam
MDP2	0-6	A11	52.7	11.5	9.3	11.1	12.4	6.8	39.9	9.0	sandy loam
Intermound	6-16	A12	43.6	11.2	9.8	11.7	13.4	5.9	42.7	5.3	sandy loam
	16-24	A13	56.0	8.8	10.3	13.4	15.4	6.1	42.2	3.9	sandy loam
	24-36+	IIC	72.4	33.4	11.8	12.4	14.8	5.0	15.0	7.7	loamy sand
RP1	0-6	A11	56.6	7.8	16.2	12.3	9.1	4.2	32.0	18.4	loam
Mound	6-12	A12	39.4	5.4	16.8	13.0	9.9	4.3	29.7	20.8	loam
	12-24	A13	23.1	6.3	19.0	13.7	10.4	4.5	27.3	18.8	sandy loam
	24-30	A14	43.9	6.1	18.6	13.2	10.2	4.6	29.1	18.3	sandy loam
	30-40	A15	60.2	7.0	20.0	14.6	11.8	4.7	28.2	13.8	sandy loam
	40+	IIC	57.1	7.8	16.1	21.9	32.8	8.3	5.6	7.6	loamy sand
RP2	0-5	A1	14.4	4.4	19.5	16.0	9.5	4.1	28.8	17.7	sandy loam
Intermound											

Table 5. Ratios of Clay to Sand and Clay to Silt for Selected Profiles.

Profile		Clay/Sand	Clay/Silt
LTR1	A1	1.13	0.38
	B21	1.03	0.37
	B22	0.83	0.51
	B23	0.90	0.49
UTR2	A1	2.20	0.37
	B21	2.01	0.38
	B22	2.05	0.42
UTR4	A1	1.68	0.38
	B21	1.92	0.33
	B22	1.65	0.35
AGD1	A1	0.29	0.25
	B1	0.36	0.39
	B21	0.63	0.42
AGD4	A1	0.26	0.36
	B1	0.36	0.40
	B21	0.40	0.56
MP1	A11	0.18	0.17
	A12	0.15	0.14
	A13	0.15	0.13
	A14	0.15	0.13
	A15	0.15	0.12
	A16	0.12	0.09
RP1	A11	0.37	0.57
	A12	0.42	0.70
	A13	0.35	0.69
	A14	0.35	0.62
	A15	0.23	0.49
MDP1	A11	0.17	0.20
	A12	0.17	0.20
	A13	0.14	0.16
	A14	0.17	0.18

Table 6.

Table 6. Free Iron Oxide Content (percent)

	Profile	Fe_2O_3
JC1	A1	1.79
	B21	1.79
	B22	1.71
	B23	1.71
JC2	A1	1.79
	B21	1.79
	B22	1.79
AGD1	A1	1.09
	B1	1.16
	B21	1.29
AGD4	A1	1.88
	B1	1.79
	B21	1.79
UTR2	A1	1.39
	B21	1.39
	B22	1.32
UTR4	A1	1.79
	B21	1.79
	B22	1.71

These data reveal a fairly uniform distribution of free iron oxide in all profiles except AGD1. Free iron increases from 1.09 percent in the A1 horizon to 1.29 percent in the B21 horizon. This can be accounted for in part by the apparent discontinuity between the B1 horizon and the B21 horizon, but some weathering and subsequent downward movement of iron may have taken place. The remainder of these data indicate that essentially no redistribution of free iron oxide has taken place during the soil forming process.

Similarly, the uniform content of amphibole, pyroxene, and biotite (Tables 1a, 2a, and 3a in the appendix) between horizons of the same profile indicate that little weathering has taken place. The presence of glass in all horizons, together with much feldspar and ferromagnesian minerals, indicates that the material is relatively fresh.

The soil morphology and particle size distribution show that these soil profiles lack distinct horizonation. The distribution of free iron oxide, iron oxide coated feldspar grains, and weatherable minerals within the profile suggests that little weathering and redistribution have taken place. This indicates that these are comparatively young soils. It follows, therefore, that the reddish color resulting from iron oxide coated grains of feldspar, has been derived from the parent material.

In addition to iron coated feldspar, UTR2 and UTR4 test significantly different for quartz and glass and AGD1 and AGD4 test significantly different for quartz, opaque minerals, and glass. LTR4 and LTR6 test significantly different only for total feldspar.

Table 3 shows further that all soil profiles on Upper and Lower Table Rocks test significantly different from each other for one or more minerals except UTR1 and LTR4. LTR1 and UTR4 test significantly different only for opaque minerals and are considered to be of the same mineral assemblage.

With this in mind, reference to Figures 1 and 2 and Tables 1, 2, and 3, shows the distribution of these mounds along with their corresponding mineral assemblages. It can be seen readily that some pairs of adjacent mounds have different mineral assemblages and some widely separated mounds have the same mineral assemblage. For example, in Table 3, UTR2 and UTR4 have different mineral assemblages and UTR1 and LTR4 have the same mineral assemblage. This type of random distribution of mounds with different mineral assemblages seems impossible to explain by lateral thrusting of soil by ice wedges and calls for the abandonment of this hypothesis.

Gopher Hypothesis

Dalquist and Scheffer (1942) maintained that Mima mounds were formed in a thin soil mantle by localized activity of gophers over long periods of time. Kelly (1948) has shown that gophers work the soil quite evenly and tend to move the soil in one direction as much as they move it in another. He stated gophers will not live in mound terrain if more suitable areas are available. Mounds provide foxes and coyotes with a distinct advantage in stalking gophers. Bretz (1913) maintained that burrowing animals could not produce mounds of such regular size and shape. Scheffer (1947) stated that pocket gophers piled up mounds containing pebbles "no larger than walnuts," yet many mounds contain coarse fragments up to several inches in size. Rodent activity also tends to mix soils in such a way that boundaries between layers within the soil mantle are gradual or diffuse. If gophers have formed the mounds in the Puget Lowlands of Washington by burrowing, they should have destroyed the abrupt contact that exists between the mounds and the underlying loose outwash gravel. This they have not done.

However, if gophers do build Mima mounds from a thin soil mantle, the particle size distribution of the soil in the mound should be the same as the unused soil remaining in the intermound area. Table 4 shows that the particle size distribution of every mound soil profile is different from the particle size distribution of its corresponding intermound soil profile. It is also apparent that the mound soil profiles contain considerably more gravel than do the intermound soil profiles. In most cases, this gravel is concentrated in the surface horizon. Table 4 shows that the intermound soil profiles on Agate Desert and Upper and Lower Table Rocks are finer textured than the soil profiles in adjacent mounds. This would suggest that the mounds are being eroded and the adjacent intermound areas are being filled. This is the normal process in nature.

When gophers build nesting chambers and construct tunnels in mounds, they pile up hills of loose soil material on the surface of the mound. Many nesting chambers cave in and much of the loose soil material is water sorted into the intermound area during the rainy season. As a result of this process, coarse fragments accumulate on the surface of the mound as lag and the finer soil material is concentrated in the intermound area. This process gradually lowers the surface of the mound and fills the adjacent intermound area. Contrary to what Dalquist and Scheffer (1942) suggested, the gophers appear to be destroying the mounds by accelerating erosion. Ellison (1946) has also shown from a study on mountain rangeland in Utah that gophers displace soil downhill and accelerate soil erosion.

Dalquist and Scheffer (1942) pointed out that there are no pocket gophers on Mima Prairie where Mima mounds are best developed. Comparison of these mounds with mounds on Mound Prairie, which supports gophers (Dalquist and Scheffer, 1942), reveals two interesting facts. The soil profile description of MP1 shows that this mound consists of 63 inches of black soil material over unconformable glacial outwash. The corresponding intermound soil profile is 5 inches deep to the same glacial outwash. In contrast, mounds on Mound Prairie appear much smaller and subdued. The profile description of MDP1 shows that this mound consists of 48 inches of black soil material over unconformable glacial outwash. The corresponding intermound soil profile is 36 inches deep to glacial outwash. Consequently, mounds on Mound Prairie appear to be only 1 to $1\frac{1}{2}$ feet high but are in reality mounds about 4 feet high with thick intermound soils. Apparently these mounds have undergone considerable erosion to form subdued mound relief with thick intermound soil profiles. This process has been accelerated on Mound Prairie where pocket gophers live in contrast to Mima Prairie where none exist.

Intermound soil profiles on Mima Prairie, Mound Prairie, and Rocky Prairie are slightly coarser textured than soil profiles in adjacent mounds. This may seem inconsistent with the argument already presented, but two explanations are possible. Table 7 contains organic matter contents of soil profiles on Mima Prairie, Mound Prairie, and Rocky Prairie. Values for these soil profiles are extremely high. For example, the organic matter content of the A11 horizon of MP1 is 32.7 percent. Kemper (1966) has shown that organic matter in excess of 2 percent adds little to aggregate stability but Baver (1935) noted that the effects of organic matter were more pronounced in soils containing small amounts of clay. Aggregates of silt and clay in these profiles could be stable enough to behave like particles of very coarse sand with respect to erosion. Further support for this argument is given by the fact that the major increase in sand in these intermound soil profiles occurs in the coarse, medium, fine, and very fine sand fractions. A second possibility may be that silt and clay particles carried into the inter-mound area by rain water are removed vertically from the profile as the water percolates through the very permeable glacial outwash.

Table 7. Organic Matter Content

	Profile	Percent
MP1	A11	32.7
	A12	24.9
	A13	21.8
	A14	18.5
	A15	15.8
	A16	11.9
	IIC	3.2
MP2	A1	31.8
MDP1	A11	27.7
	A12	25.2
	A13	21.8
	A14	23.1
	IIC	4.2
MDP2	A11	26.3
	A12	21.4
	A13	14.1
	IIC	5.1
RP1	A11	25.3
	A12	22.0
	A13	21.0
	A14	19.6
	A15	13.1
	IIC	0.8
RP2	A1	26.7

From the data presented, it is apparent that gravel fragments are concentrated on the surface of mounds. Also, the particle size distribution is different between mound soil profiles and adjacent intermound soil profiles. These two facts definitely weaken the idea of Dalquist and Scheffer (1942) about mound formation. Consider with this, the evidence already advanced regarding the random distribution of mounds with different mineral assemblages, and this hypothesis becomes unacceptable.

Erosional Hypothesis

Ritchie (1953) suggested that Mima mounds were formed by water flowing across partially thawed, polygonally fissured ice fields. Fast moving water scoured the intermound area deeply to form high mounds like those on Mima Prairie. Slower moving water removed less thawed soil material from intermound areas to form shallow mounds like those on Mound Prairie.

If mounds originated from water erosion of a soil mantle containing as much gravel as mounds in Thurston County, it is logical to expect concentration of gravel fragments in the intermound area as a result of this process. Erosion of 6 feet of soil of the same composition as that in MP1 mound should concentrate 2 to 3 feet of gravel in the resulting intermound areas as lag. Examination of Table 4 shows that gravel has been concentrated in the mound rather than in the intermound area. This is true for all mound and intermound soil profiles. For example, the A11 horizon of MDP1 contains 62.6 percent gravel and the A11 horizon of MDP2 contains 52.7 percent gravel. Similarly, the A1 horizon of LTR1 contains 4.3 percent gravel and the A1 horizon of LTR2 contains 0.3 percent gravel.

In some areas, cobbles are concentrated between mounds. In other areas, intermound soils are free of cobbles. Figures 6 and 7 show the concentration of cobble fragments around the edge of mounds on Upper Table Rock and Agate Desert respectively. Patterson (1940) has shown that as soil freezes, ice develops vertical structure under coarse fragments and is interstitial around fines. Consequently, coarse fragments are thrust upward in the soil. As the ground ice thaws from the top down, the ice containing fines, that is not insulated by an overlying coarse fragment, melts first. The fines slump down and replace the ice as it slowly melts from under the coarse fragments. In this manner, coarse fragments are gradually moved upward in the soil by frost action. This process would remove most of the cobble fragments from the mounds and gravity would concentrate them in their present location in the intermound area. It follows, therefore, that intermound areas containing cobbles occur adjacent to mounds that originally contained cobbles and cobble-free intermound areas occur adjacent to mounds that were cobble free.

Ritchie (1953) went on to say that "mounds in any one area have

Figure 6. Cobble distribution showing concentration around the edge of a mound on Upper Table Rock.

Figure 7. Cobble distribution showing concentration around the edge of two joining mounds on Agate Desert.

a uniform maximum height, indicating that they were carved from a common mantle locally of a uniform thickness." Contrary to this statement, mounds in the same area are not of uniform height. Mima Prairie and Rocky Prairie both contain areas of low mounds in association with high mounds. This is also characteristic of mound prairies in Jackson County.

This hypothesis fails to explain how a 5 to 8 foot thick soil mantle containing over 50 percent gravel can be washed away by water erosion and leave the resulting area almost stripped of gravel. It fails also to explain how mounds can have such remarkable regularity of shape. Similarly, it does not explain the random distribution of mounds of different mineral assemblages, and further evaluation of this hypothesis is not needed.

Loess Hypothesis

Those who support the loess hypothesis maintain that mounds were formed as the result of accumulation of soil material around clumps of vegetation (Shaw, 1927), (Freeman 1926, 1932). Mounds of this type are common in desert areas. However, these mounds are oriented in the direction of the prevailing wind, and they lack the hemispheroidal shape of Mima mounds.

Mounds studied in Jackson County, Oregon and Thurston County, Washington have no particular orientation. Their shapes are remarkably circular when viewed from above. The soil material in these mounds gives no morphological evidence of wind assortment. Table 4 shows that all mounds contain coarse fragments of such a magnitude that wind movement must be ruled out. This hypothesis also fails to account for the random distribution of mounds of different mineral assemblages. These facts make it impossible to link Mima mound formation to wind movement and accumulation of soil material.

Conditions of an Acceptable Hypothesis

Any working hypothesis that successfully explains the origin of Mima mounds in Thurston County, Washington and Jackson County, Oregon should recognize the following facts:

1. Mima mounds have no regularity of spacing or arrangement.
2. There is, without exception, a sharp contact between the mound and the underlying substratum. Figure 8 shows the contact between a mound on Mima Prairie and the underlying stratified outwash.
3. The mounds have a remarkable regularity of shape. Almost without exception, they consist of oblate hemispheroids convex upward.
4. Mima mounds have a random distribution such that adjacent

Figure 8. View of mound on Mima Prairie showing the abrupt contact between the mound and the underlying stratified outwash.

mounds can have different mineral assemblages and soil colors.

5. In the same general area, mounds commonly occur on adjacent surfaces of different elevations. Agate Desert and Upper Table Rock differ in elevation by eight hundred feet.
6. Mima mounds are constructional forms. Their regularity of shape cannot be explained successfully by erosion. Surfaces on which mounds occur are slightly higher than the surrounding drainageways. These surfaces are not subject to erosion or deposition from present stream overflow.
7. Cobble distribution is independent of mound formation. Bretz (1913) stated, "The Walricks Prairie sections show beyond any doubt that a portion of this prairie surface was uniformly cobble strewn, and that subsequent to this, the Mima type mounds were constructed on this floor, burying the cobbles beneath them, and leaving the portions in the intermound areas still cobble strewn."

Depositional Origin - A New Theory

Bretz (1913) discussed several limitations of a successful hypothesis on mound formation and stated,

> Agencies which might have operated under the limitations above enumerated are practically limited to ice and water, either of which may have been

> standing, or moving, or both. The time of operation was during Vashon glacial retreat and deposition of the outwash. Current bedding and delta bedding in the Mima gravel pit show that water operated in both ways during the aggradation of the gravel plain. If ice was present, it obviously was in fragmentary masses from the adjacent glacier, or had formed on the surface of standing water beyond the ice. If it operated in dynamic phase in construction of the mounds, its motion must have come from the energy of flowing water, or from expansion due to freezing, since no glacial ice thrust could have occurred in many mound localities, nor in most of them where adjacent to the moraine, without having left some indisputable record of its occurrence.
>
> It may be suggested tentatively that if a sheet of ice several feet thick could be formed over the surface of an outwash gravel plain and could subsequently be flooded so that stream-carried debris would be deposited on its surface, it might, on melting, develop pits into which the surficial debris would gravitate. Since water is densest at 39°F., the lower interstices of the gravel in the pits of the postulated sheet of ice would become filled with water at this temperature. Since such water would be 7° warmer than the adjacent ice, it would cause deepening and enlarging of the pits after the earthy accumulation had become so thick that warming of the gravel by the sun ceased to be a direct factor in formation of the pits. Sliding and washing of the surface debris into these pits would expose interpit areas, and the melting of such areas would then proceed more slowly than when rock fragments strewed it, and absorbed the sun's heat.
>
> Some such set of conditions might give rise, on final melting of the ice, to mounds; these being without structure, without assortment, and superposed on current-bedded gravels as are the Mima type mounds.

He went on to say,

> We might conceive of an outwash plain becoming flooded with water and a sheet of ice forming over the whole through some exceptional and local combination of conditions, but it is almost

> impossible to postulate the repetition of such an occurrence on every mound-bearing surface, especially slopes.

Ritchie (1953) suggested that during the winter in the Puget Lowlands, a sheet of ice froze on the surface of a floodplain. Spring floodwaters floated the ice and attached soil material into impounded water where the soil was deposited on the mound prairies. These two ideas suggest an interesting possibility.

Suppose, as Bretz (1913) has suggested, that the land surface was inundated by water impounded behind an ice dam. Vashon glacier served to impound water in the Puget Lowlands. Similarly, an ice or earth dam on the Rogue River between Gold Ray Dam and Grants Pass could have impounded water over the surfaces of Upper and Lower Table Rocks and Agate Desert. An ice sheet several feet thick formed over the surface of the water. This was subsequently covered with stream-carried material. The distribution pattern would be related to the streams depositing the soil material on the surface of the ice. Consequently, streams heading in volcanic uplands would deposit different soil material than streams heading in metamorphic uplands. In this manner, a soil mantle several feet thick would be deposited on the surface of the ice. The mineral composition would vary correspondingly. Thickness of the deposit would generally decrease in the direction of stream flow. Some areas of the ice, especially toward the center and down-stream portions, would be free of soil material. This would provide a natural drainageway for the streams. Excess water would gradually be drained off and carried away downstream. In this manner, a soil mantle several feet thick would be gradually built up on the surface of the ice.

Weeks and Lee (1962) have described the formation of "pancake ice" in North Star Bay, Thule, Greenland. As a result of offshore winds, the ice sheet in the bay is broken into polygonal pieces of ice. After the winds subside, thin sheet ice forms between the polygonal pieces, cementing them together into "floe or pan-agglomerate". This they called pancake ice.

This same process, applied to an ice sheet with a thin soil mantle on its surface, would produce polygonal icebergs covered with soil material. Wind and water currents would tend to move these icebergs around over the surface of the water and mix them. Some icebergs would tend to melt faster than others. Those that melted the fastest would sink slowly to the bottom of the lake where the soil would slump into mounds.

Many icebergs would continue to float on the surface of the water. Some of these icebergs would capsize and lose their soil load, but many would remain upright. As the water receded, these icebergs would come to rest on the bottom of the lake. The ice would melt and the soil material would settle to the ground to form mounds. Superficial erosion would develop the present shape of the mounds and help to partially fill the intermound areas. Mounds that were deposited on elevated outwash plains, high terraces, and mesas would be preserved. Those that were deposited on floodplains would either be destroyed by erosion or be drowned by recent alluvium.

Evidence in Support of this Hypothesis

The depositional hypothesis satisfies all of the conditions of an acceptable hypothesis. It is unique in explaining the sharp contact between the mound and the underlying substratum, the regularity of mound shape, the random distribution of mounds, and the occurrence of mounds on surfaces of different elevations.

Upper and Lower Table Rocks are capped with a basalt flow about 125 feet thick. Petrographic examination of thin sections shows that this basalt consists of phenocrysts of plagioclase, augite, and iron ore in a second generation ground mass of the same minerals and glass. In addition to these minerals, mounds occurring on Upper and Lower Table Rocks contain quartz, biotite, chlorite, amphibole, and hypersthene. This clearly demonstrates that the mounds consist of transported material. Gravel content rules out the possibility of loess. Alluvial deposition of material on top of either Upper or Lower Table Rock would not have been possible during Late Pleistocene because these surfaces rise 800 feet above the surface of Agate Desert. However, ice-rafted mounds could easily have been deposited on Upper and Lower Table Rocks and Agate Desert as the water receded. This would have been possible even though these adjacent surfaces differ in elevation by 800 feet.

Regularity of shape is also consistent with the idea of ice-rafted mounds. Polygonal icebergs are formed when an ice sheet breaks up. Consequently, the resulting mounds will have the same polygonal shape. On flat land, mounds are almost circular in outline. On slopes, the soil material will tend to slump down hill giving the mound an elongation in the direction of the slope.

The sharp contact between the mound and the substratum is a prominent feature of all mounds. Apparently no mixing of these two materials took place during mound formation. This would be true of ice-rafted mounds because the soil mound was separated from the substratum by the iceberg that rafted it into position. As the ice melted, the water seeped slowly away and the soil material gradually settled onto the present substratum forming a sharp contact. Differential melting of the ice and settling of the soil into the mound would destroy all bedding and render the mound without geologic structure.

The random distribution of mounds seems almost impossible to explain unless ice rafting is accepted. Wind and water action would tend to mix the icebergs and ultimately result in a random distribution of icebergs on the surface of the water. As the water receded, the icebergs would come to rest on the ground surface producing a random distribution of mounds.

According to Bretz (1913), Newcomb (1940, 1952), Malde (1964), and Kaatz (1959), mound formation took place during the Pleistocene Epoch. The soil morphology and particle size distribution show that the mound soils studied lack distinct horizons. The clay to sand and clay to silt ratios indicate that there has been very little translocation of clay. The presence of fresh feldspar, ferromagnesian minerals, and glass in all horizons suggests that little weathering has taken place. These facts indicate that mound formation is more recent than the Pleistocene Epoch.

The depositional hypothesis suggests that much water was impounded at the time of mound formation. Further field studies could be done to determine if shoreline features such as beach deposits, strand lines, and terraces occur in association with areas of Mima mounds.

CONCLUSIONS

The results of this investigation show that the periglacial ice wedge hypothesis, the gopher hypothesis, the erosional hypothesis, and the loess hypothesis do not satisfactorily explain the origin of Mima mounds in Jackson County, Oregon and Thurston County, Washington. Because these hypotheses are inadequate, a depositional hypothesis is suggested that satisfies the conditions of a successful hypothesis. The depositional hypothesis is unique in explaining the regularity of mound shape, the random distribution of mounds with different mineral assemblages, the occurrence of mounds on surfaces of different elevations, and the abrupt contact between the mounds and the underlying substrata.

Even though the depositional hypothesis suggested in this study satisfactorily explains the origin of Mima mounds in Jackson County, Oregon and Thurston County, Washington, it may not necessarily explain the origin of Mima mounds in general. However, when investigation shows that Mima mounds in other areas have the same characteristics as those in this study, the depositional hypothesis might apply equally well in explaining their origin.

BIBLIOGRAPHY

Arkley, Rodney. 1948. Comments and criticisms. The Mima mounds. Scientific Monthly 66: 175-176.

Arkley, Rodney and Herrick G. Brown. 1954. The origin of Mima mound (Hogwallow) microrelief in the far western states. Soil Science Society of America Proceedings 18: 195-199.

Barnes, G. W. 1879. The hillocks or mound formations of San Diego, California. American Naturalist 18: 565-571.

Baver, L. D. 1935. Factors contributing to the genesis of soil microstructure. American Soil Survey Association Bulletin 16: 55-56.

Branner, J. C. 1905. Natural mounds or hog "wallows". Science 21: 514-516.

Bretz, J. Harlen. 1913. The mounds of the Vashon outwash. In: Glaciation of the Puget Sound region, by J. Harlen Bretz. Washington Geological Survey Bulletin 8: 81-108.

Brewer, Roy. 1964. Fabric and mineral analysis of soils. London, John Wiley and Sons, Incorporated. 470p.

Campbell, Marius R. 1906. Natural mounds. Journal of Geology 14: 708-717.

Dalquist, Walter W. and Victor B. Scheffer. 1942. The origin of the Mima mounds of western Washington. Journal of Geology 50: 68-84.

Day, P. R. 1956. Report of the committee on physical analysis. Soil Science Society of America Proceedings 20: 167-169.

Dietz, Robert S. 1945. The small mounds of the gulf coastal plain. Science 102: 596-597.

Eakin, H. M. 1932. Periglacial phenomena in the Puget Sound region. Science 75: 536.

Ellison, Lincoln. 1946. The pocket gopher in relation to soil erosion on the mountain range. Ecology 27: 101-114.

Fosberg, Maynard A. 1965. Characteristics and genesis of patterned ground in Wisconsin time in a chestnut soil zone of southern Idaho. Soil Science 99: 31-37.

Freeman, O. W. 1926. Scabland mounds of eastern Washington. Science 64: 450-451.

________________. 1932. Origin and economic value of the Scabland mounds of eastern Washington. Northwest Science 6(2): 37-40.

Gibbs, George, 1855. Geology of the central portion of Washington Territory. In: Reports of explorations and surveys to ascertain the most practicable and economical route for a railroad from the Mississippi River to the Pacific Ocean Vol. 1, p. 473-486. (U. S. House of Representatives. 33d Congress, 2d Session. Executive Document no. 91)

Grant, Chapman. 1948. Mima mounds. Journal of Geology 56: 229-231.

Hilgard, E. W. 1884. Report on the physical and agricultural features of the state of California. In: Tenth Census of the United States, Vol. 6, p. 649-783.

________________. 1905. The prairie mounds of Louisiana. Science 21: 551-552.

Hill, Robert T. 1906. On the origin of the small mounds of the lower Mississippi Valley and Texas. Science 23: 704-706.

Holdredge, C. P. and H. B. Woods. 1947. Mound and depression topography of the Central Valley of California and other areas. (Abstract) Geological Society of America Bulletin 58: 1253-1254.

Kaatz, Martin R. 1959. Patterned ground in central Washington. A preliminary report. Northwest Science 33: 145-156.

Kelly, Allen D. 1948. Comments and criticisms. The Mima mounds. Scientific Monthly 66: 174-175.

Kemper, W. D. 1966. Aggregate stability of soils from western United States and Canada. Washington, D. C. 52p. (U. S. Dept. of Agriculture. Technical Bulletin 1355)

Knechtel, M. M. 1952. Pimple plains of eastern Oklahoma. Geological Society of America Bulletin 63(3): 689-699.

Koons, Frederick C. 1948. The sand mounds of Louisiana and Texas. Scientific Monthly 66: 297-300.

Krinitzsky, E. L. 1949. Origin of pimple mounds. American Journal of Science 247: 706-714.

Larrison, R. J. 1942. Pocket gophers and ecological succession in the Wenas region of Washington. The Murrelet 23: 34-41.

Le Conte, J. 1877. Hog wallow or prairie mounds. Nature 16: 530.

Malde, Harold E. 1964. Patterned ground in the western Snake River Plain, Idaho, and its possible cold-climate origin. Geological Society of America Bulletin 75(1): 191-207.

Masson, Peter H. 1949. Circular soil structures in northeastern California. California, Department of Natural Resources, Division of Mines Bulletin 151: 61-78.

Melton, Frank A. 1935. Vegetation and soil mounds. Geographical Review 25: 430-433.

Neilson, James M. 1960. Geomorphology and glacial geology of southwestern Baffin Island, District of Franklin, Northwest Territories, Canada. In: International Geological Congress Report of the Twenty-First Session, Coppenhagen, 1960. Vol. 4, Pt. 21. Copenhagen, Det Beringske Bogtrykkeri. p. 90-104.

Newcomb, R. C. 1940. Hypothesis for the periglacial "fissure polygon" origin of Tenino Mounds, Thurston County, Washington. Geological News-Letter Geological Society of the Oregon Country 6: 182.

_______________. 1952. Origin of the Mima mounds, Thurston County Region, Washington. Journal of Geology 60: 461-472.

Olmsted, Robert K. 1963. Silt mounds of Missoula flood surfaces. Geological Society of America Bulletin 74(1): 47-54.

Patterson, T. T. 1940. The effects of frost action and solifluxion around Baffin Bay and in the Cambridge District. Geological

Society of London Quarterly Journal 96: 99-130.

Pewe, Troy L. 1948. Origin of the Mima mounds. Scientific Monthly 66: 293-296.

Piper, C. V. 1905. The basalt mounds of the Columbia lava. Science 21: 824-825.

Price, W. Armstrong. 1949. Pocket gophers as architects of Mima (pimple) mounds of the western United States. Texas Journal of Science 1(1): 1-16.

________________. 1950. Origin of pimple mounds. American Journal of Science 248: 355-360.

Purdue, A. H. 1905. Concerning the natural mounds. Science 21: 823-824.

Retzer, John L. 1945. Morphology and origin of some California mounds. Soil Science Society of America Proceedings 10: 360-367.

Ritchie, Arthur M. 1953. The erosional origin of the Mima mounds of southwestern Washington. Journal of Geology 61: 41-50.

Rogers, G. O. 1893. Drift mounds near Olympia, Washington. American Geologist 11-12: 393-399.

Scheffer, Victor B. 1947. The mystery of the Mima mounds. Scientific Monthly 65: 283-294.

________________. 1948. Mima mounds: a reply. Journal of Geology 56: 231-234.

________________. 1958. Do fossorial rodents originate Mima-type microrelief? American Midland Naturalist 59: 503-510.

Shaw, C. F. 1927. Profile development and the relationship of soils in California. In: First International Congress of Soil Science Proceedings and Papers, Washington, D. C. Vol. 4 p. 291-317.

Simonson, Roy W. 1959. Outline of a generalized theory of soil genesis. Soil Science Society of America Proceedings 23: 152-156.

Stallings, H. L. 1948. The Mima mounds. Scientific Monthly 66: 269-270.

Swenson, Richard M. and F. F. Riecken. 1955. Movement of iron in the development of loess-derived Brunizen soils. Soil Science 79:177-186.

U. S. Department of Agriculture. Soil Survey Staff. 1951. Soil Survey manual. Washington. 503p. (Handbook no. 18, and supplement replacing p. 173-188, 1962)

Upham, Warren. 1904. Glacial and modified drift in and near Seattle, Tacoma and Olympia. American Geologist 34:203-214.

Walkley, A. and I. A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science 37:29-38.

Wallace, A. R. 1877. Glacial drift in California. Nature 15:274.

Washburn, A. L. 1956. Classification of patterned ground and review of suggested origins. Geological Society of America Bulletin 67:823-866.

Waters, Aaron Clement and Charles W. Flagler. 1929. Origin of the small mounds of the Columbia River Plateau. American Journal of Science, ser. 5, 18:309-224.

Weeks, W. F. and O. S. Lee. 1962. The salinity distribution in young sea-ice. Arctic 15(2):93-108.

Whitney, Dudly. 1948. San Jouquin Valley hog wallows. Scientific Monthly 66:356-357.

Wilkes, Charles. 1845. Puget Sound and Okanagan. In: Narrative of the United States explbring expedition during the years 1838, 1839, 1840, 1841, 1842. Vol. 4. Philadelphia, Lea & Blanchard. p. 409-440.

APPENDIX

Table 1a. Mineral Composition of Soil Profiles From Mounds on Jenny Creek Mound Prairie (percent)

Profile		Iron Coated Feldspar	Total Feldspar	Biotite-Chlorite	Pyroxene	Amphibole	Quartz	Opaque Minerals	Glass	Unknown Iron Coated	Other
JC1	A1	32.0	69.7	12.7	0.3	7.0	0.0	3.7	6.0	0.3	0.3
	B21	33.7	74.0	10.7	0.3	6.7	0.0	3.3	4.3	0.7	0.0
	B22	35.7	73.7	11.7	0.0	8.0	0.0	1.7	4.0	0.7	0.3
	B23	32.7	72.3	9.7	0.0	8.3	0.0	4.3	4.0	1.0	0.3
JC2	A1	43.7	69.7	12.0	0.0	8.0	0.0	5.0	3.0	1.0	1.3
	B21	44.7	69.3	12.3	0.7	7.0	0.0	7.0	3.0	0.7	0.0
	B22	42.7	69.7	12.0	0.7	6.3	0.0	4.3	5.7	1.3	0.0
JC3	A1	56.0	63.0	15.7	0.0	9.7	0.0	5.0	3.0	0.7	3.0
	B21	59.7	68.0	12.7	0.0	8.3	0.0	3.7	4.0	1.0	2.3
	B22	56.7	66.7	12.3	0.0	7.7	0.0	5.7	4.7	0.3	2.7

Table 2a. Mineral Composition of Soil Profiles From Mounds on Agate Desert (percent)

Profile		Iron Coated Feldspar	Total Feldspar	Biotite-Chlorite	Pyroxene	Amphibole	Quartz	Opaque Minerals	Glass	Unknown Iron Coated	Other
AGD1	A1	46.7	75.0	2.0	1.0	9.0	8.7	0.3	0.3	2.0	1.7
	B1	45.7	74.7	3.0	0.0	9.3	7.7	1.0	2.0	1.3	1.0
	B21	47.7	80.3	2.0	0.7	6.0	7.0	0.7	0.0	2.3	1.0
	IIB22	35.3	64.0	17.3	0.0	6.7	4.3	1.0	2.7	3.7	0.3
AGD4	A1	61.7	79.3	2.3	0.7	7.7	2.7	1.7	2.0	3.3	0.3
	B1	56.7	76.7	4.0	0.0	7.7	3.3	1.7	3.0	2.7	1.0
	B21	58.3	77.3	3.0	1.0	6.7	4.7	1.3	2.0	2.3	1.7
	IIB22	42.3	63.3	10.0	1.0	7.3	1.7	2.0	10.3	4.0	0.3
	IIB23	42.7	67.0	9.7	1.0	6.3	1.3	3.0	8.7	3.0	0.0

Table 3a. Mineral Composition of Soil Profiles From Mounds on Upper and Lower Table Rocks (percent)

Profile		Iron Coated Feldspar	Total Feldspar	Biotite-Chlorite	Pyroxene	Amphibole	Quartz	Opaque Minerals	Glass	Unknown Iron Coated	Other
LTR1	A1	35.0	46.7	15.3	0.7	11.7	5.7	9.0	3.3	6.3	1.3
	B21	39.3	54.7	16.0	0.0	8.0	6.0	5.7	1.0	7.7	1.0
	B22	34.7	49.0	15.3	0.0	15.7	6.3	4.3	2.7	5.7	1.0
	B23	36.7	50.7	20.3	0.3	12.3	5.0	4.0	1.7	5.3	0.3
LTR3	A1	30.7	44.3	21.3	13.7	6.0	0.0	2.3	4.3	7.0	1.0
	B21	39.7	54.0	16.1	8.3	3.7	0.3	3.7	4.0	8.7	1.3
	B22	33.3	50.0	16.7	11.0	5.3	0.0	4.7	4.3	6.7	1.0
LTR4	A11	48.7	64.3	12.7	0.7	12.0	2.0	3.0	2.0	3.3	0.0
	A12	45.7	59.3	13.3	0.0	13.7	2.0	4.0	2.0	4.0	1.7
	B21	45.7	61.0	15.0	0.0	14.7	1.3	0.7	2.3	3.7	1.3
	B22	49.3	63.0	10.0	0.0	13.0	1.7	3.3	2.0	6.0	1.0
LTR6	A1	41.3	50.3	14.0	0.3	19.0	1.7	2.3	3.0	7.0	2.3
	B21	42.3	49.7	16.0	0.3	16.3	1.3	4.7	1.7	8.0	2.0
	B22	43.7	52.0	14.7	1.0	16.0	1.3	3.7	2.7	7.7	1.0
UTR1	A1	54.7	62.0	11.0	0.0	11.7	1.7	4.7	3.3	5.3	0.3
	B21	50.7	59.7	14.3	0.7	12.7	1.7	2.7	3.3	4.0	1.0
	B22	53.3	62.3	14.0	0.0	12.7	2.0	3.3	1.0	3.3	1.3
UTR2	A1	21.3	55.0	12.0	0.0	18.7	6.7	2.0	5.0	0.3	0.3
	B21	22.3	54.0	13.3	0.0	17.0	6.7	1.7	5.3	1.3	0.7
	B22	22.7	53.7	13.7	0.3	14.3	5.7	1.7	8.3	1.3	1.0
UTR4	A1	38.0	50.0	17.3	0.0	16.3	5.7	4.3	2.0	4.0	0.3
	B21	37.7	50.0	17.0	0.3	15.0	5.7	2.7	4.0	4.3	1.0
	B22	36.3	48.7	19.7	0.0	16.0	5.3	1.7	3.0	4.7	1.0

Table 3a. (continued)

Profile		Iron Coated Feldspar	Total Feldspar	Biotite-Chlorite	Pyroxene	Amphibole	Quartz	Opaque Minerals	Glass	Unknown Iron Coated	Other
UTR6	A1	45.7	53.3	17.3	5.3	8.7	1.3	2.7	3.3	7.3	0.7
	B21	45.0	52.7	17.7	5.3	10.0	0.7	1.7	2.7	8.7	0.7
	B22	44.7	54.7	15.0	5.3	9.7	0.7	2.7	4.0	7.3	0.7

SOIL PROFILE DESCRIPTIONS

Soil Profile		JC1 mound soil
A1	0-6"	Dark brown (10YR 3/3) loam, brown (10YR 5/3) dry; weak very coarse platy breaking into moderate very fine subangular blocky structure; slightly hard, friable, non-sticky and non-plastic; common roots; (pH 6.4); clear smooth boundary.
B21	6-15"	Dark brown (10YR 3/3) loam, brown (10YR 5/3) dry; weak medium and fine subangular blocky structure; slightly hard, friable, non-sticky, non-plastic; common roots; common fine tubular pores; (pH 6.3); gradual wavy boundary.
B22	15-26"	Dark brown (10YR 3/3) loam, brown (10YR 5/3) dry; weak medium and fine subangular blocky structure; slightly hard, friable, non-sticky, non-plastic; common roots; many fine and medium tubular pores; (pH 6.4); gradual wavy boundary.
B23	26-36"	Dark brown (10YR 3/3) loam, brown (10YR 5/3) dry; moderate medium subangular blocky structure; many clean sand grains on ped surfaces; slightly hard, friable, slightly sticky, slightly plastic; common roots; many fine and medium tubular pores; (pH 6.4); abrupt wavy boundary.
IIR	36"+	Unweathered basalt bedrock.

Soil Profile		JC2 mound soil
A1	0-3"	Dark brown (7.5YR 3/3) loam, brown (10YR 5/3) dry; weak medium and coarse platy structure, the upper 1 1/2 inches is a vesicular crust; slightly hard, friable, non-sticky, non-plastic; common roots; 5% fine gravel fragments; (pH 6.2); clear smooth boundary.
B21	3-9"	Dark brown (7.5YR 3/3) loam, brown (7.5YR 5/3) dry; weak medium subangular blocky breaking into weak very fine subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; common roots; many fine tubular pores; (pH 6.2); gradual wavy boundary.
B22	9-20"	Dark brown (7.5YR 3/3) loam, brown (7.5YR 5/3) dry; moderate medium subangular blocky breaking into moderate very fine subangular blocky structure; common roots; many fine tubular pores; 2% spherical shot 1 to 3 mm in size; (pH 6.2); abrupt wavy boundary.
IIR	20"+	Unweathered basalt bedrock.

Soil Profile		JC3 mound soil
A1	0-4"	Dark reddish brown (5YR 3/3) loam, dark brown (7.5YR 4/4) dry; weak fine subangular blocky breaking into weak very fine granular structure; slightly hard, friable, non-sticky, non-plastic; common roots; 20% fine gravel; (pH 6.7); clear smooth boundary.
B21	4-15"	Dark reddish brown (5YR 3/4) loam, reddish brown (5YR 5/4) dry; weak medium and fine subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; common roots; many fine tubular pores; 10% fine gravel; (pH 6.6); gradual smooth boundary.
B22	15-24"	Dark reddish brown (5YR 3/4) loam, reddish brown (5YR 5/4) dry; moderate medium and fine subangular blocky structure; dark ped coatings; slightly hard, friable, slightly sticky, slightly plastic; common roots; many fine and medium tubular pores; 10% fine gravel; (pH 6.5); abrupt wavy boundary.
IIR	24"+	Unweathered basalt bedrock.

Soil Profile		AGD1 mound soil
A1	0-5"	Dark brown (10YR 3/3) loam, light brownish gray (10YR 6/2) dry; cloddy breaking into moderate coarse subangular blocky structure; hard, friable, non-sticky, non-plastic; common roots; many very fine tubular pores; 15% gravel; (pH 6.1); gradual smooth boundary.
B1	5-12"	Dark brown (10YR 3/4) loam, brown (10YR 5/3) dry; weak medium subangular blocky structure; hard, friable, slightly sticky, non-plastic; common roots; many very fine to medium tubular pores; 30% gravel; (pH 6.3); gradual smooth boundary.
B21	12-21"	Dark brown (10YR 3/4) clay loam, brown (10YR 5/3) dry; moderate medium subangular blocky structure; very hard, firm, sticky, slightly plastic; few roots; many very fine and fine tubular pores; 10% gravel; (pH 6.2); abrupt wavy boundary.
IIB22	21-23"	Brown (10YR 4/3) clay, pale brown (10YR 6/3) dry; massive; very hard, very firm, very sticky, plastic; few roots; 20% gravel; (pH 6.1); abrupt wavy boundary.
IIICm	23"+	Silica cemented duripan containing much gravel.

Soil Profile		AGD4 mound soil
A1	0-2"	Dark brown (7.5YR 3/3) gravelly loam, brown (7.5YR 5/3) dry; weak coarse platy structure; slightly hard, friable, non-sticky, non-plastic; many roots; 20% gravel; (pH 6.1); clear smooth boundary.
B1	2-5"	Dark brown (7.5YR 3/3) gravelly loam, brown (7.5YR 5.3) dry; weak medium and fine subangular blocky breaking into weak very fine subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; common roots; many fine tubular pores; 20% gravel; (pH 6.1); clear smooth boundary.
B21	5-12"	Dark brown (7.5YR 3/3) gravelly clay loam, brown (7.5YR 5/3) dry; moderate medium subangular blocky structure; hard, firm, sticky, plastic; common roots; many fine and medium tubular pores; 20% gravel; (pH 6.5); abrupt smooth boundary.
IIB22	12-16"	Brown (7.5YR 5/4) gravelly clay; massive; very firm, very sticky, very plastic; few roots; 30% gravel (pH 6.3); clear smooth boundary.
IIB23	16-23"	Dark gray brown (2.5YR 4/2) gravelly clay; massive; very firm, very sticky, very plastic; few roots; 35% gravel; (pH 6.3); abrupt wavy boundary.
IIICm	23"+	Silica cemented duripan containing much gravel.

Soil Profile		LTR1 mound profile
A1	0-5"	Dark brown (7.5YR 3/2) loam, brown (7.5YR 5/4) dry; weak fine and very fine subangular blocky structure; slightly hard, friable, slightly sticky, non-plastic; few very fine spherical shot; many worm casts; many roots; many interstitial pores; occasional gravel-sized quartzitic fragment; (pH 6.3); clear wavy boundary.
B21	5-24"	Dark brown (7.5YR 3/2) loam, brown (7.5YR 5/4) dry; weak medium subangular blocky structure; slightly hard, friable, slightly sticky, non-plastic, few very fine spherical shot; many worm holes and worm casts; common roots; many fine and medium tubular pores; occasional basalt and quartzitic fragment; (pH 6.3); gradual smooth boundary; (this horizon broken in the middle for laboratory analysis)
B22	24-32"	Dark brown (7.5YR 3/3) loam, brown (7.5YR 5/3) dry; weak medium subangular blocky structure; slightly hard, friable, slightly sticky, non-plastic; few very fine spherical shot; many fine splotches of manganese dioxide; common roots; many fine and medium tubular pores; occasional gravel fragment; (pH 6.0); abrupt wavy boundary.
IIR	32"+	Unweathered fractured basalt bedrock.

Soil Profile		LTR3 mound soil
A1	0-4"	Dark brown (10YR 3/3) loam, brown (10YR 5/3) dry; moderate fine granular structure; slightly hard, friable; slightly sticky, non-plastic; common roots; many interstitial pores; 10% pebble-sized fragments of basalt; (pH 5.7); gradual wavy boundary.
B21	4-12"	Dark brown (10YR 3/4) loam, yellowish brown (10YR 5/4) dry; weak medium and fine subangular blocky structure; slightly hard, friable, slightly sticky, non-plastic; common worm holes and worm casts; common roots; many fine and medium tubular pores; 5% pebble-sized fragments of basalt; (pH 5.6); gradual wavy boundary.
B22	12-18"	Dark brown (10YR 3/4) loam, brown (10YR 5/4) dry; weak medium and fine subangular blocky structure; slightly hard, friable, slightly sticky, non-plastic; common worm holes and worm casts; common roots; many fine and medium tubular pores; many pebble and gravel-sized fragments of basalt; (pH 5.5); abrupt wavy boundary.
IIR	18"+	Unweathered fractured basalt bedrock.

Soil Profile		LTR4 mound soil
A11	0-2"	Dark brown (10YR 3/3) loam, brown (10YR 5/3) dry; strong fine and very fine granular structure; slightly hard, friable, slightly sticky, non-plastic; many worm casts; many roots; (pH 6.4); abrupt smooth boundary; (this horizon is all worm casts)
A12	2-7"	Dark brown (10YR 3/3) loam, brown (10YR 5/3) dry; weak coarse prismatic breaking into weak very fine subangular blocky structure; hard, friable, slightly sticky, slightly plastic; common worm holes and worm casts; common roots; many very fine and common fine tubular pores; (pH 6.3); abrupt wavy boundary.
B21	7-14"	Dark brown (7.5YR 3/3) loam, brown (7.5YR 5/3) dry; weak medium and coarse subangular blocky breaking into moderate very fine subangular blocky structure; slightly hard, friable, slightly sticky, non-plastic; many worm holes and worm casts; common roots; many fine, medium and coarse tubular pores; (pH 6.2); gradual wavy boundary.
B22	14-25"	Dark brown (7.5YR 3/3) loam, brown (7.5YR 5/3) dry; similar to horizon above but with very dark grayish brown castings on ped surfaces; (pH 6.0); abrupt wavy boundary.
IIR	25"+	Unweathered fractured basalt bedrock.

Soil Profile		LTR6 mound soil
A1	0-5"	Dark brown (7.5YR 3/3) loam, brown (7.5YR 5/3) dry; cloddy; hard, friable, slightly sticky, non-plastic; few worm casts; common roots; (pH 6.3); abrupt wavy boundary.
B21	5-16"	Dark brown (7.5YR 3/3) loam, brown (7.5YR 5/3) dry; weak coarse prismatic breaking into moderate fine subangular blocky strucutre; slightly hard, friable, slightly sticky, non-plastic, many worm holes and worm casts; common roots; many fine and medium tubular pores; (pH 6.1); gradual wavy boundary.
B22	16-25"	Dark brown (7.5YR 3/3) loam, brown (7.5YR 5/3) dry; weak coarse prismatic breaking into weak medium and fine subangular blocky structure; slightly hard, friable, slightly sticky, non-plastic; many worm holes and worm casts; common roots; many fine and medium tubular pores; 5% gravel-sized fragments of basalt; (pH 5.9); abrupt wavy boundary.
IIR	25"+	Unweathered fractured basalt bedrock.

Soil Profile		UTR1 mound soil
A1	0-7"	Dark brown (10YR 3/3) clay loam, brown (10YR 4/3) dry; cloddy breaking into moderate medium granular structure; slightly hard, friable, sticky, plastic; many roots; many fine tubular pores; (pH 6.2); clear smooth boundary.
B21	7-15"	Dark brown (7.5YR 3/4) clay loam, brown (7.5YR 5/4) dry; weak coarse prismatic breaking into moderate fine subangular blocky structure; slightly hard, friable, sticky, plastic; many worm holes and worm casts; many roots; many fine tubular pores; (pH 6.0); gradual wavy boundary.
B22	15-24"	Dark brown (7.5YR 3/4) clay loam, brown (7.5YR 5/4) dry; strong very fine subangular blocky structure; dark coatings on peds; slightly hard, friable, sticky, plastic; many worm holes and worm casts; many roots; many fine tubular pores; (pH 6.0); abrupt wavy boundary.
IIR	24"+	Unweathered fractured basalt bedrock.

Soil Profile		UTR2 mound soil
A1	0-5"	Dark gray brown (10YR 4/2) silt loam; light gray (10YR 7/2) dry; cloddy; hard, friable; slightly sticky, slightly plastic; few worm casts; many roots; many fine tubular pores; common spherical shot of manganese dioxide up to 2 mm in size; occasional pebble sized fragment of quartzite and basalt; (pH 5.8); clear smooth boundary.
B21	5-12"	Dark gray brown (10YR 4/2) silt loam, light gray (10YR 7/2) dry; clean sand and silt grain coat ped surfaces; hard, friable, slightly sticky, slightly plastic; common roots; many fine and medium tubular pores; common spherical manganese dioxide shot up to 2 mm in size; (pH 5.9); gradual smooth boundary.
B22	12-23"	Dark gray brown (10YR 4/2) silt loam, light gray (10YR 7/2) dry; weak coarse prismatic breaking into weak medium subangular blocky structure; clean sand and silt grains coat ped surfaces; hard, friable, sticky, plastic; common roots; many fine and medium tubular pores; common spherical manganese dioxide shot up to 2 mm in size; (pH 5.9); abrupt wavy boundary.
IIR	23"+	Unweathered fractured basalt bedrock.

Soil Profile		UTR4 mound soil
A1	0-7"	Dark brown (7.5YR 3/4) silt loam, light brown (10YR 6/3) dry; cloddy; hard, friable; slightly sticky, slightly plastic; many roots; few very fine tubular pores; occasional gravel fragment; (pH 6.1); clear smooth boundary.
B21	7-17"	Dark brown (7.5YR 3/4) silt loam, brown (7.5YR 5/4) dry; weak coarse prismatic breaking into weak medium subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; common roots; many fine and medium tubular pores; (pH 6.2); gradual wavy boundary.
B22	17-27"	Dark brown (7.5YR 3/4) silt loam, brown (7.5YR 5/4) dry; weak coarse prismatic breaking into weak medium subangular blocky structure; dark colored ped coatings; slightly hard, friable, slightly sticky, slightly plastic; common roots; many fine and medium tubular pores; (pH 6.1); abrupt wavy boundary.
IIR	27"+	Unweathered fractured basalt bedrock.

Soil Profile		UTR6 mound soil
A1	0-5"	Dark brown (10YR 3/3) loam, light yellowish brown (10YR 6/4) dry; weak coarse prismatic breaking into fine and medium subangular blocky structure; slightly hard, friable, non-sticky, non-plastic; many roots; 10% pebble and gravel-sized fragments of basalt; (pH 5.7); clear smooth boundary.
B21	5-13"	Dark brown (10YR 3/3) loam, brown (10YR 5/3) dry; weak medium subangular blocky structure; soft, friable, non-sticky, non-plastic; many roots; many very fine and fine tubular pores; (pH 5.7); gradual smooth boundary.
B22	13-24"	Dark brown (10YR 3/3) loam, brown (10YR 5/3) dry; weak medium subangular blocky structure; soft, friable, non-sticky, non-plastic; many roots; many very fine and fine tubular pores; (pH 5.8); abrupt wavy boundary.
IIR	24"+	Unweathered fractured basalt bedrock.

Soil Profile		MP1 mound soil
A11	0-4"	Black (10YR 2/1) moist, gravelly loam; moderate very fine subangular and granular structure; friable, non-sticky, non-plastic; matted roots; 40% gravel; (pH 5.6); clear smooth boundary.
A12	4-12"	Black (10YR 2/1) moist, gravelly loam; moderate very fine subangular blocky structure; friable, non-sticky, non-plastic; many roots; 40% gravel; (pH 5.4); gradual wavy boundary.
A13	12-24"	Black (10YR 2/1) moist, gravelly loam; moderate very fine subangular blocky structure; friable, non-sticky, non-plastic; many roots; 40% gravel; (pH 5.3); gradual wavy boundary.
A14	24-36"	Black (10YR 2/1) moist, gravelly loam; moderate very fine subangular blocky structure; friable, non-sticky, non-plastic; many roots; 40% gravel; (pH 5.4); gradual wavy boundary.
A15	36-50"	Black (10YR 2/1) moist, gravelly loam; moderate very fine subangular blocky structure; friable, non-sticky, non-plastic; many roots; 30% gravel; (pH 4.9); gradual wavy boundary.
A16	50-63"	Very dark brown (10YR 2/2) moist, gravelly loam; moderate very fine subangular blocky structure; friable, non-sticky, non-plastic; many roots; 30% gravel; (pH 5.5); abrupt wavy boundary.
IIC	63-70"+	Dark yellowish brown (10YR 4/4) moist, loose sand and gravel; (pH 5.8).

Note: A13, A14 and A15 were arbitrary separations for laboratory analysis.

Soil Profile		MDP1 mound profile
A11	0-6"	Black (10YR 2/1) moist, gravelly loam; moderate very fine granular structure; friable, non-sticky, non-plastic; matted roots; 35% gravel; (pH 5.5); gradual smooth boundary.
A12	6-12"	Black (10YR 2/1) moist, gravelly loam; moderate very fine granular structure; friable, non-sticky, non-plastic; many roots; 35% gravel; (pH 5.4); gradual wavy boundary.
A13	12-24"	Black (10YR 2/1) moist, gravelly loam, moderate very fine granular structure; friable, non-sticky, non-plastic; many roots; 35% gravel; (pH 5.5); gradual wavy boundary.
A14	24-36"	Very dark brown (10YR 2/2) moist, gravelly loam; moderate very fine granular structure; friable, non-sticky, non-plastic; many roots; 25% gravel; (pH 5.5); abrupt wavy boundary.
IIC	36"+	Dark yellowish brown (10YR 4/4) moist, gravelly and cobbly loamy sand; loose; (pH 5.6).

Soil Profile		RP1 mound soil
A11	0-6"	Black (10YR 2/1) moist, gravelly loam; moderate very fine granular structure; friable, non-sticky, non-plastic; matted roots; (pH 5.6); clear smooth boundary.
A12	6-12"	Black (10YR 2/1) moist, gravelly loam; moderate very fine granular structure; friable, non-sticky, non-plastic; many roots; (pH 5.5); gradual wavy boundary.
A13	12-24"	Black (10YR 2/1) moist, gravelly loam; moderate very fine granular structure; friable, non-sticky, non-plastic; many roots; (pH 5.6); gradual wavy boundary.
A14	24-36"	Black (10YR 2/1) moist, gravelly loam; moderate very fine granular structure; friable, non-sticky, non-plastic; many roots; (pH 5.6); gradual wavy boundary.
A15	36-40"	Very dark brown (10YR 2/2) moist, gravelly loam; moderate very fine granular structure; friable, non-sticky, non-plastic; many roots; (pH 5.6); abrupt wavy boundary.
IIC	40"+	Dark yellowish brown (10YR 4/4) cobbly and gravelly loamy sand; loose; (pH 5.4).