MIMA MOUNDS

AN EVALUATION OF PROPOSED ORIGINS WITH SPECIAL REFERENCE TO THE PUGET LOWLAND

by
A. L. WASHBURN

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES

REPORT OF INVESTIGATIONS 29

1988

WASHINGTON STATE DEPARTMENT OF
Natural Resources

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MIMA MOUNDS

AN EVALUATION OF PROPOSED ORIGINS WITH SPECIAL REFERENCE TO THE PUGET LOWLAND

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ABSTRACT

The origin of the Mima mounds of the Puget Lowland of Washington State and of the widely distributed, apparently similar (Mimalike) mounds elsewhere has been debated for over 100 years. Of the many explanations that have been offered, the most promising are critically reviewed. The fossorial-rodent hypothesis has been popular with biologists but entails difficulties in its type region. Another hypothesis with apparently fewer problems and equally wide applicability here and elsewhere is runoff erosion combined with vegetation anchoring.

Other reasonable hypotheses probably applicable in some regions but not to the Puget Lowland include volume changes in expandable clays (gilgai hypothesis); wind combined with vegetation anchoring; and runoff erosion combined with desiccation cracking or permafrost cracking. Further research is needed on the relative importance of these hypotheses and possibly others, but no single hypothesis explains Mimalike mounds everywhere.

INTRODUCTION

The origin of the Mima mounds of the Puget prairies and of Mimalike mounds elsewhere has been a mystery for more than 100 years ever since they were first sighted by Wilkes (1845, p. 313, 415) in 1840, and it continues to be debated.

Exactly how widespread Mimalike mounds are is not known, but it has been suggested they occur in a number of places in North America (Fig. 1) and the world. Other names that have been used in different places and are frequently regarded as synonymous include hogwallows (in California), prairie mounds[1], pimple mounds, pimpled plains, prairie pimples, silt mounds, and others.

The present review will focus primarily on the Mima mounds of Mima Prairie and on some other nearby prairies of the Puget Lowland. It will stress the evidence and some new observations from these prairies but without excluding evidence regarding origin from occurrences elsewhere. Because the fossorial-rodent hypothesis is presently widely accepted by biologists and many others for Mimalike mounds wherever they may be, a critical review of the evidence for this hypothesis and for some of the other hypotheses that have been suggested seems timely.

Perhaps the most that can be said for the present effort is that it offers a broad up-to-date survey of the Mima mound problem. The writer's own observations are limited, having been restricted to organizing some class field trips and undertaking occasional fieldwork. The review is intended to stimulate much needed rigorous research and lead to resolution of a many facetted problem that has long puzzled observers of Mima mounds and similar features.

Metric units are adopted throughout except where the original observation was reported in English units, in which case the latter is given in parentheses. Radiocarbon dates are reported in years Before Present (yr B.P., taken to mean before 1950; Colman and others, 1987, p. 315). Soil horizon designations follow the usages of the authors cited; for subsequent changes, see Guthrie and Witty (1982).

A draft of this review was distributed to those participating in a University of Washington, Quaternary Re-

[1] Not to be confused with the much larger prairie mounds of quite different pattern and origin in Alberta and the northern Plains states. See, for example, Bik (1969), Bleuer (1974) and Gravenor (1955).

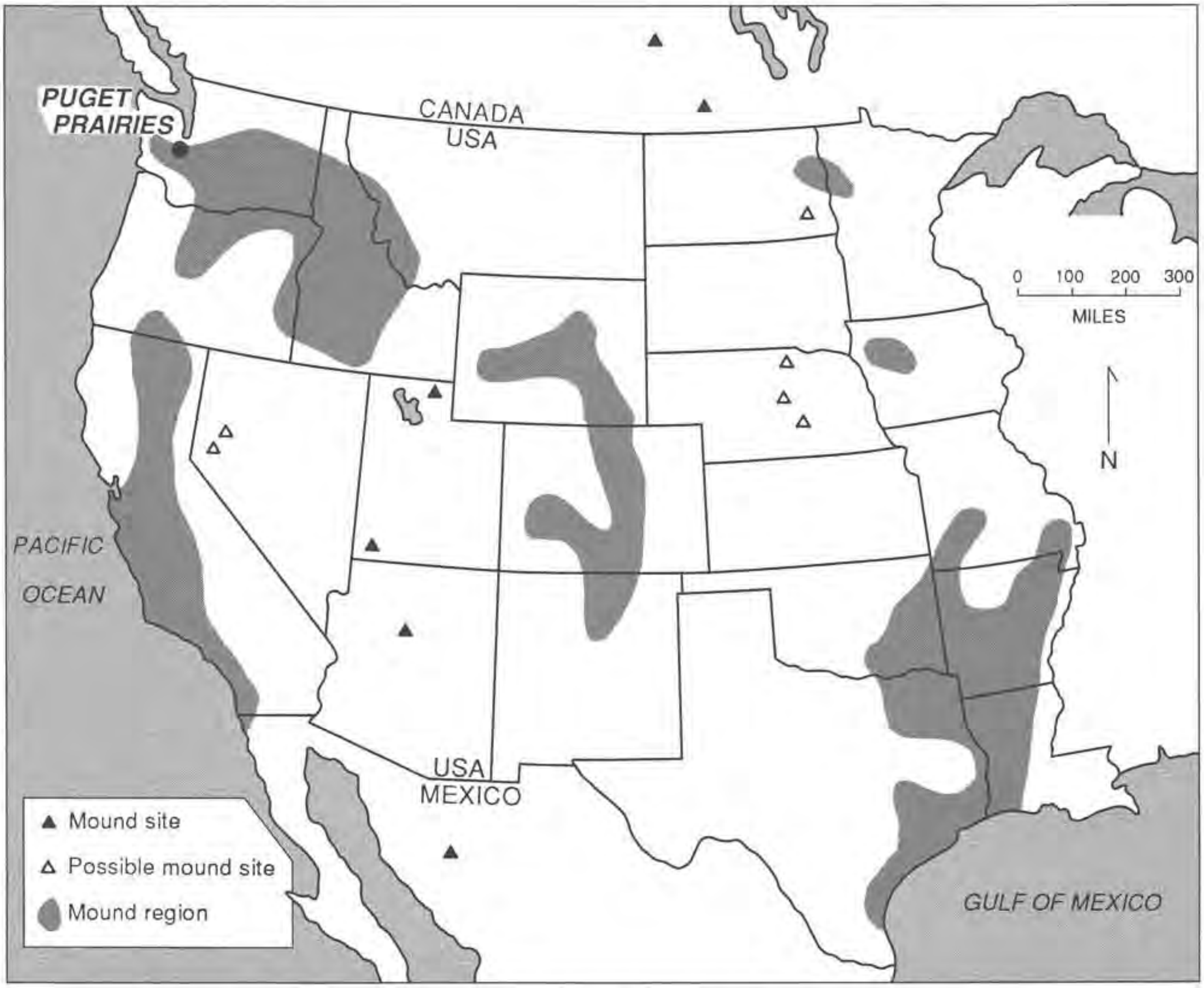

Figure 1.–Distribution of Mimalike mounds in North America (after Cox, 1984a, p. 38; updated by G. W. Cox, San Diego State Univ., written commun., 1986).

search Center, field trip to Mima Prairie and vicinity in May 1986. The review was subsequently somewhat revised based on helpful comments from a number of persons. In particular the writer is grateful to V. B. Scheffer who introduced him to the Mima mound problem; to Martin Kaatz who showed him some of the Columbia Plateau mounds; to various landowners and their representatives for access to critical areas before liability and insurance posed difficulties; to G. W. Cox and P. H. Zedler for helpful comments; to P. D. Lea, Michael McFaul, R. C. Paeth, J. B. Pyrch, and L. A. K. Tallyn for copies of their theses; and to colleagues at the University of Washington for their contributions, especially Larry Bliss, Arthur Kruckeberg, Stephen Porter, Minze Stuiver, Matsuo Tsukada, and Fiorenzo Ugolini; to Patra Leaming and Katherine Reed for their superb editorial work; and to his wife and field assistant Tahoe. Donald W. Hiller prepared the maps and assisted with the production of this publicaton.

THE MOUNDS OF THE PUGET LOWLAND PRAIRIES

Location and Climate

The principal mound-bearing prairies of the Puget Lowland are situated in Thurston County (Fig. 2). The climate is maritime. Summers tend to be cool and dry, winters mild and wet. At Olympia Municipal Airport (just north of the prairies to be discussed), the normal annual temperature and precipitation are 10°C and 1,164 mm (Table 1).

Geology

The Puget prairies are located on outwash of the last glaciation in the Puget Lowland, the Vashon Stade of the Fraser Glaciation, which culminated about 14,000 radiocarbon years ago (Porter, 1970; Porter and Carson, 1971, p. 411; see also Thorson, 1980, p. 304, 316).

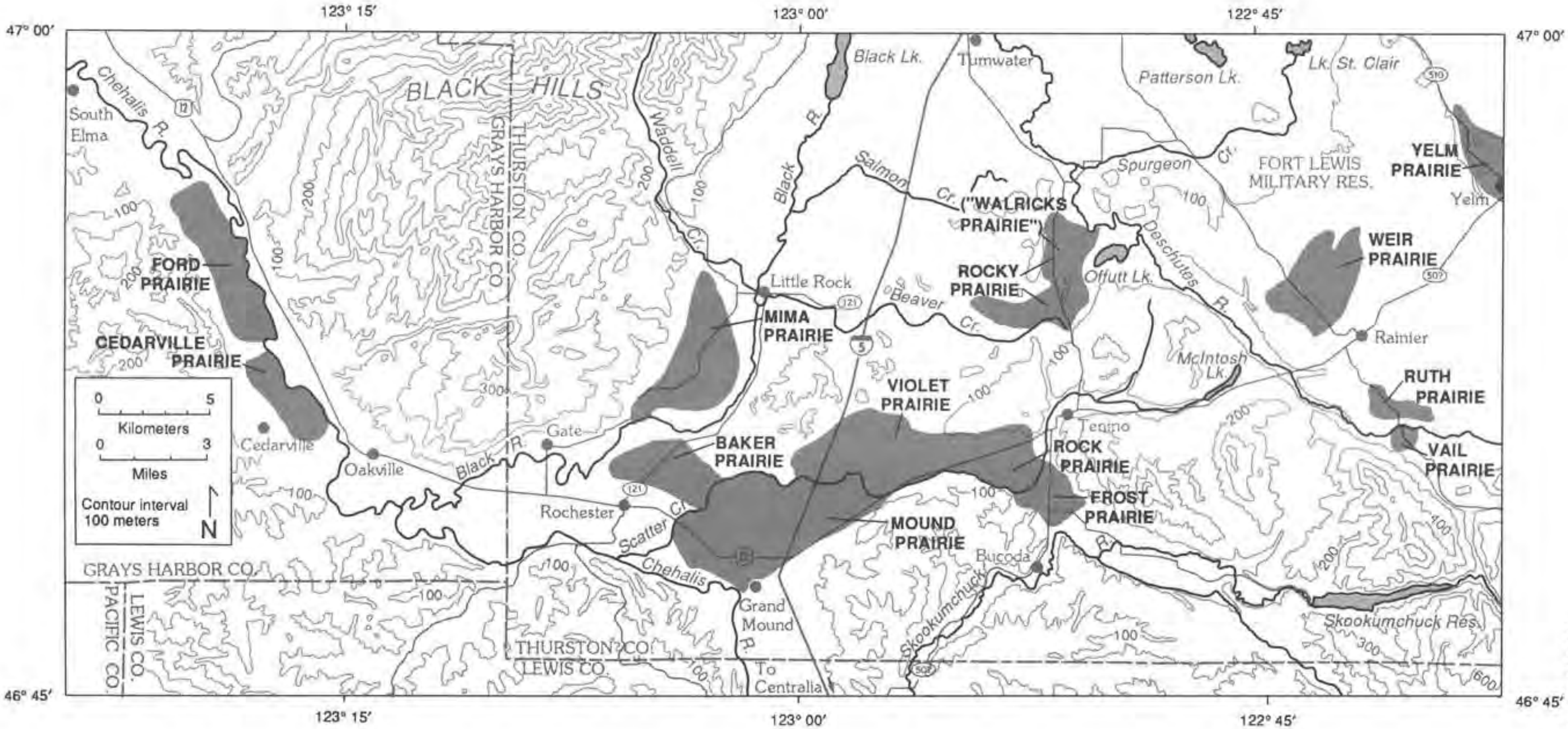

Figure 2.–Location of Puget prairies. Lost Lake Prairie and Scott's Prairie, mentioned in text, are near Shelton, Washington, and are 29 kilometers west-northwest and 32 kilometers northwest of Tumwater, respectively.

Table 1. Temperature and precipitation summary, Olympia Municipal Airport, Washington. Altitude 57.9 m (Phillips, 1960, p. 13; converted to SI units) T, trace

	Temperature (°C)			Precipitation (mm)				
		Extremes					Snow, sleet	
Month	Normal[a]	Highest	Lowest	Normal[a] total	Maximum monthly	Minimum monthly	Mean total	Maximum monthly
January	2.8	17.2	-17.8	169.9	503.9	21.3	221.0	1143.0
February	4.4	19.4	-18.3	156.5	286.5	88.6	73.7	449.6
March	6.5	23.9	-10.6	114.3	257.3	59.4	55.9	523.2
April	9.1	29.4	-4.4	59.4	121.4	9.4	T	2.5
May	12.3	33.3	-3.9	42.2	148.1	3.8	0.0	0.0
June	14.9	38.3	1.1	32.5	164.6	1.0	0.0	0.0
July	17.1	39.4	2.8	18.3	68.1	T	0.0	0.0
August	17.2	37.2	2.8	16.8	57.7	0.0	0.0	0.0
September	14.5	35.0	-1.7	45.7	99.6	1.5	0.0	0.0
October	10.6	29.4	-5.6	114.3	252.2	39.4	T	T
November	6.4	23.3	-18.3	172.0	320.3	35.3	40.6	315.0
December	4.1	15.6	-11.1	220.0	319.8	57.9	40.6	368.3
Year	10.0	39.4	-18.3	1161.8	503.9	0.0	431.8	1143.0

[a] "Normal values are based on the period 1921-1950 and are means adjusted to represent observations taken at the present standard location." (Phillips, 1960, p. 16).

> "Deglaciation was accompanied by a complex succession of meltwater-channel and ice-margin-lake stages which probably encompassed less than 1000 years.... Glacial drainage through ... [the Chehalis Valley] channel diminished substantially about 13,000 years ago. . . ." (Porter, 1970).

Ice-marginal conditions at the maximum extent of the Vashon Stade Puget Lobe and at subsequent retreat stages in the prairie region have been described and illustrated in some detail by Lea (1984, p. 1-70). In places, melting of stagnant ice in an approximate 15-km-wide belt inside the outer limit of the Puget Lobe of Vashon age resulted in the outwash having a pronounced kame-and-kettle topography (Porter and Carson, 1971, p. 411). Ice had apparently retreated to Lake Washington by about 13,400 years ago (Leopold and others, 1982a, b), a date supported by a basal peat date of 13,650 ± 550 yr B.P. (L-346A, Broecker and Kulp, 1957, p. 1325; see also Rigg and Gould, 1957, p. 357-358, 362).

Pollen Profiles and Vegetation

Pollen profiles (Fig. 3A) of a sediment core from Mineral Lake (lat. 46°44'N., long. 122°10'W.) in the Puget Lowland beyond the southern limit of the Vashon ice advance have been interpreted as showing that conifers dominated the area of the present prairies soon after the Vashon Stade and deposition of the Vashon outwash (Tsukada and others, 1981, fig. 1, p. 732, 735). This forested period was terminated by the advent of a drier and/or warmer climate here and in many parts of the world that is commonly known as the Hypsithermal interval despite this interval being time transgressive and requiring redefinition (Wright, 1976, p. 591-594). In the Puget Lowland the time of maximum warmth, according to Hansen (1947, p. 119), began just before deposition of the Mazama ash—there are four Mazama ash falls, but probably the only one to reach the Puget Lowland occurred about 6,900 yr B.P. (S. C. Porter, Univ. of Washington, oral commun., 1988). However, the pollen profiles from Mineral Lake show that a drier and warmer climate started as early as 10,000 years ago and was followed almost immediately by a period of maximum warmth. The beginning of this period is shown by a sudden decline of *Pinus* and *Picea* and the appearance of *Pseudotsuga* and the bracken *Pteridium aquilinum*. The climate, which was also drier and perhaps warmer than at present, lasted until about 7,000 years ago (zones PIa and PIb) when the reappearance of *Tsuga heterophylla* indicated moister conditions. However, summers may have remained warm to 5,000 years ago (zone PII), at which time a rise in *Tsuga heterophylla* and decline in *Pteridium aquilinum* signalled increased moisture and/or cooling.[2] Prairie fires attributed largely to Indians inhibited re-establishment of trees until the coming of settlers.

[2] The statement by Tsukada and others (1981, p. 735) that "Zones PIa and PII correspond to the mid-Holocene therman [sic] maximum" should have read "Zones PIa, PIb, and PII correspond to the mid-Holocene thermal maximum". Former greater dryness than at present is established, but whether it was accompanied by former higher temperatures in the Puget Lowland is uncertain (Matsuo Tsukada, Univ. of Washington, oral commun., 1985).

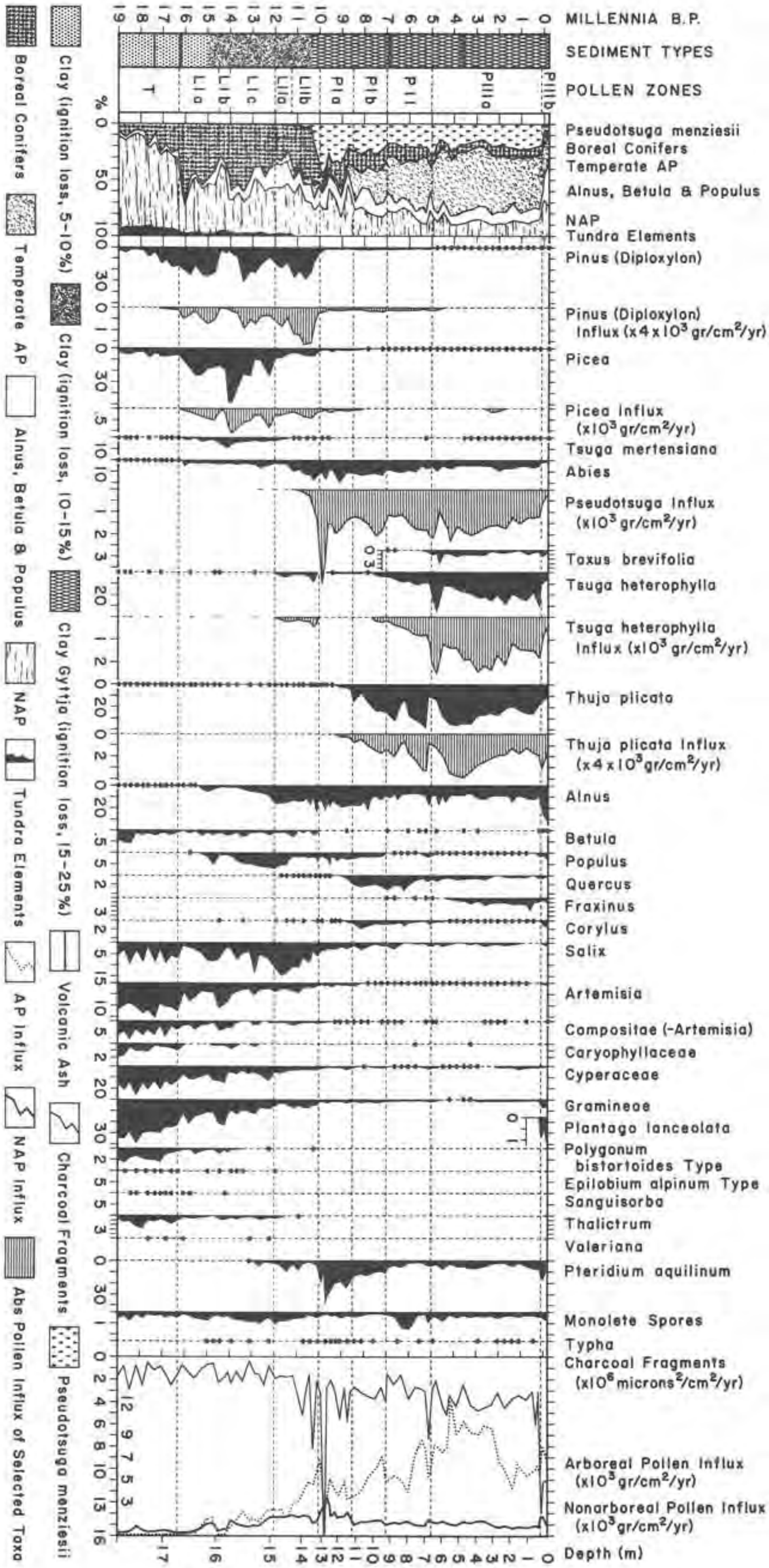

Figure 3A.–Pollen diagram of selected taxa for a 17.75-m sediment core from Mineral Lake, Puget Lowland, Washington. AP, arboreal pollen; NAP, nonarboreal pollen; Abs, absolute. (From Tsukada and others, 1981, fig. 1, p. 732.

The palynological interpretation of the early postglacial history by Leopold and others (1982a) is somewhat different. They investigated a sediment core from Lake Washington (Seattle) and concluded that lignin compositions suggest a treeless source region for the pollen in the central Puget Lowland prior to about 11,000 years ago (or 10,500 years ago; Barnosky, 1983, p. 56), after which their interpretation is similar but more specific regarding warming in that from about 10,000 to 7,000 years ago there was

> "...an open forest of Douglas fir and alder or a forest mosaic and a climate both warmer and drier than at present" (Leopold and others, 1982a, p. 1306).

However, they place the termination of Holocene warming in the region at 7,000 years ago with the advent of moister and (they believed) cooler conditions rather than extending the Hypsithermal interval some 2,000 years longer.

Barnosky (1983, fig. 2-8, p. 54, see also p. 52-61; 1985) showed that development of *Picea-Pinus-Tsuga* parkland and then *Pinus* parkland followed withdrawal of the Vashon Stade glacial lobe from the areas of Davis Lake (lat. 46°33'N.; long. 122°15'W.) and Nisqually Lake (lat. 47°02'N.; long. 122°38'W.) in the Puget Lowland. Her study suggests that postglacial migration lag of conifers (*Pseudotsuga, Tsuga, Thuja*) was of negligible duration.

> "*Pinus contorta* spread rapidly on outwash and apparently became the dominant tree in the stagnant-ice terrain of the southern Puget Lowland" (Barnosky, 1984, p. 625).

A minimal migration lag was envisaged by Hansen (1947, p. 77-78) and is supported by Porter and Carson's (1971) discovery of cedar logs, dated at 12,430 ± 160 to 12,700 yr B.P., apparently deposited in association with remnant stagnant ice less than 1 km inside the drift border of the Puget Lobe.

As reported by Tsukada and Schlichte (1973, p. 3), analyses of soil organic matter in a mound on Mima Prairie and from an unmounded phase of the Spanaway soil on Weir Prairie yielded the radiocarbon dates indicated in Table 2A. Additional radiocarbon dates were determined by the University of Washington Quaternary Isotope Laboratory from samples collected by the present writer (Table 2B).

Tsukada and Schlichte (1973, p. 3) commented that

> "The absolute pollen number (gr/g) in the Weir Prairie diagram showed an abrupt decline with depth, indicating that the pollen does not migrate downward through these soils to a great extent. The total pollen number taken from within the [Mima Prairie] mound, however, shows a much less abrupt decrease with depth, indicating that mixing of the soil by some means has taken place. The radiocarbon dates on the soil organic matter remaining after treatment with HCl and NaOH solutions show that the rate of radiocarbon age increase with depth is much more rapid in the unmounded Weir Prairie soil than it is in the mound soil. The greater mixing of younger organic matter from the soil surface has produced the more gradual rate of age increase in the organic matter of the mounds.
>
> "In the pollen diagrams of both the Mima mound and the unmounded Weir Prairie[3], the upper parts of the diagram show an increase in the relative percentages of *Tsuga heterophylla*. This increase is also noted in the Nisqually Lake core beginning at about 3,800 years B.P.

Table 2A. Radiocarbon dates on soil organic matter from Mima mound, Mima Prairie, and from unmounded Spanaway soil, Weir Prairie (after Tsukada and Schlichte, 1973, p. 3)

Sample location	Depth (cm)	Radiocarbon age (yr B.P.)	UW no.
Mima Prairie	35-36	1,640 ± 70	256
Mima Prairie	125-126	2,750 ± 75	257
Weir Prairie	17-18	1,575 ± 85	263
Weir Prairie	55-56	3,685 ± 100	264

Table 2B. Radiocarbon dates on soil organic matter from Mima mound, Mima Prairie. Data from Minze Stuiver (Univ. of Washington, written commun., 1986)

Sample location[a]	Depth (cm)	Radiocarbon age (yr B.P.)	UW no.
Mima Prairie	100-115	2,340 ± 30	1892
	115-130	2,630 ± 30	1893
	130-155	3,580 ± 40	1894
	155-170	4,180 ± 100	1895

[a] See also Table 9, this report.

[3] Weir Prairie as a whole is not completely free of mounds, but mounds tend to be in "smaller and fainter concentrations" (McFaul, 1979, p. 38).

and is thought to be caused by a cooling of the climate which allowed *Tsuga* to increase in numbers. Disturbance in the mounds evidently ceased before 3,800 years B.P. because if it had not, the record of this *Tsuga* increase would have been obliterated by the mixing.[4]

"The late-glacial and early postglacial pollen types (*Pinus* and *Picea*) are not observed in these soils due to the fact that they have been decomposed over that long period of time.[5]

"At the top of each soil pollen diagram can be seen an increase in the percentage of non-arboreal pollen (NAP). This is due to increases in the amounts of weedy species such as *Plantago*, *Rumex*, and *Taraxacum* which are favored by man's disturbances."

A pollen profile from a Mima mound on Mima Prairie (Fig. 3B) shows no late-glacial characteristics such as abundant spruce. The presence of *Tsuga heterophylla* and *Corylus* indicate a post-7,000-yr-B.P. age for these taxa (Matsuo Tsukada and Shinya Sugita, Univ. of Washington, oral commun., 1985). The absence of late-glacial characteristics is puzzling in view of the evidence from Mineral Lake (Fig. 3A) and the reports by Barnosky (1983) and Porter and Carson (1971) discussed above. Possible factors in explanation include decomposition of older pollen, destruction by fire (supported by presence of charcoal in the mound soil), and nondeposition because of pollen being carried past the area by the original depositional processes. The fact that the oldest radiocarbon ages reported from the mounds (Tables 2A, 2B) are younger than 4,180 yr B.P. and the uncertainties involved are discussed later in connection with the fossorial-rodent hypothesis for the origin of the mounds.

[4] Because the chronology of mound development may provide critical evidence as to origin, further data should be obtained not only from Mima Prairie, where pocket gophers are presently absent, but also from prairies where they are known to be active.

[5] Ken Schlichte (Forest Soil Scientist, Washington Dept. of Natural Resources, written commun., 1988) reported that

> "I have found abundant Douglas-fir phytoliths in the surface soils at the center of Mima Prairie and other prairies of the Puget Lowland. This suggests that Douglas fir had occupied the prairies for a long time prior to their establishment, because of the very limited distance that needles containing the phytoliths are likely to have been carried by the wind."

It would be interesting to see if phytoliths also occur within the mounds with the view to perhaps dating their carbon content. (See Wilding, 1967.)

The vegetation of the Puget prairies during recorded history is discussed by Lang (1961, p. 9-11), among others.

The present vegetation of the prairies is somewhat variable from prairie to prairie in that

> "...the deep-soiled prairies bear a lush vegetation of grasses and annuals, whereas the thin-soiled prairies bear a sparse cover consisting mainly of mosses and lichens" (Dalquest and Scheffer, 1944, p. 324).

Detailed descriptions of the prairie vegetation include those by del Moral and Deardorff (1976), Evans and others (1975), Giles (1970), Klotz and Smith (1975), and Lang (1961, p. 9-63).

McFaul (1979, p. 59) reported that

> "...preliminary examination of samples collected at 20 centimeter intervals through a soil A horizon of a mima mound on Rock Prairie suggests a high percentage of pollen which today are found in Histosolic environments."

However, lack of gleying argues against a relict bog environment (R. G. Reider, Univ. of Wyoming, written commun., 1987).

Soils

Pedogenically, the soils of the Puget prairies discussed belong to the Spanaway series formed under prairie vegetation, whereas the neighboring Everett soil series formed under Douglas-fir forest (Ness, 1958, p. 54-55; Ugolini and Schlichte, 1973). The Spanaway series is classed as a sandy-skeletal mixed, mesic Andic Xerumbrept, the typical pedon being the Spanaway gravelly sandy loam–fern-grass prairie (Table 3).

Mima Mounds

General

As used in the following, the term Mima mound will be restricted to mounds in the Puget Lowland prairies—hereafter termed Puget prairies for short—that are similar to the Mima mounds of Mima Prairie and are presumably of the same origin in view of their proximity and similar characteristics and occurrence. This corresponds to the sense in which the term 'Mima type' was first used (Bretz, 1913, p. 82). The term 'Mima mound' has subsequently come to be used in a much wider sense for occurrences in other, sometimes distant regions, but still implying an assumption of similar origin. However, this is a dangerous assumption, although the need to entertain and test the possibility of a common origin is unquestioned. To avoid confusion, the term 'Mimalike' is adopted here for such occurrences, thereby reserving Mima mound for the Puget prairie occurrences.

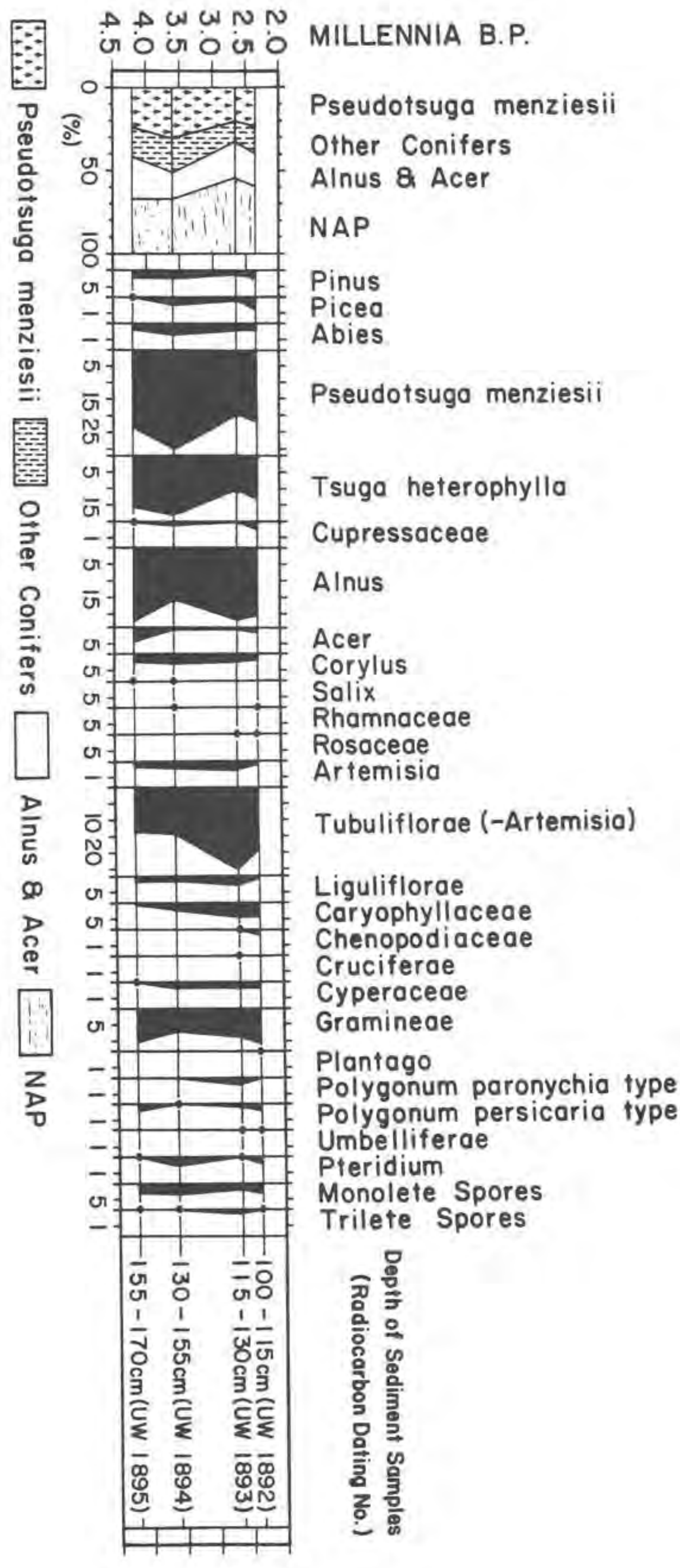

Figure 3B.–Pollen diagram, Mima mound, Mima Prairie. (See also Table 2B.) NAP, nonarboreal pollen. (Data from Matsuo Tsukada, Univ. of Washington, written commun., 1986; analysis by Shinya Sugita, Univ. of Washington.)

Table 3. Spanaway series typical pedon: Spanaway gravelly sandy loam–fern-grass prairie (after U.S. Soil Conservation Service , 1982; see also Zulauf, 1979, p. 60)

Horizon	Depth (cm)	Description
Oa	0-2.5 (0-1 in.)	Black (10YR 2/1) well decomposed organic matter, very dark brown (10YR 2/2), dry; mostly from grass roots and moss. 0-4 cm (0-1.5 in.) thick.
A	0-36 (0-14 in.)	Black (10YR 2/1) gravelly sandy loam, very dark grayish brown (10YR 3/2), dry; weak, fine granular structure; soft, very friable, nonsticky and nonplastic; many fine roots; very high in organic matter content, has mellow, sooty feel; 35% pebbles; strongly acid (pH 5.4); clear smooth boundary. 25-51 cm (10-20 in.) thick.
Bw	36-46 (14-18 in.)	Dark grayish brown (10YR 4/2) very gravelly sandy loam, grayish brown (10YR 5/2), dry; weak, fine subangular blocky structure; soft, very friable, nonsticky and nonplastic; common fine roots; 50% pebbles, 10% cobbles; medium acid (pH 5.8); clear smooth boundary. 8-20 cm (3-8 in.) thick.
2C	46-152 (18-60 in.)	Light brownish gray (10YR 6/2), dry; extremely gravelly sand; single grained; loose; few roots; 60% pebbles, 10% cobbles, slightly acid (pH 6.1).

Note: Range in Characteristics

Solum thickness ranges from 36 to 71 cm (14-28 in.). Content of coarse fragments in the control section averages 50 to 90 percent. Mean annual soil temperature ranges from 9° to 12°C (48°-54°F). These soils are usually moist but are dry in the moisture control section for 75 to 90 consecutive days following summer solstice. The weighted average texture of the control section is within the very gravelly sand or extremely gravelly sand range. The umbric epipedon is 25 to 51 cm (10-20 in.) thick.

The A horizon has hue of 10YR through 5YR, value of 2 to 4 dry, and chroma of 1 or 2 moist and dry. It has weak granular or blocky structure and is medium acid or strongly acid.

The Bw horizon has value of 4 or 5 dry and 3 or 4 moist. It is very gravelly sandy loam, very gravelly loam, or extremely gravelly sandy loam. It has weak fine or medium blocky structure and is strongly acid to slightly acid.

The 2C horizon has hue of 7.5YR to 2.5Y, value of 5 or 6 dry and 4 or 5 moist, and chroma of 2 through 4 dry or moist. It is extremely gravelly sand or extremely gravelly loamy sand. It is massive or single grained and is slightly acid or neutral.

The first detailed description of the Mima mounds was by Bretz (1913, p. 81-108), whose description is still one of the best overviews of the Puget prairie mounds. Since then these mounds have been repeatedly described by various investigators, especially Dalquest and Scheffer (1942), McFaul (1979), Newcomb (1952), Noble and Molenaar (1965), Paeth (1967), and Ritchie (1953).

Mima mounds are mainly circular to elliptical (Figs. 4-7). They consist of gravelly sandy loam, nonbedded and black, which overlies bedded Vashon outwash. The outwash commonly occurs at or near the surface of the intermound areas but tends to be obscured by vegetation. In at least a few places the intermound areas constitute a shallow closed depression of uncertain origin. Apparently similar features in the Central Valley of California have been ascribed to downward eluviation of fines (Holdredge and Wood, 1947). As described by Dalquest and Scheffer (1942, p. 69-76), the mounds range in height from 30 cm or less (<1 ft) to 2 m (7 ft), and in diameter from 2.5 m (8 ft) to as much as 12 m (40 ft). Other authors cite somewhat different dimensions. McFaul (1979, p. 1) reported Mima Prairie mounds roughly 2.4 m or more high. Newcomb (1952, fig. 2, p. 464) showed diameters as great as 18 m (60 ft) for Mima Prairie and 21 m (70 ft) for mounds he measured but whose location he did not specify. The mounds are densely distributed, as many as 20-25 mounds occurring per hectare (8-10 per acre) (Scheffer, 1969). A single mound may contain 38 m^3 (50 yd^3) of soil (Scheffer, 1984, p. 6).

The mound material contains rounded pebbles but shows no stratification in contrast to the bedded, rounded outwash gravels beneath, a contrast that has been ascribed to bioturbation (mixing by animals) of the mound material (Dalquest and Scheffer, 1944, p. 323).

Mount "roots" or extensions of the black mound soil into the bedded outwash gravel (Fig. 8) have been described as "root-like" by Bretz (1913, p. 84) and as "abandoned, earth-filled gopher tunnels and nests" by Dalquest and Scheffer (1942, p. 80-81). The presence of matted prairie vegetation in some mound roots supports this interpretation, but perhaps decay of tree roots is a possibility in places.

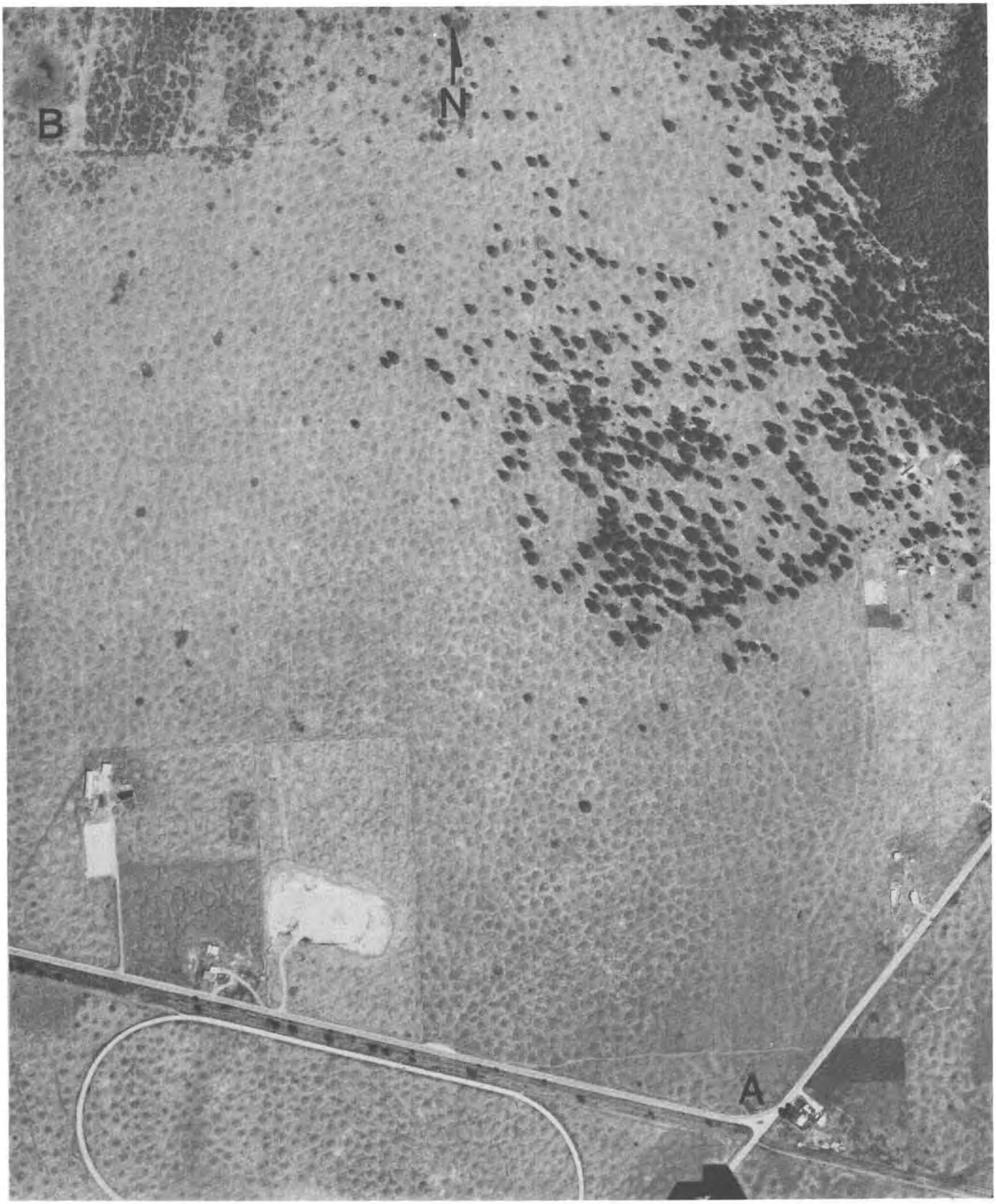

Figure 4.–Air photo of Mima mounds on Mima Prairie. Scale: 1 centimeter = approximately 72 meters. Enlargement of part of Washington Department of Natural Resources photo no. NW-78 22A-20. A, intersection of Bordeaux Road and Mima Road; B, kettle hole.

Figure 5.–Typical Mima mounds, Mima Prairie.

Figure 6.–Cross section of a Mima mound in a road cut, Mima Prairie. Scale indicated by vegetation. Note contrast between dark mound soil and underlying outwash gravel.

Figure 7.–Cross section of a Mima mound in a gravel pit, north side of Bordeaux Road, Mima Prairie.

Figure 8.–Mound root, Mima Prairie.

Bretz (1913, p. 84) also noted a "...double convex lens shape to the black silt aggregation....", and Dalquest and Scheffer (1942, p. 73) reported this material as resting in a depression in the bedded gravel. Newcomb (1952, p. 463)[6] reported that in many places the black coloration includes the stratified gravel, and he reported that

> "The depth to which this black coloration extends...is roughly proportional to the thickness of the black soil mound above...."

However, observations by Noble and Molenaar (1965, p. 64) support the earlier reports. Interestingly, depressions are also reported by Freeman (1926, 1932) and Olmsted (1963, p. 48-49) as occurring quite generally in basalt bedrock below mounds of the Columbia Plateau; Olmsted also reported depressions in coarse gravel of the Plateau. However, Waters and Flagler (1929, p. 221-222) failed to observe such depressions and their general occurrence remains to be confirmed. Freeman (1926) and Olmsted (1963, p. 50, 52) thought of the depressions as sediment traps, which might also be the case in the prairie gravels, or the depressions might be a record of gopher activity as Larrison (1942, p. 37, 39) and Dalquest and Scheffer (1942, p. 1) believed. Also the depressions are similar to those left by windthrow of trees (Thomas Dunne, Univ. of Washington, oral commun., 1984).

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[6] Newcomb's (1952, p. 465) citation of Bretz on this point is incorrect.

Mima mounds occur with and without underlying depressions as observed by the present writer; Arkley and Brown (1954, p. 196) found this to be true also for Mimalike mounds in Merced and Stanislaus Counties, California. In addition, the present writer has seen Mima mound cross sections that exhibited downward colorations that were reminiscent of Newcomb's observations but were like mound roots in shape, rather than biconvex. In any event, without confirmation of the universality of the biconvex shape, it would be premature to follow Price (1950, p. 358) in making this feature a strict requirement for categorizing a Mima (or pimple) mound as such (see also Krinitzsky, 1950).

Mound groupings as seen in air photos show elongate and curving trends, reflecting drainage patterns (Fig. 4; also shown in Fig. 13, Violet Prairie), as noted by Campbell (1962, p. 10). Individual mounds tend to be elliptical with long axis parallel to the group trend, and in places the mounds have a blunt upslope end (Ritchie, 1953, p. 48). Less commonly the upslope end is the narrower. The overall mound pattern is clearly old as shown by lack of channelling today except in a few places where modern drainage has been diverted to mound areas; where there is contemporary runoff, it tends to be guided by the old mound distribution.

The overall distribution of Mima mounds (as the term is here used) is restricted, so far as known, to the prairies on recessional outwash of the Vashon Stade. This outwash surface descends along a complex of terraced former drainageways that emanated from the ice at different places and times. The highest of the prairies with Mima mounds is Lost Lake Prairie at an altitude of 146 m, the lowest probably Cedarville Prairie at an altitude of 24 m. According to Dalquest and Scheffer (1944, p. 325), gopher-inhabited Mima-mounded prairies, arranged according to decreasing mound height, are Rocky, Baker (Rochester), Mound (Grand Mound), Vail, Lost Lake (near Shelton, Wash.), and Scott's (also near Shelton) Prairies. (See Fig. 2.) Mima Prairie carries the largest Mima mounds, at 2.4 m or more high (McFaul, 1979, p. 1), and is the type locality, but it is no longer inhabited by gophers. Scott's Prairie mounds average about 0.5 m (2 ft) high (Dalquest and Scheffer, 1942, p. 69, 72, 81).

In addition to Mima mounds, Bretz (1913, p. 82, 86-87) also recognized Ford-type mounds. These differ from the Mima type in being larger, more irregular, containing larger stones, lacking their characteristic black soil, and being essentially kamelike. Ford mounds have a more restricted occurrence and probably no genetic relationship to Mima mounds. They are regarded as a separate problem and are only incidentally noted in this review.

Mima Prairie

For the most part the mounds of Mima Prairie are free of trees, but trees, mainly Douglas fir, are presently encroaching from the prairie margin (Giles, 1970). Treeless mounds are characterized by low herbaceous vegetation comprising grasses (dominantly *Agrostis diegoensis, Festuca idahoensis, Holcus lanatus*), mosses (especially *Rhacomitrium canescens, Polytrichum juniperinum*), and lichens (the larger clumps, comprising *Cladonia mitis* and *Cladonia rangiferina*) (Giles, 1970, p. 13-14). The distribution of vegetation has also been discussed in considerable detail by del Moral and Deardorff (1976), Evans and others (1975), and Klotz and Smith (1975).

Mima mounds occur not only on the low gradient of the general prairie surface but also in places on the somewhat steeper side slope of an old outwash channel on the east part of the prairie beyond the Bordeaux-Mima Road junction and, as noted by Bretz (1913, p. 93), on the terrace front represented by a break in slope between upper and lower levels of Mima Prairie. Some of the other prairies show similar mound/slope relationships (Bretz, 1913, p. 94).

The maximum side-slope angles of a number of mounds in the outwash channel referred to above were measured by laying an Abney level on a 2.4-m-long aluminum bar placed in quadrants parallel and at right angles to the channel. As summarized in Table 4, 24 of 26 mounds examined during three traverses across the bed of the channel had their steepest slopes facing approximately northeast upslope along the channel. Of the remaining two mounds, one showed no difference in slope steepness, the other had a 2° steeper downslope side. On the average, the greater angle on the upslope side of the 24 mounds was 2.4° greater than for the downslope side. It was notable that the steepest slopes were on the highest mounds. Ritchie (1953, p. 44, 48) reported that "blunter" upslope sides are characteristic of the Puget Lowland Mima mounds.

On Mima Prairie, low Mima mounds occur on the bottom and sides of a small kettle hole on the west side of the prairie (Figs. 4, 9), as first reported by Bretz (1913, p. 89, plate 4, fig. 2). Very low mounds, some less than 30 cm (1 ft) high (Newcomb, 1952, p. 348), occur in some intermound areas (Fig. 10).

As at all the prairies, most of the stones in the nonbedded black mound loam and the underlying bedded outwash are well rounded.

Paeth (1967) and Giles (1970) described the soil of several mounds and intermound areas on Mima Prairie (Tables 5 and 6), and Mark Weber (Univ. of

Table 4. Mound geometry

Mima Prairie
(26 mounds)

	Mound slopes facing				
	NE (upslope)	SE	SW (downslope)	NW	Remarks
Steepest slope (occurences)	24	0	1	0	1 mound with uniform slopes (< 0.5° difference) omitted
Average angle, all 26 mounds	11.8°	*	9.4°	*	

Rocky Prairie
(10 mounds)

	Mound slopes facing				
	N	E (downslope)	S	W (upslope)	Remarks
Steepest [or equal to steepest] slope (occurrences)	8	3	0	1	Occurrences exceed number of mounds because one mound had equally steep N and E slopes and one had equally steep N and W slopes
Average angle, all 10 mounds	12.1°	9.8°	7.6°	9.0°	

	Mound elongation				
		N-S	E-W		Remarks
Mounds (occurrences)		1	5		4 mounds omitted (3 had uniform diameters [< 0.5 m difference]; one too irregular to measure)
Average difference between mound length and width		0.8 m	1.2 m		

Violet Prairie
(12 mounds)

	Mound slopes facing				
	NE (upslope)	SE	SW (downslope)	NW	Remarks
Steepest [or equal to steepest] slope (occurrences)	6	7	0	2	Occurrences exceed number of mounds because one mound had equally steep NE and NW slopes, and 2 mounds had equally steep NE and SE slopes
Average angle, all 12 mounds	9.8°	10.1°	7.6°	8.3°	One mound with uniform slopes (< 0.5° difference) omitted

	Mound elongation				
		NE-SW	NW-SE		Remarks
Mounds (occurrences)		9	0		3 mounds with uniform diameters (± 0.1 m) omitted
Average difference between mound length and width	1.3 m				

*Not measured.

Figure 9.–Mounds in kettle hole, Mima Prairie.

Figure 10.–Low mound in intermound area, Mima Prairie.

Table 5. Grain-size distribution in Mima mounds and intermound areas, Mima Prairie, Mound Prairie, and Rocky Prairie (after Paeth, 1967, table 4, p. 21-22; see also figs. 3-5, p. 10; p. 60-61)[a]

				Sand[c] (%)							
Profile	Depth (cm)[b]	Horizon	Gravel (%)	Very coarse	Coarse	Medium	Fine	Very fine	Silt[c] (%)	Clay[c] (%)	Textural class[d]
Mima Prairie											
Mound	0-10	A11	59.8	5.2	4.7	3.6	3.1	1.2	19.1	3.2	Loam
	10-30	A12	66.4	3.9	4.2	3.3	2.7	0.9	16.3	2.3	Loam
	30-61	A13	70.3	2.6	3.7	2.9	2.6	1.0	15.1	2.0	Silt loam
	61-91	A14	60.7	3.3	5.1	3.9	3.4	1.3	19.7	2.6	Silt loam
	91-127	A15	56.9	4.0	5.0	4.1	3.5	1.4	22.5	2.7	Silt loam
	127-160	A16	56.5	3.8	4.9	4.2	3.7	1.4	23.4	2.2	Silt loam
	A-horizon average		61.8	3.8	4.6	3.7	3.2	1.2	19.4	2.5	
				/---		16.5		---/			
	160-178+	IIC	86.6	2.8	4.3	2.3	1.1	0.3	1.5	1.1	Loamy sand
	C horizon		86.6	/---		10.8		---/	1.5	1.1	
Intermound	0-13	A1	55.0	7.4	8.5	7.0	4.9	1.4	9.0	6.8	Sandy loam
	A horizon		55.0	/---		29.2		---/	9.0	6.8	
Mound Prairie											
Mound	0-15	A11	62.6	4.5	3.3	4.2	4.7	1.9	15.6	3.2	Loam
	15-30	A12	60.2	4.3	3.7	4.5	4.9	2.2	16.9	3.3	Loam
	30-61	A13	59.3	3.9	3.4	4.8	5.5	2.3	18.0	2.8	Loam
	61-91	A14	44.4	5.1	4.7	6.6	7.2	3.2	24.4	4.4	Loam
	A-horizon average		56.6	4.4	3.8	5.0	5.6	2.4	18.7	3.4	
				/---		21.2		---/			
	91-122	IIC	75.3	3.8	3.1	4.7	4.4	1.4	5.8	1.4	Sandy loam
	C horizon		75.3	/		17.4		/	5.8	1.4	
Intermound	0-15	A11	52.7	5.4	4.4	5.2	5.9	3.2	18.9	4.3	Sandy loam
	15-41	A12	43.6	6.3	5.5	6.6	7.6	3.3	24.1	3.0	Sandy loam
	41-61	A13	56.0	3.9	4.5	5.9	6.8	2.7	18.6	1.7	Sandy loam
	A-horizon average		50.8	5.2	4.8	5.9	6.8	3.1	20.5	3.0	
				/---		25.8		---/			
	91-122	IIC	72.4	9.2	3.3	3.4	4.1	1.4	4.1	2.1	Loamy sand
	C horizon		72.4	/---		21.4		---/	4.1	2.1	
Rocky Prairie											
Mound	0-15	A11	56.6	3.4	7.0	5.3	3.9	1.8	13.9	8.0	Loam
	15-30	A12	39.4	3.3	10.2	7.9	6.0	2.6	18.0	12.6	Loam
	30-61	A13	23.1	4.8	14.6	10.5	8.0	3.5	21.0	14.5	Sandy loam
	61-76	A14	43.9	3.4	10.4	7.4	5.7	2.6	16.3	10.3	Sandy loam
	76-102	A15	60.2	2.8	8.0	5.8	4.7	1.9	11.2	5.5	Sandy loam
	A-horizon average		44.6	3.5	10.0	7.4	5.7	2.5	16.1	10.2	
				/---		29.1		---/			
	102-102+	IIC	57.1	3.3	6.9	9.4	14.1	3.6	2.4	3.3	Loamy sand
	C horizon		57.1	/---		37.3		---/	2.4	3.3	
Intermound	0-13	A1	14.4	3.8	16.7	13.7	8.1	3.5	24.7	15.2	Sandy loam
	A horizon		14.4	/---		45.8		---/	24.7	15.2	

[a] Grain sizes follow U.S. Department of Agriculture classification.

[b] Depth originally given in inches.

[c] Recalculated as percent of total sample; sand, silt, and clay originally given as percent of total < 2 mm.

[d] Textural class as given by Paeth, based on sand, silt, and clay as percent of total < 2 mm.

Table 6. Grain-size distribution in Mima mounds and intermound areas, Mima Prairie and Rocky Prairie (after Giles, 1970, tables 11 and 12, p. 45-56; see also p. 41-44)[a]

	Depth (cm)	Gravel (%)	Sand, silt, and clay combined (%)		
Mima Prairie[b]					
Prairie zone					
Mound:					
NE slope	0-15	59.9	40.1		
SE slope	0-15	59.9	40.1		
SW slope	0-15	59.9	40.1		
Average	0-15	59.9	40.1		
Intermound	0-15	65.6	34.4		
Ecotone					
Mound:					
N slope	0-15	59.9	40.1		
S slope	0-15	59.9	40.1		
Average	0-15	59.9	40.1		
Forest					
Mound:					
N slope	0-15	59.9	40.1		
S slope	0-15	59.9	40.1		
Average	0-15	59.9	40.1		
Intermound	0-15	65.6	34.4		
Average					
Mound	0-15	59.9	40.1		
Intermound	0-15	65.6	34.4		
			Sand[c] (%)	Silt[c] (%)	Clay[c] (%)
Rocky Prairie					
Mound top:	0-15	58.4	24.8	13.3	3.5
NE slope	0-15	61.1	22.8	13.5	2.6
SW slope	0-15	57.6	27.8	11.7	2.9
Average	0-15	59.0	25.1	12.8	3.0
Intermound	0-15	68.8	21.7	7.8	1.7

[a] Grain sizes follow U.S. Department of Agriculture classification.

[b] The repetition of identical values in the Mima Prairie data is puzzling and probably in error; Giles offered no comment on it. The values are omitted in consolidating Mima mound grain-size averages (Table 13).

[c] Recalculated as percent of total sample; sand, silt, and clay originally given as percent of total < 2 mm.

Washington, written commun., 1970)[7] investigated the soils of three well-exposed cross sections of mounds in a Mima Prairie gravel pit abutting the north side of Bordeaux Road about 1 km west of its intersection with Mima Road (Figs. 4, 6, 7). Weber recognized four horizons–O_0, A_1, B_3, and C. He noted that the black (10 YR 2/1) A_1 mound horizon overlies the C-horizon bedded outwash with angular unconformity, but he was uncertain whether the iron-stained B_3 (10 YR 3/2) horizon represented a truncated paleosol or was a pedogenic phase of the overlying soil. He also found that the grain-size distribution (Fig. 11, Table 7) differs sharply between the relatively fine-grained A_1 (mound) horizon and the coarser C (bedded outwash) horizon, with the B_3 horizon generally following the grain-size characteristics of the A_1 horizon. Unfortunately, Weber's report, like many others, omitted data on the stone sizes in the gravel. In places, the present writer has noted a sharp-edged, discontinuous deposit of silica on stones in the bedded outwash.

Weber also reported Atterberg indices of the solum (that is, excluding C horizon): Liquid limits 33.0-56.4 percent and plastic limits 31.4-59.3 percent, both ranges generally decreasing with depth. Consequently, the soil of the solum could be classed as a low-plastic, organic silt. An analysis of organic-matter content has been given by Paeth (Table 8) and R. S. Sletten (Table 9). One-cycle shrinkage tests by Weber yielded a linear shrinkage of 0.81-3.49 percent, without any apparent trend with depth.

The origin of the black, nonbedded deposit overlying the bedded outwash is problematical. It has been interpreted as "overwash" of glacial streams (Dalquest and Scheffer, 1942, p. 69) and as reflecting the decreased competency of outwash streams as the ice withdrew northward (McFaul, 1979, p. 49, 60-61). As already noted, the lack of bedding has been generally attributed to bioturbation, but windthrow of trees prior to prairie development may also be involved. The contact with the bedded outwash is generally planar and appears to be erosional in some places but to represent continuous aggradation in others, consistent with subsiding flood waters. Some of the silt may well be loess. The stones are predominantly pebble size (that is, up to 6.4 cm in longest diameter in Wentworth classification). The fact they tend to be isolated and scattered supports the bioturbation interpretation. Cobbles up to at least 9 cm in maximum diameter are also present well within the black mound soil of Mima Prairie as determined by the present writer when digging into a mound section along a road cut. A small boulder weighing 3.4 kg and having diameters of 8, 15, and 20 cm was noted on the slope of

[7] Weber's observations are summarized in some detail, since they are from an unpublished student report and are otherwise unavailable.

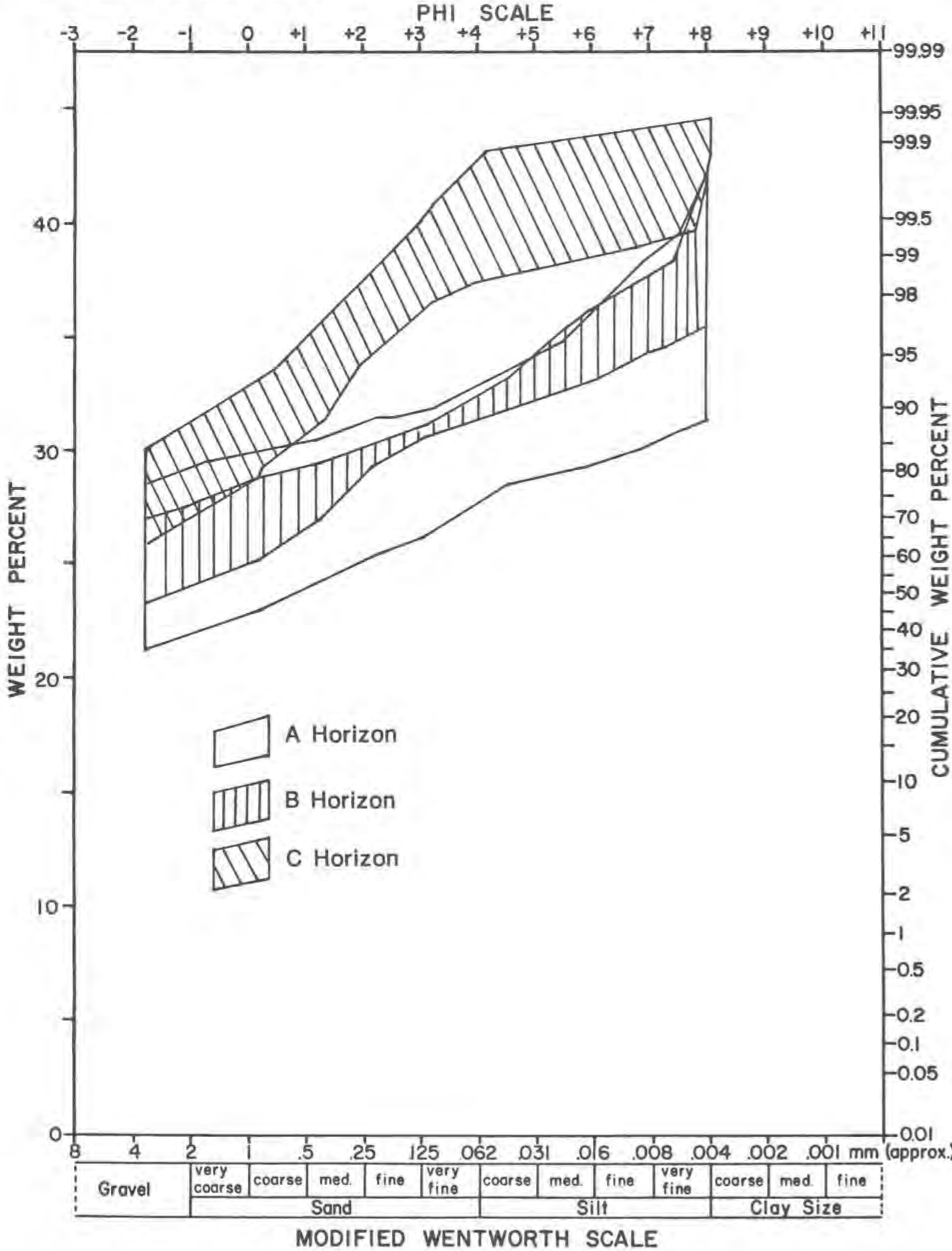

Figure 11.–Envelopes of grain-size distributions of A, B, and C horizons of three Mima mounds in a gravel pit, Mima Prairie, north side of Bordeaux Road, about 1 km west of intersection with Mima Road (after Mark Weber, Univ. of Washington, written commun., 1970).

Table 7. Grain-size distribution and soil color of Mima mounds, Mima Prairie (after Mark Weber, Univ. of Washington, written commun., 1970)[a]

	Horizon	Depth[b] (cm)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Munsell color
Mound 1	A1	0-19	72.1	16.5	/-----11.4-----/		10YR 2/1
	A1	19-46	70.0	16.4	12.9	0.7	10YR 2/1
	A1	46-76	68.3	17.1	14.1	0.5	10YR 2/1
	A1	76-107	73.1	14.7	11.8	0.4	10YR 2/1
	A1	107-137	61.7	22.2	14.0	2.1	10YR 2/1
	A1	137-157	78.3	12.5	8.9	0.3	10YR 2/1
	A1	157-168	70.7	17.5	11.2	0.6	10YR 2/1
	A-horizon average		70.6	16.7	12.2	0.8	
	B3	168-203	53.1	34.8	11.4	0.7	10YR 3/2
	B horizon		53.1	34.8	11.4	0.7	
	C	203-234	72.5	26.0	1.4	0.1	10YR 3/3
	C	234-264	80.0	19.6	0.3	0.1	10YR 3/3
	C-horizon average		76.2	22.8	0.8	0.1	
Mound 2	A1	0-30	66.0	16.8	16.4	0.8	10YR 2/1
	A1	30-74	64.6	19.1	16.0	0.3	10YR 2/1
	A-horizon average		65.3	18.0	16.2	0.6	
	B3	74-86	74.8	13.8	11.1	0.3	10YR 3/2
	B horizon		74.8	13.8	11.1	0.3	
	C	86-117	79.6	19.8	0.5	0.1	10YR 3/3
	C	117-147	89.7	9.9	0.3	0.1	10YR 3/3
	C-horizon average		84.6	14.8	0.4	0.1	
Mound 3							
West profile	A1	8-11	81.1	9.1	6.3	3.5	10YR 2/1
	A1	15-19	55.0	25.9	18.6	0.5	10YR 2/1
	A1	23-27	57.1	25.0	17.6	0.3	10YR 2/1
	A1	30-34	70.0	16.0	13.7	0.3	10YR 2/1
	A1	38-42	68.5	17.4	13.6	0.5	10YR 2/1
	A1	46-50	74.6	13.5	11.7	0.2	10YR 2/1
	A1	53-57	72.0	15.0	12.5	0.3	10YR 2/1
	A1	61-65	67.2	18.8	13.5	0.5	10YR 2/1
	A1	69-72	53.0	26.3	20.1	0.6	10YR 2/1
	A-horizon average		66.5	18.6	14.2	0.7	
North profile	Oo	0-5	39.0	27.0	27.1	6.9	10YR 2/1
	A1	5-15	62.6	21.0	6.1	10.3	10YR 2/1
	A1	15-30	43.5	32.0	16.7	7.8	10YR 2/1
	A1	30-41	72.9	14.2	8.2	4.7	10YR 2/1
	A-horizon average		59.7	22.4	10.3	7.6	
	B3	41-56	80.6	18.4	1.0	-----	10YR 3/2
	B horizon		80.6	18.4	1.0	-----	
	C	56-74	70.4	29.5	0.1	-----	10YR 3/3
	C horizon		70.4	29.5	0.1		

[a] Grain sizes follow modified Wentworth classification (essentially comparable to U.S. Department of Agriculture classification for most purposes, main difference being clay sizes <0.004 mm rather than <0.002 mm as in U.S.D.A. classification).

[b] Depth originally given in inches.

Table 8. Organic matter in Mima mounds, Mima Prairie, Mound Prairie, and Rocky Prairie (after Paeth, 1967, table 7, p. 30)[a]

	Depth[b] (cm)	Horizon	Organic matter (%)
Mima Prairie			
Mound	0-10	A11	32.7
	10-30	A12	24.9
	30-61	A13	21.8
	61-91	A14	18.5
	91-127	A15	15.8
	127-160	A16	11.9
		A-horizon average	21.0
	160-178+	IIC	3.2
		C horizon	3.2
Intermound	0-13	A1	31.8
		A horizon	31.8
Mound Prairie			
Mound	0-15	A11	27.7
	15-30	A12	25.2
	30-61	A13	21.8
	61-91	A14	23.1
		A-horizon average	24.4
	91-122	IIC	4.2
		C horizon	4.2
Intermound	0-15	A11	26.3
	15-41	A12	21.4
	41-61	A13	14.1
		A-horizon average	20.6
	91-122	IIC	5.1
		C horizon	5.1
Rocky Prairie			
Mound	0-15	A11	25.3
	15-30	A12	22.0
	30-61	A13	21.0
	61-76	A14	19.6
	76-102	A15	13.1
		A-horizon average	20.2
	102-102+	IIC	0.8
		C horizon	0.8
Intermound	0-13	A1	26.7
		A horizon	26.7

[a] "Organic matter was determined by the Walkley-Black (1934) method" (Paeth, 1967, p. 12).

[b] Depth originally given in inches.

a mound about 150 m south of the wooden viewing platform at the Mima Mounds Preserve Interpretive Center. The mound is at the open edge of the area where isolated trees are invading the prairie, but the mound was treeless. The boulder was flat lying and well imbedded in the moss and grass surface to a depth of 8 cm, and, except for rootlets curving beneath it at the edges, it rested on black, organic-rich pebbly silt, characterized by ant activity. The boulder was partially lichen covered and much darker colored on its upper than lower surface. It had obviously been in its present position for a long time. It lay 69 cm above the low point of the adjacent intermound area, which exhibited some cobbles, and 57 cm above the break in slope at the mound base. No other stones were seen on the mound above the intermound flat, and there was no evidence that the bedded outwash gravel lay higher in the mound than around it. If the boulder was not originally part of the mound, man may be responsible for its presence, but small animals were not.

Three more large stones were found imbedded at the base of a sizeable Douglas fir on a mound some 10 m distant. Unlike the small boulder on the treeless mound, these stones lay on a duff that included decayed evergreen needles. The tree base made a bulge on the mound side. As with some other mounds having trees and surface stones[8], the significance of these stones is doubtful.

Table 9. Carbon and organic matter in Mima mound, Mima Prairie. Data from R. S. Sletten (Univ. of Washington, written commun., 1987)

Depth[a] (cm)	Horizon	Carbon[b] (%)	Organic matter[c] (%)
110-115	A	2.9	5.0
115-130	A	3.4	5.9
130-155	A	1.5	2.6
	A-horizon average		4.5

[a] Mound was same one sampled for radiocarbon dating (Table 2B).

[b] Walkley-Black carbon.

[c] Walkley-Black carbon multiplied by 1.724.

[8] Large cobbles are present on mound surfaces in the treed area near the Interpretive Center and start of the Mima Mounds Nature Trail at the north end of Mima Prairie. These cobbles are only slightly imbedded in the mound surfaces, and the area was disturbed during logging operations in the 1930s and in 1960. Since the cobbles may have reached their present position during these operations or have been brought up from the bedded outwash underlying the mounds as the result of uprooting of trees by wind (see Denny and Goodlett, 1956; Troedsson and Lyford, 1973, p. 10-13), they can not be accepted as *in-situ* mound material. However, all the Puget prairie stones whose measurements are reported here were from treeless mounds in areas commonly believed to have been treeless for thousands of years and only recently subject to invasion by a fringe of isolated trees as illustrated at the Interpretive Center.

Figure 12.–Stone in mound crest, Rocky Prairie.

Mima Prairie also carries a few of the Ford-type mounds, described earlier as being characterized by coarser material and lacking the black soil of the Mima mounds. Ford-type mounds are rare on Mima Prairie but are present at the south end in the immediate vicinity of Gate. In places Mima mounds are reported to lie on the flanks of Ford mounds (Bretz, 1913, p. 95), and they seem to be clearly the younger of the two. Ford mounds are better developed on some of the other prairies (Bretz, 1913, p. 86).

Mound Prairie

Mound Prairie is mentioned by Bretz (1913, p. 86, 88, and elsewhere)[9], who probably included the areas presently known as Violet Prairie and Rock Prairie. The soil of Mound Prairie has been described by Paeth (1967) (Table 5), including its organic-matter content (Table 8).

Rock Prairie

Rock Prairie differs from Mima Prairie in having several unusually prominent Ford-type mounds that are similar to kames in appearance and have circular depressions of uncertain origin at their top. These mounds are similar or identical to the ones Bretz (1913, p. 86) described from Mound Prairie, and since his description appears to include the area of the present Rock Prairie, the identical mounds may be involved. Excavation by archeological colleagues and the writer showed no indication of possible human origin of the depressions. These mounds probably have no genetic relation to the Mima mounds, which occupy outwash surfaces below them.

McFaul (1979, p. 55-56) reported that measurements of 50 mounds on Rock Prairie showed mean slope angles ranging from 8.9° to 10.1°, which led him to conclude that the slopes were essentially uniform. Their orientation with respect to drainage direction was not specified.

The southeast end of Rock Prairie is characterized by a terrace scarp that carries a few Mima mounds, similar to the situation Bretz described for Mima Prairie.

[9] Bretz used the name Grand Mound Prairie but the shorter form is now common in federal and state publications.

Table 10. Grain-size distribution and soil pH of Mima mounds, Rocky Prairie (after McFaul, 1979, table 8, p. 50; see also p. 45-49)[a]

	Depth[b] (cm)	Horizon	Gravel (%)	Sand[c] (%)	Silt[c] (%) Coarse	Silt[c] (%) Fine	Clay[c] (%)	pH
Mound 3								
	8	A	56.8	22.9	2.4	9.2	8.6	5.0
	30	A	48.2	25.7	2.7	13.4	9.6	5.05
	107	A	69.6	16.5	1.6	6.1	6.2	5.15
	A-horizon average		58.2	21.7	2.2	9.6	8.1	
					/-----11.8-----/			
	142	B	72.1	17.6	1.4	3.4	5.4	5.55
	152	C	63.1	29.1	0.9	1.9	5.1	5.58
Mound 4[d]								
	5-8	A	58.4	21.4	3.4	8.2	8.6	4.95
	38	A	26.5	40.2	5.3	14.4	13.6	5.15
	A-horizon average		42.4	30.8	4.4	11.3	11.1	
					/-----15.7-----/			
	71	B	68.6	19.1	1.9	4.1	6.2	5.3
	91	C	76.9	17.9	0.0	1.7	3.5	5.45
Intermound (M5)								
	5-15	A	27.2	40.3	4.1	12.5	15.9	5.05
	18-30	A	50.7	29.1	4.5	7.7	8.0	5.18
	A-horizon average		39.0	34.7	4.3	10.1	12.0	
					/-----14.4-----/			
	48	B	52.9	30.1	1.6	6.3	9.1	5.2
	71	C	44.7	41.8	1.7	4.4	7.4	5.35

[a] Grain sizes follow U.S. Department of Agriculture system.

[b] Depths originally given in inches.

[c] Recalculated as percent of total sample; sand, silt, and clay originally given as percent of total <2 mm.

[d] At break in slope adjacent to intermound area.

Rocky Prairie

Rocky Prairie includes the area Bretz (1913, p. 88) described as Walricks or Eaton's Prairie. It is somewhat similar to Rock Prairie in having larger stones on the surface between the Mima mounds. Large stones also occur on the mounds. For instance, cobbles or boulders were found well imbedded in pebbly silt at or near the crest of seven Mima mounds (Fig. 12). Five of the stones ranged in weight from 2.2 to 7.3 kg, and two boulders appreciably exceeded 7.5 kg (scale limit), the diameters of the largest one measuring 16, 21, and 35 cm. One of the stones (4.7 kg) was in a treed mound, the others not. Unlike the large cobbles at the surface of the treed mounds at the north end of Mima Prairie, these stones could well be *in situ* except for those on the treed mound. Where there are large trees, slight soil rises as much as 30 cm high at the trunks were noted in places, also above radiating tree roots. Especially in intermound areas, such rises tend to be obvious sites of stones, including small boulders. Former trampling by cattle, of which there was ample evidence, probably contributed to exposure of the stones in these areas.

All the mounds described above are Mima mounds. None conform in the least to Bretz' description of Ford mounds, but the area also contains a kamelike rise that corresponds to the Ford type in bearing a few Mima mounds on its surface.

Soil descriptions from Rocky Prairie have been presented by Paeth (1967) (Table 5), Giles (1970) (Table 6), and McFaul (1979) (Table 10). Percentages of soil organic matter are shown in Tables 8 and 11.

Ten mounds, located in an approximately east-west, irregular channel-like depression leading east toward Offutt Lake, were measured with respect to orientation of the steepest slopes. Here, contrary to the situation at Mima Prairie (and Violet Prairie, discussed later) and to initial expectation, eight of ten mounds, measured east-west and north-south, had their steepest slope facing either east downslope along the depression or north toward a rise roughly parallelling it (Table 4). Only one of the ten mounds had its steepest side facing upgradient along the depression. However, it became apparent that the original gradient of the depression was almost certainly westerly, the direction both of the present drainage slightly farther west and of the early drainage as the ice withdrew, and that the present opposite gradient reflects local slumping due to wasting of buried ice. Kettle holes abound to the east, especially the large basin of Offutt Lake itself.

Measurements were also made north-south and east-west parallel to the mound surface. Of the ten mounds, five averaged 1.2 m longer east-west than north-south. Three mounds showed a difference of less than 0.5 m and were regarded as essentially circular, and one mound was slightly elongated north-south.

Table 11. Organic matter in Mima mounds, Rocky Prairie (after McFaul, 1979, table 9, p. 58)[a]

	Depth (cm)	Horizon	Organic matter (%)
Mound 3			
	30.5	A	27.6
	106.7	A	21.4
		A-horizon average	24.5
Mound 4			
	5-7.6	A	26.0
	38.1	A	30.9
		A-horizon average	28.4
Intermound (M5)	5-15.2	A	28.8

[a] ". . . a La Motte No. 5020 apparatus was used to determine the organic matter content (Walkley and Black, 1934)" (McFaul, 1979, p. 33). "Based on 'the conventional assumption . . . that organic matter contains 58% carbon' (see Hesse, 1971 [1972], [p.] 209), the percentages of organic carbon were multiplied by 1.724 to obtain the total organic matter percentages" (McFaul, 1979, p. 57). The assumption is open to question (Hesse, 1972, p. 209, 246).

The small size of the sample makes the results questionable, but they suggest that the mounds were affected by the early westerly drainage. The relatively steep slopes facing both north and east may reflect lateral erosion or southerly components to the original westerly drainage.

Violet Prairie

Violet Prairie is an excellent example of Mima mounds conforming to a braided stream pattern, with the mounds occurring on surfaces at slightly different altitudes (Fig. 13). The mounds are low and consist of black gravelly silt as shown by abundant fossorial-rodent spoil heaps. Sporadic cobbles are apparent in intermound areas, and some of the higher intermound areas are small, shallow depressions that may be kettle holes. Prominent channels occur at different levels. One of the higher channels near the northwest side of the Tenino-Grand Mound highway trends north-south and lies 2.5 m below a bar paralleling it on its east side. The bar, like the rest of the surface and the channel itself, carries low Mima mounds, the one at the north end of the bar being 0.5 m high. In places the mounds seem to guide the channel as it reaches the top of a 3-m-high scarp separating it from a lower, more prominent broad channel

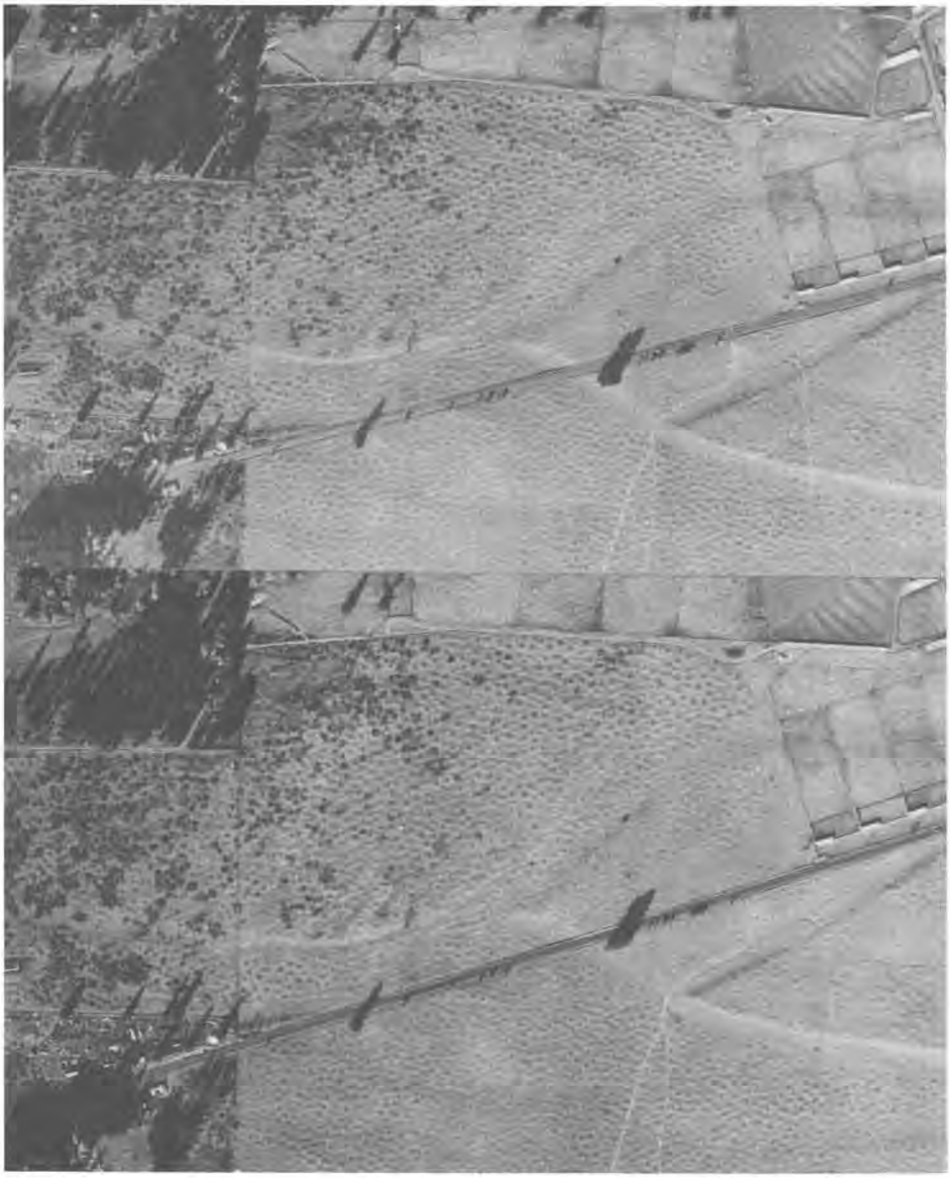

Figure 13.–Mound-related drainage pattern, Violet Prairie. Stereoscopic pair prepared from photos 10 and 11, Washington Department of Transportation I.D. no. 3430-0-6, 1984. Scale 1:12,000.

trending northeast-southwest parallel to the northwest side of the highway. From here, this lower channel branches upslope, with one branch crossing the highway and continuing on Rock Prairie. The northeast-southwest section of the lower channel has a southeast cross-channel descent of about 2 m from the base of the 3-m scarp rising to the higher surface. A number of low mounds similar to those on the higher surfaces but generally somewhat better developed occur in this northeast-southwest channel section.

The geometry of 12 of these mounds, which are from 0.3 m to 1.1 m high, was examined along three traverses across the channel. As at the Mima Prairie location described earlier, there was a consistent difference in the inclination of mound slopes as summarized in Table 4. The mound slopes facing northeast up the channel and southeast across it were (with one exception) the steepest both on average and individually. The lowest angles on average were on the southwest (downslope) sides of the channel, but individually the trend was somewhat inconsistent. Regardless of orientation, the side slopes with the lowest angles corresponded to the lowest mounds.

The exact boundary of individual mounds was difficult to determine, but repeated measurement (on the curved mound surfaces) showed that mound lengths

Table 12. Grain-size distribution and organic matter in unmounded Spanaway soil, Weir Prairie

(Data from Liyuan Wang, Univ. of Washington, written commun., 1987)

Depth (cm)	Horizon	Sand[a] (%)	Silt[a] (%)	Clay[a] (%)	Carbon[b] (%)	Organic matter[c] (%)
0-27	A1	84.0	13.6	2.4	9.78	16.86
27-48	A2	79.1	17.5	3.4	5.77	9.92
		A-horizon average				13.4
46-68	Bw	86.1	6.9	7.0	2.88	4.95
68-100+	C	92.6	5.0	2.4	0.68	1.17

(Modified from Ugolini and Schlichte, 1973, table 2, p. 223)

Depth (cm)	Profile no.	Horizon	Carbon[b] (%)	Organic matter[c] (%)
0-40	(1)	A1	14.4	24.8
0-30	(2)	A1	12.2	21.0
0-28	(3)	A1	15.6	26.9
		A-horizon average		24.2
40-58	(1)	B2	7.4	12.8
30-50	(2)	B2	7.3	12.6
28-52	(3)	B2	8.2	14.1
58-81	(1)	B3	3.6	6.2
50-75	(2)	B3	3.9	6.7
52-75	(3)	B3	3.2	5.5
		B-horizon average		9.6
81+	(1)	IIC2	3.1	5.3
75+	(2)	IIC2	3.4	5.9
75+	(3)	IIC2	2.9	5.0
		C-horizon average		5.4

[a] Grain sizes follow U.S. Department of Agriculture classification.

[b] Walkley-Black carbon. The 77% correction factor omitted by Ugolini and Schlichte (1973, p. 221; table 2, p. 223) has been applied to their readily oxidizable carbon determinations.

[c] Walkley-Black carbon multiplied by 1.724. Not given by Ugolini and Schlichte in their table 2, but here added for comparison with organic matter determinations in Tables 8, 9, 11, 13, and 14 of present report.

parallel to the channel exceed mound widths in nine of the 12 mounds. The remaining three mounds are equidimensional. Considering all 12 mounds, the average length exceeds the average width by 0.9 m, the actual differences ranging from 0 to 2.5 m. For the nine elongate mounds, the average difference is 1.3 m. The elongation is consistent but small compared to the average mound length of 11.6 m and width of 10.3 m—a L/W ratio of 1.13 for the nine mounds.

The comparatively steep northeast (upslope) sides of the elongate mounds support the view that the mounds were subject to erosion while the channel still carried drainage. Although the low L/W ratio argues against the mounds having attained a typical fluvial equilibrium form with a L/W ratio near 3-4:1 (Komar, 1983), its value >1 is quite consistent with some fluvial modification. The reason for the steeper southeast than northwest mound sides may lie in fluvial hydraulics, with drainage flowing deeper and longer on the southeast sides because of the cross-channel slope to the southeast.

A detailed mound-measurement program involving much larger samples from the Puget prairies is needed.

Weir Prairie

Weir Prairie soils nearly 5 km (3 mi) northwest of the town of Rainier (Fig. 2) were discussed by Ugolini and Schlichte (1973), who provided various parameters for a mound-free area as part of a comparison of the Spanaway soil series with the Everett series. Subsequently, additional analyses from the same area were made by Liyuan Wang (Univ. of Washington, written commun., 1987). Table 12 shows Weir Prairie grain-size and organic-matter analyses, compared with summary analyses of mounded Spanaway soils from other prairies.

Discussion

The various soil grain-size distributions and soil organic-matter contents of the Mima mounds and intermound areas given in Tables 5-12 are summarized in Table 13. The data trend is reasonably consistent for the A and C horizons of the different prairies, but some of the grain-size analyses for the B horizon tend to parallel those of the A horizon, others the C horizon, and some are intermediate. This probably reflects the fact that in

Table 13. Average grain-size distribution and content of organic matter in Mima mounds and intermound areas, Mima Prairie, Mound Prairie, and Rocky Prairie, in percent

	A horizon				B horizon				C horizon				Organic matter	
	Gravel	Sand	Silt	Clay	Gravel	Sand	Silt	Clay	Gravel	Sand	Silt	Clay	A horizon	C horizon
Mima Prairie														
Table 4														
Mound	61.8	16.5	19.4	2.5					86.6	10.8	1.5	1.1		
Intermound	55.0	29.2	9.0	6.8										
Table 5														
Mound 1	70.6	16.7	12.2	0.8	53.1	34.8	11.4	0.7	76.2	22.8	0.8	0.1		
Mound 2	65.3	18.0	16.2	0.6	74.8	13.8	11.1	0.3	84.6	14.8	0.4	0.1		
Mound 3														
W profile	66.5	18.6	14.2	0.7										
N profile	59.7	22.4	10.3	7.6										
Average	65.6	18.9	13.2	2.4	64.0	24.3	11.2	0.5	80.4	18.8	0.6	0.1		
Table 6														
Mound	59.9	/---------40.1---------/												
Intermound	65.6	/---------34.4---------/												
Average (excl. Table 6)														
Mound	63.7	17.7	16.3	2.4					83.5	14.8	1.0	0.6		
Intermound	55.0	29.2	9.0	6.8										
Table 8														
Mound													21.0	3.2
Intermound													31.8	
Table 10														
Mound													(4.5)[a]	
Mound Prairie														
Table 4														
Mound	56.6	21.2	18.7	3.4					75.3	17.4	5.8	1.4		
Intermound	50.8	25.8	20.5	3.0					72.4	21.4	4.1	2.1		
Table 8														
Mound													24.4	4.2
Intermound													20.6	5.1
Rocky Prairie														
Table 4														
Mound	44.6	29.1	16.1	10.2					57.1	37.3	2.4	3.3		
Intermound	14.4	45.8	24.7	15.2										
Table 6														
Mound														
Top	58.4	24.8	13.3	3.5										
NE slope	61.1	22.8	13.5	2.6										
SW slope	57.6	27.8	11.7	2.9										
Average	59.0	25.1	12.8	3.0										
Intermound	68.8	21.7	7.8	1.7										
Table 7														
Mound 3	58.2	21.7	11.8	8.1	72.1	17.6	4.8	5.4	63.1	29.1	2.8	5.1		
Mound 4	42.4	30.8	15.7	11.1	68.6	19.1	6.0	6.2	76.9	17.9	1.7	3.5		
Average	50.3	26.2	13.8	9.6	70.4	18.4	5.4	5.8	70.0	23.5	2.2	4.3		
Intermound (M5)	39.0	34.7	14.4	12.0	52.9	30.1	7.9	9.1	44.7	41.8	6.1	7.4		

[a] Lower A horizon only (sample depths 110-155 cm). Excluded from Average, All Tables.

Table 13. Average grain-size distribution and content of organic matter in Mima mounds and intermound areas (continued)

	A horizon				B horizon				C horizon				Organic matter	
	Gravel	Sand	Silt	Clay	Gravel	Sand	Silt	Clay	Gravel	Sand	Silt	Clay	A horizon	C horizon
Table 8														
Mound													20.2	0.8
Intermound													26.7	
Table 9														
Mound 3													24.5	
Mound 4													28.4	
Average													26.4	
Intermound (M5)													28.8	
Average, All Tables														
Mounds														
Mima Prairie														
Table 4	61.8	16.5	19.4	2.5					86.6	10.8	1.5	1.1		
Table 5	65.6	18.9	13.2	2.4	64.0	24.3	11.2	0.5	80.4	18.8	0.6	0.1		
Table 8													21.0	3.2
Mound Prairie														
Table 4	56.6	21.2	18.7	3.4					75.3	17.4	5.8	1.4		
Table 8													24.4	4.2
Rocky Prairie														
Table 4	44.6	29.1	16.1	10.2					57.1	37.7	2.4	3.3		
Table 6	50.9	25.1	12.8	3.0										
Table 7	50.3	26.2	13.8	9.6	70.4	18.4	5.4	5.8	70.0	23.5	2.2	4.3		
Table 8													20.2	0.8
Table 9													26.4	
Average	56.3	22.8	15.6	5.2	67.2	21.4	8.3	3.2	73.8	21.6	2.5	2.0	23.0	2.7
Intermound														
Mima Prairie														
Table 4	55.0	29.2	9.0	6.8										
Table 8													31.8	
Mound Prairie														
Table 4	50.8	25.8	20.5	3.0					72.4	21.4	4.1	2.1		
Table 8													20.6	5.1
Rocky Prairie														
Table 4	14.4	45.8	24.7	15.2										
Table 6	68.8	21.7	7.8	1.7										
Table 7	39.0	34.7	14.4	12.0	52.9	30.1	7.9	9.1	44.7	41.8	6.1	7.4		
Table 8													26.7	
Table 9													28.8	
Average	45.6	31.4	15.2	7.7	52.9	30.1	7.0	9.1	58.6	31.6	5.1	4.8		

Table 14. Summary comparison, A and C horizons in mounded and unmounded Spanaway soil, Puget prairies, in percent, derived from Tables 12 and 13.

Mounds	A Horizon				C Horizon			
	Gravel[a]	Sand	Silt+ clay	Organic matter	Gravel[a]	Sand	Silt+ clay	Organic matter
Mima Prairie	63.7	17.7	18.8	21.0	83.5	14.8	1.6	3.2
	-----	48.8	51.8		-----	89.7	9.7	
Mound Prairie	56.6	21.2	22.1	24.4	75.3	17.4	7.2	4.2
	-----	48.8	50.9		-----	70.4	29.1	
Rocky Prairie	51.3	26.8	21.8	23.3	63.6	30.4	6.1	0.8
	-----	55.0	44.8		-----	83.5	16.8	
Average[b]	56.3	22.8	20.8	23.0	73.8	21.6	4.5	2.7
	-----	52.2	47.6			82.4	17.2	
Unmounded Spanaway soil								
Weir Prairie		81.6	18.4	13.4[c] 24.2[d]	-----	92.6	7.4	1.17[c] 5.4[d]

[a] Averages omitting gravel are recalculated from the line above to permit comparison with Weir Prairie grain sizes for which gravel determinations were lacking. Differences from 100% result from rounding.

[b] Some of these final averages with gravel differ slightly from those in "Average, All Tables" in Table 13 because the latter averages involve a somewhat different combination of data.

[c] Table 12-Liyuan Wang (Univ. of Washington, written commun., 1987).

[d] Table 12-Ugolini and Schlichte (1973).

the field the B horizon is far less obvious than either the black nonbedded A horizon or the light-colored bedded C horizon to which it tends to be transitional. Further, a number of the analyses do not include the B horizon, which in such cases may or may not have been recognized in the field. Consequently, B-horizon data are omitted from most of the following discussion of grain-size contrasts.

Comparison of A and C horizons in mounded and unmounded Spanaway soil (Table 14) yields a number of interesting points.

1. The striking contrast already noted between the black nonbedded A horizon of the mounds and the underlying light-colored bedded C horizon of the outwash is emphasized by the grain-size distributions. This is exemplified by the overall lower percentages of gravel and higher percentages of fines (silt + clay) in the A horizon (56.8% and 21.0%) than in the C horizon (72.7% and 5.3%) for the three prairies combined, and is confirmed by the averages for the individual prairies.
2. The averages of the A and C mound horizons show that *within each horizon* the proportion of fines is reasonably constant among the prairies.
3. The trend noted in 2. above suggests a similarity of stream regimens consistent with the A-horizon sediments of each prairie being deposited as the result of a sudden reduction in carrying power (competence) as if by overbank flooding of the *same* stream(s) that deposited the bedded gravel. The trend does not support a quite unrelated episode of deposition such as that suggested by Paeth (1967, p. 37-44).
4. Table 13 reflects Paeth's analyses (Table 5) that some mounds contain more gravel than do the intermound areas. He explained this somewhat surprising finding by inferring that fines have been washing off the mounds to the intermound areas as the result of fossorial-rodent activity, but he was troubled by the fact his analyses showed more sand than fines in the Puget prairie intermound profiles (Paeth, 1967, p. 27-30). The difficulty disappears if the assumption is made that sand sizes are more readily washed from mound surfaces than the more cohesive fines. However, Paeth's (1967, p. 27, 31-32) conclusions that mounds in a given prairie are characterized by a higher gravel content than in the intermound areas is contradicted by his data for Mound Prairie when comparing A horizons as a whole rather than A_{11} horizons only (Table 5), and by Giles' grain-size data for Mima and Rocky Prairies (Table 6), which (especially for Rocky Prairie) contrast sharply with Paeth's data.[10]

[10] In addition to grain-size distributions and organic-matter contents, Paeth (1967, tables 1-3, p. 15-16; p. 17, 25-26; tables 1a-3a, p. 50-54) examined the mineral content of mounds in Jackson County, Oregon, which appear to be similar to the Columbia Plateau mounds, and concluded that "...some pairs of adjacent mounds have different mineral assemblages and some widely separated mounds have the same mineral assemblage" (Paeth, 1967, p. 26). Similar data are lacking for the Washington occurrences.

5. The very limited data for unmounded Spanaway soil on Weir Prairie suggest a significantly higher content of sand and lower content of fines than for the mounded prairies.
6. In general, the available data are still insufficient for detailed, statistically valid conclusions, and it is clear that more mound and intermound analyses are needed, including depth measurements to the bedded outwash.

HYPOTHESES OF ORIGIN OF MIMA MOUNDS AND MIMALIKE MOUNDS

General

More than 30 hypotheses have been proposed for the origin of Mimalike mounds (Cox, 1984a). Some of them have been reviewed a number of times, among the more comprehensive reviews being those by Campbell (1906), Holland (1952, p. 52-58), Melton (1929, 1954), Newcomb (1952, p. 469-472), Vitek (1973, p. 12-36), and Zedler and Ebert (1979, p. 19-33). Many are so speculative as to be of historical value only and are not discussed here. Discussion of Spackman and Munn's (1984) hypothesis that Mimalike mounds in the Laramie Basin, Wyoming, are the result of cryostatic pressure is also omitted, since the critical intrusive features described are absent in the Mima mounds of the Puget prairies. Similarly, Zedler's (1987, p. 33-36) subsidence hypothesis for the southern California vernal pool topography is inapplicable to the Mima mounds, as demonstrated by their even contact with the underlying outwash. There remain the following hypotheses that are either commonly considered to be leading contenders or that have pertinent background value.

The discussion is organized according to whether the hypotheses are *primarily* based on deposition, erosion, or neither. The "neither" category, here represented by the gilgai hypothesis, will be discussed first.

Gilgai Hypothesis

Gilgai are low mounds and shallow depressions associated with clays, especially swelling clays. Gilgai are especially well described for Australia but also appear to be widespread elsewhere. Several variations of the gilgai hypothesis exist.

The first published statement of the hypothesis appears to be that by Hilgard (1884a, p. 130)[11] who applied it to hogwallows of the central prairie region of Louisiana.

> "Its distinctive character is the occurrence of prairies, mostly small, partly of the black calcareous soil, partly of that stiff and intractable kind popularly known as "hog-wallow" from its rough, humpy surface–the result of the mud-cracks which form in it during the dry season, and, being partially filled up with dry earth, compel a bulging of the ground whenever wetted by rains."

It is apparent from equally early descriptions of hogwallows and associated soils in the central prairie region of Mississippi (Hilgard, 1884b, p. 253-258) and in Arkansas (Loughridge, 1884a, p. 563) and Texas (Loughridge, 1884b, p. 693) that similar conditions were recognized there.

In basic concept, Hilgard's explanation differs little from some modern explanations for traditional gilgai. Although varying in specifics, most gilgai hypotheses involve desiccation cracking of expandable clays, infilling of cracks, and volume expansion of the soil upon subsequent wetting (Edelman and Brinkman, 1962; Hallsworth and others, 1955, p. 25-30; White and Bonestell, 1960; White and Agnew, 1968). Still other explanations have been offered, including differential soil settling (Harris, 1958), plastic flow (Beckman and others, 1981) as a result of volume changes, and loadcasting with diapiric upward movement of clays (Paton, 1974).

Given the appropriate conditions of expandable clays subject to drying and wetting, some Mimalike mounds may well be explainable as traditional gilgai or gilgai in combination with other processes. Zedler and Ebert (1979, p. 31-35) held that both differential settling and selective erosion were additional factors in the origin of the gilgai/vernal pool topography of San Diego County, California. Related reports by Greenwood and Abbott (1980, p. 43-47) on the Del Mar Mesa, by Abbott (1982) on the Linda Vista Terrace, and by Abbott (1983) also emphasized the presence of expandable clays and of desiccation and highlighted the importance of differential erosion by wind in enlarging crack intersections and creating the pools of what Greenwood and Abbott termed "the mima mound-vernal pool topography". In the San Marcos area of San Diego County, "...a process analogous to the formation of gilgai in Vertisols" was held responsible for a large "mima mound" on the basis of its soil characteristics, including "skewed peds and striated slickensides on peds throughout the B2 horizon" (Borst, 1975, p. 21)—features typical of some gilgai (White and Bonestell, 1960).

However appropriate for some Mimalike mounds elsewhere, the gilgai hypothesis and its variants seem inapplicable to the Puget prairie Mima mounds, as discussed later in connection with runoff-erosion/desiccation cracking, because

1. Expandable clays are largely lacking.
2. Diapiric loadcasting effects and widespread differential settling are absent as shown by numerous mound cross sections.

[11] Not Hilgard (1906) as cited by Paton (1974, p. 236).

Depositional Hypotheses

General

A number of different hypotheses have been suggested based on processes leading to a depositional (constructional) origin of Mimalike mounds. Agents include ice, liquid water, wind, and animals. It has been suggested that vegetation may be a controlling factor in places.

Ice

Ice as the *depositional* agent for Mima mounds was first proposed by Bretz (1913, p. 102-106) in his classic report "Glaciation of the Puget Sound region".

> "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" (Bretz, 1913, p. 105-106).

Subsequently, a different form of the hypothesis was suggested by Paeth (1967, p. 37-44), who called for ice dams, ponding, and deposition from "icebergs"—polygonally fractured, sediment-covered, floating lake ice.

These hypotheses have not found much favor because of objections such as the following, the first recognized by Bretz himself.

1. "The great range in altitude and the widespread distribution of the Mima type mounds constitute a serious objection to this hypothesis. 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" (Bretz, 1913, p. 106).
2. While the necessary temperature conditions existed in the Puget Lowland, they do not in many other places where Mimalike mounds occur—a circumstance unknown to Bretz. The Paeth "iceberg"-deposition concept also suffers from this defect.
3. The ice dams required by the Paeth concept are highly speculative (see also Noble and Molenaar, 1965, p. 65), as are some of the other aspects.
4. Evidence cited in support of the Paeth concept can also be explained in other ways.

Fluvial Deposition

Fluvial deposition as the cause of Mimalike mounds (pimple mounds) was argued by Krinitzsky (1949) on the basis of widespread regional occurrences associated with alluvial surfaces in Arkansas, Louisiana, Missouri, Oklahoma, Tennessee, Texas, and Washington. This association was the primary evidence cited; it was illustrated, for instance, by photographs showing pimples conforming to accretion ridges on point bars. He suggested that vegetation helped to preserve the mounds after the alluvial surfaces were abandoned.

Objections to the hypothesis include

1. The spatial association cited by Krinitzsky does not prove genesis. For instance, supporters of the fossorial-rodent hypothesis could argue that the mounds are on abandoned alluvial deposits precisely because rodents found those deposits the most habitable.
2. There appears to be a notable absence of detailed studies or actual observations of Mimalike mounds being deposited by fluvial processes alone.
3. Some Mimalike mounds are believed to be younger than any associated alluvial surface (Paeth, 1967, p. 41, 43).

Fluvial Deposition/Vegetation Anchoring

A brief but well-illustrated report by Gangmark and Sanford (1963) ascribed mounds along the flooplain of the Sacramento River near Red Bluff, California, to clumps of vegetation initiating fluvial deposition of small mounds in the lee of the vegetation during flooding, combined with shaping of the mounds by interactive erosion as currents changed direction. The small mounds tended toward a teardrop shape with the blunt end directed upstream. Higher and farther from an active channel, photographs showed larger, ellipsoidal mounds parallel to the stream flow. A well-developed mound here measured 1 m (3 ft) high, 4 m (13 ft) broad, and 6 m (20 ft) long and consisted of sand, silt, and scattered stones resting on gravel and coarse sand.

Sequential forms were reported leading from the smaller forms to well-developed and apparently Mimalike mounds. The authors concluded that

> "Under conditions of equilibrium, mounds attained a stable form and continued to increase in size" (Gangmark and Sanford, 1963, caption, fig. 22, p. 218).

Low ("pimple" or "prairie") mounds at Pipkin Marsh in southwest Jefferson County on the Texas coast have been ascribed to aggradation and vegetation anchoring, rather than to erosion on the basis of their archeological content, although nick points attest to some erosion, perhaps by storm surges (Aten and Bollich, 1981). The geology of the deposit and relative importance of fluvial vs. marine processes and the exact origin of these mounds remain to be established.

Objections to the predominant role of fluvial deposition and vegetation anchoring as the cause of Mimalike mounds include

1. With respect to observations of Gangmark and Sanford:
   (a) The spatial association described does not necessarily prove genesis. Conceivably, some of the mounds could have been erosional remnants of a more extensive cover of fine sediment.
   (b) Assuming the origin of the small forms as described by the authors, photographic evidence of the intermediate stages between them and the well-developed larger mounds is largely lacking.
   (c) Analysis is lacking of how mounds reaching a stable form continued to increase in size.
2. More generally, except for the report by Gangmark and Sanford, there appears to be a notable lack of supporting studies or eyewitness accounts of mound growth by interactive fluvial deposition and erosion.

Nevertheless, the clear association of apparently Mimalike mounds and evidence of their fluvial shaping is an important fact addressed later in discussing the runoff-erosion/vegetation-anchoring hypothesis.

Eolian Activity/Vegetation Anchoring

The hypothesis that eolian activity and vegetation anchoring are primarily responsible for Mimalike mounds is based on the ability of shrubs to cause deposition and retention of windblown sediments. The hypothesis was argued by Barnes (1879) on the basis of observations near San Diego, California, where he reported the process to be then active and as having built mounds 30-122 cm (1-4 ft) high and 3-15 m (10-50 ft) in diameter, separated in some situations by gravelly areas. He cited the role of *Rhus laurina*, *Simmondsia californica*, and *Isomeris arborea* as being particularly important, and he thought that gophers were "...in exceptional cases, an adjunct of the wind in heaping up material about the plant" (Barnes, 1879, p. 568). The general hypothesis was also held for mounds in the same region by Ellis and Lee (1919, p. 29 and plate 8) and Hertlein and Grant (1944, p. 17-19). The mounds described by Ellis and Lee were up to about 1 m (3 ft) high and 4 1/2 m (15 ft) in diameter. Hilgard (1905) and Shaw (1928, p. 308-310; see also 1937) regarded the hogwallows of the San Joaquin Valley (San Joaquin soil series) as undoubtedly due to wind deposition because of clump vegetation. Shaw cited contemporary examples of mound creation due to creosote bush or sagebrush on Imperial Mesa in the Colorado Desert of Imperial County, California; G. W. Cox (San Diego State Univ., written commun., 1986) also regards these as accretion forms.

A modified form of the hypothesis was applied by Olmsted (1963) to silt mounds of the Spokane (Lake Missoula) flood surface on the Columbia Plateau. These mounds may or may not be analogous to Mimalike mounds elsewhere, but Olmsted noted that they contained stones as much as 25 cm (10 in.) long; he suggested that human activity during mound growth explained the presence of the larger stones.

Eolian deposition, in addition to other origins, has also been advocated for the pimple mounds of western Louisiana, eastern Texas, southwestern Arkansas, and southeastern Oklahoma (Slusher, 1967; see also Quinn, 1961). In a brief note, Slusher described these mounds as circular, as much as about 1 m (3 ft) high and 15-46 m (50-150 ft) in diameter, and consisting of sandy loam or silt loam. Anchoring vegetation was not mentioned. As evidence that they were accumulation forms, he cited (1) an A_2 horizon corresponding to the mound form but a planar B_{2t} horizon paralleling the general slope of the land rather than the mound surface, and (2) the lack in the B_2 horizon of any evidence of bioturbation or disturbance by gas, water, or oil pressures. Since the observed mounds did not occur on the most recent sediments, Slusher suggested an origin by eolian activity during late Pleistocene aridity.

An objection to application of the hypothesis for many Mimalike mounds is the apparently fatal fact that grain sizes (including stones) in some mounds are too large to have been transported by wind.

Fossorial Rodents

A depositional hypothesis that has been widely adopted by biologists explains the Mima and Mimalike mounds as the work of fossorial (burrowing) rodents, such as the pocket gopher *Thomomys mazama* (*Thomomys talpoides*) in the case of Mima Prairie. Turner (1896, p. 681-683) suggested the possibility that rodents might be responsible for mounds in California; Campbell (1906) argued that burrowing animals were the cause of similar mounds, and he indicated the possible importance of gophers without specifying pocket gophers. Koons (1926, p. 13-20; see also 1948) formulated the concept further, but the hypothesis was primarily developed by Dalquest and Scheffer (1942). It has been vigorously supported by Price (1949, 1950) and a number of biologists, and more recently in some detail by Cox (1984a)[12], Cox and Gakahu (1986), and Cox and others (1987a) on the basis of detailed studies in California, southern Colorado, the Columbia Plateau in Oregon, Washington (Mima Prairie), and elsewhere including the highlands of Kenya (see also Cox and Gakahu, 1983, 1984, 1985, 1987). The hypothesis has also been advocated for mounds in Argentina (Cox and Roig, 1986) and South Africa (Cox and others, 1987b).

Cox (1984a, p. 38), a strong supporter of the hypothesis, summarized it as follows:

> "Based on observations at Mima Prairie and several other locations in western Washington, Dalquest and Scheffer postulated that Mima mounds were formed by pocket gophers or similar animals that tunnel outward from their nest sites, causing the backward displacement of soil. They suggested that the mounds are found where such mammals nest year after year. The nests, and thus the mounds, are at a fixed distance from one another because of territorial requirements. Those who subscribe to this hypothesis note that the shallow basement layer in the soil becomes waterlogged in wet weather. Fossorial rodents, such as pocket gophers, can survive only in high spots where the soil is well drained. If such spots exist, the animals establish their nests in them every year. Since gophers usually dig their foraging tunnels outward, they continually displace soil toward the nest. The soil they mine is pushed backward through the tunnel system before being deposited on the surface or packed into an abandoned chamber."

The following evidence was cited by Dalquest and Scheffer (1942, p. 81-82):

(1) "1. The Mima mound is constructed entirely of soil materials small enough to be moved by gophers.

(2) "2. Materials too large to be moved by gophers appear beneath the mound or in the intermound region.

(3) "3. Mound roots extending into the gravel bed correspond to the size and shape of tunnels and nest excavations occupied by living gophers, and roots have been found in various stages from the occupied burrow of a gopher to one long since abandoned.

(4) "4. Mima mounds are found only on prairies where gophers now live or quite certainly once lived but are absent from prairies which, though geologically similar, yield no traces of gophers.

(5) "5. The characteristic features of the mounds—namely, areal distribution, distribution with relation to grosser ground relief, size, and shape—are in conformity with the habits of pocket gophers."

After elaborating the hypothesis somewhat further, Scheffer (1947, p. 293) added the following evidence:

(6) "1. Mima-type mounds are distributed along the Pacific Coast exclusively in the range of the pocket gopher. On the north, both the mounds and the gophers terminate abruptly in the vicinity of Puget Sound.

(7) "2. Burrowing animals with habits similar to those of the gopher, namely, the ground squirrel (*Citellus*) and the mole (*Scapanus*), are known to occur on many of the mound prairies. We may deduce, however, that these animals are not pertinent to the formation of mounds since there are no ground squirrels in western Washington and no moles on most of the mound prairies of California.

(8) "3. Mima-type mounds are found only where there is a thin layer of workable soil on top of a dense substratum. It is significant that the substratum is of no particular geological formation. Thus near San Diego and Fresno, the substratum is a hardpan of cemented soil; a few miles southeast of Mount Hood, in Oregon, the substratum is basaltic rock; and in Puget Sound it is bedded gravel.

(9) "4. Where gophers are working in deep sandy soil unlimited by a basement they never form Mima-type mounds. In other words, their up-and-down movements are not restricted or localized. In deep soil near Olympia, Wash., only fifteen miles from the mound display at Mima, gophers have been working for untold years, and the surface of the ground is still so level that it is used as an airfield.

(10) "5. The usual agent in the formation of hillocks and mounds is geological deposition of one kind or another. This agent can hardly be responsible for mounds of the Mima type. Deposition, whether by ice, wind, or water, depends on a moving vehicle, and movement always results in a deposit which is aligned in one general direction. Mima-type mounds, as may be seen from aerial photographs, are unoriented. Also, deposition does not produce round mounds on a sloping terrain, as are occasionally seen on the gopher prairies.

[12] Cox (1984a, p. 36) following Scheffer (1947, p. 293) correctly emphasized that mounds are associated with the occurrence of shallow silty soil overlying a "...basement layer–bedrock, hardpan, densely bedded gravel, heavy clay, or a permanent water table". Although he regarded this underlying layer as impermeable, it would seem he meant this more in a gopher than hydrological sense, since the Vashon outwash of the Puget prairies tends to be highly permeable.

(11) "6. For similar reasons, the agency of erosion may be dismissed. Erosion is generally the result of a moving vehicle. We may point out, further, that on the Puget Sound prairies, the mounds are draped the year around with a mossy turf that protects them from wind and rain-water erosion. And, in countless cases, the hollows between the mounds are completely closed depressions from which there is no rapid outflow of water—simply drainage through the porous gravel bed.[13]

(12) "7. Only by a liberal use of the imagination can we conceive of a set of geological forces capable of producing the elaborate structure of the mounds, namely: the fluffy, unstratified soil of the mound adjoining a distinctly bedded substratum; the presence of 'gopher-size' rocks in the mound as compared with the heavy cobbles beneath and beside the mound; the curious dip in the substrate beneath the mound; the mound roots; and the sunken depression usually found on the summit."

(The "curious dip in the substrate beneath the mound" refers to the biconvex lens shape of the mound material, discussed earlier in describing the mounds of Mima Prairie.)

Scheffer (1958, p. 507) expanded "...the theory to include other species of fossorial rodents as well as gophers." Thus evidence favoring the fossorial-rodent hypothesis includes:

(13) Reports of contemporary observations of mound building activities by various kinds of fossorial rodents. Price (1949, p. 10) emphasized that "A mature mima mound has been built in 5 years...." This statement is presumably based on Koons' observation of two "sand mounds" in Texas. "After five years both had attained fair size...." (Koons, 1926, p. 18; 1948, p. 299). Koons (1926, p. 6) had noted that the kinds of mounds he was discussing normally had a diameter range of 1.2 to 9.1 m (4-30 ft) and a relief of "not often" over 60 cm (2 ft). Also, there is an account of a mound about 7 m in diameter having developed beneath a house in 17 years (Bailey, 1923, p. 23), which was subsequently cited by others (Price, 1949, p. 12; Scheffer, 1984, p. 8) as supporting evidence.

(14) "The black horizon [of the Mima Prairie mounds] is more than 30 inches [76 cm] thick on many of the mounds, which is much thicker than in most prairie soils of normal development, and lends weight to Scheffer's hypothesis" (Thorp, 1949, p. 190). The same point has been emphasized by F. C. Ugolini (Univ. of Washington, oral commun., 1984).

(15) Cox and Gakahu (1984) calculated that for mounds they studied on Mount Kenya, the volume of soil in mounds that reach 2 m high and 20 m in diameter matches the amount of soil missing between mounds on the assumption of a former uniformly thick soil layer corresponding to mean mound height.

(16) Displacement of markers in tunnels of fossorial rodents in San Diego County, California, shows that there is a tendency for such rodents to move more soil towards mounds (273 markers) than away from them (149 markers) (Cox, 1984b, p. 1401). This tendency is supported by volumetric soil measurements (Cox, 1984c, p. 42-43) and subsequent work (Cox and Allen, 1987a).

(17) "Contrary to all but the fossorial gopher hypothesis, gravel and small pebbles that such rodents are able to move were concentrated in mound soils" (Cox, 1984b, p. 1397; see also 1984c, p. 41).

(18) Statistical studies of mounds in San Diego County show that "The spacing of mounds tended towards uniformity, but intermound distance increased significantly with increase in mound size" (Cox, 1984b, p. 1397, see also p. 1403-1404).

(19) Statistical analyses of "small-rock" content and ratios (larger stones were excluded) and of moundfield geometry strongly support the fossorial-rodent hypothesis and argue against erosion, frost sorting, and wind hypotheses, according to Cox and Gakahu (1986; see also Cox and others, 1987a). Defining "small rocks" as gravel (8-15 mm diameter) and pebbles (15-50 mm), and regarding 50 mm as the maximum size rock a fossorial rodent can transport, they cite the following evidence as favoring the fossorial-rodent hypothesis (Table 15): (a) the small-rock content is greater on mounds than in intermound areas (see also point 17 above), greater at mound tops than edges, and greater at mound edges than in intermound areas; (b) the gravel:pebble ratio is greater at mound edges or in intermound areas than at tops; (c) mean pebble mass is greater in intermound areas than at mound tops or edges; also statistics showing that (d) mound volume has a strong direct relation to intermound distance (see also 18 above) and strong inverse relation to volumes of neighboring mounds (Table 15).[14]

[13] Nikiforoff (1941, p. 38), noting the intermound depressions in the Central Valley of California, raised the same objection.

[14] In Cox and Gakahu (1986, p. 496) the Mima Prairie column is shifted upward as the result of a missing entry so that mean density, height, and diameter are misplaced. The missing entry is 36 (number of mounds) (G. W. Cox, oral commun., 1987).

Table 15. Some hypotheses of mound origin compared with "small-rock" content and with moundfield geometry of Mimalike mounds and intermound areas (after Cox and Gakahu, 1986)

Predicted feature	Erosion hypothesis	Wind-deposition hypothesis	Frost-sorting hypothesis	Fossorial-rodent hypothesis
Small-rock content				
a. Mound vs. intermound concentration	Greater in intermound	Greater in intermound	Greater in intermound	Greater on mound
Mound top vs. edge concentration	Less on top	Much less on top	Less on top	Greater on top
Mound edge vs. intermound concentration	Similar, or somewhat less at edge	Much less to somewhat less at edge	Greater in intermound	Greater at edge
b. Gravel/pebble ratio	Greatest on mound top	Greatest on mound top	Greatest on mound top	Greatest at mound edge or intermound
c. Mean pebble mass	Low on top, intermediate at edge, high in intermound	Low on top, intermediate at edge, high in intermound	Low on top, intermediate at edge, high in intemound	Similar at top and edge, greater in intermound
Moundfield geometry				
d. Mound dispersion pattern	Random to slightly uniform	Random to slightly uniform	Strongly uniform	Strongly uniform
e. Mound volume vs. intermound distances	No relation to weak direct relation	No relation to weak direct relation	Direct relation	Strong direct relation
f. Mound volume vs. volumes of neighboring mounds	No relation to weak inverse relation	No relation to weak inverse relation	No relation	Strong inverse relation

(20) The fact that the oldest radiocarbon ages determined to date in the Mima mounds of Mima Prairie are younger than 4,180 ± yr B.P., with ages decreasing upward in the profile (Tables 2A and 2B), appears to argue for an age that would be entirely consistent with the fossorial hypothesis but inconsistent with alternative hypotheses calling for a late-glacial age.

As reviewed above the evidence seems convincing, but difficulties remain that need to be carefully examined, particularly with respect to Mima Prairie and other Puget prairies.

1. Evidence (1) (and in part Evidence (12)) does not apply to all mounds on Mima Prairie or Rocky Prairie, nor does it apply to a number of mounds elsewhere to which the fossorial-rodent hypothesis has been applied. The largest mound pebbles that fossorial rodents have been credited with carrying have a maximum diameter of about 5 cm. Thus the heaviest mound pebble found by Dalquest and Scheffer (1942, p. 78) in "fresh gopher hills" weighed 137 grams, which (assuming it had a specific gravity of 2.9) would correspond to a sphere with a diameter of about 4.5 cm or a cube with sides of about 3.6 cm. According to plot studies in Colorado, pocket gophers (*Thomomys talpoides*) tend to avoid rocks more than 2.5 cm in diameter, and they rarely move rocks more than 5 cm in diameter (Hansen and Morris, 1968, p. 395); the 5-cm limit was also accepted by Cox and Gakahu (1986). However, isolated but much larger stones well imbedded at the crests and slopes of several Mima mounds of Mima Prairie and Rocky Prairie were noted in the prairie descriptions. Ritchie (1953, p. 43) reported finding more than

50 stones ranging from 10 cm (4 in.) to 51 cm (20 in.) in diameter inside mounds well above their base, although he did not specify in which of the Puget prairie mounds these stones were found. Campbell (1962, p. 10) referred to isolated boulders in mounds of this region.

Small cobblestones are not uncommon in mounds of the Central Valley of California (Nikiforoff, 1941, p. 36). In similar hogwallow microrelief on the lava and basalt beds southeast of Chico, California, there are rock fragments as much as 30 cm (1 ft) in diameter imbedded in the mounds, and hogwallows in areas of the Redding soil complex contain stones nearly 15 cm (6 in.) in diameter (Nikiforoff, 1941, p. 36-37). A stone measuring 13 x 15 cm (5 x 6 in.) was found inside a Mimalike mound in Minnesota (Ross and others, 1968, fig. 2, p. 175).[15]

If it is argued that the large stones of the Puget prairie mounds might have been brought up from the underlying outwash by windthrow of trees, this contradicts the fossorial-rodent hypothesis that the mounds were constructed in a prairie environment (see point 24 below). Frost heaving of large stones from the base of the mounds might be invoked (Price, 1949, p. 7), but if this were the explanation, there should be many such stones in mounds or at their surface, which is not the case. Even if it is argued that such large stones were introduced, it is not clear that evidence based on the mounds containing only "gopher-size stones" is very convincing, since the sediments overlying the bedded coarse outwash may have been relatively free of large stones when the sediments were first deposited. Grain-size analyses for the unmounded Spanaway gravelly sandy loam (Ness, 1958, p. 53-55) support this view. The contrary view implies the original presence of large stones in the mound material, which is contradictory except for the possibility that such stones may now lie at the base of mounds as the result of downward settling from animal activity (Price, 1949, p. 9). However, this supposition is weakened because (1) braided streams might well have first winnowed out fine material and left a stony lag accumulation before subsiding and depositing the mound material as a blanket; or (2) (if the gravel is more concentrated below the mound than elsewhere) this might be the result of erosion below the original mound base and development of a C-horizon pedestal, an argument cited in favor of runoff erosion and permafrost cracking (Ritchie, 1953, p. 45, 48).

[15] Although some Mimalike mounds in southwest San Diego County, California, have been reported to contain cobbles "at every level" (Nadolski, 1969, p. 30, 35), the report is questioned by G. W. Cox (written commun., 1987).

2. Evidence (2) merely confirms the nature of the bedded outwash underlying the mounds.

3. Granting the gopher origin of the mound roots (as opposed to tree roots), Evidence (3) merely shows that pocket gophers once inhabited mounds on Mima Prairie as they now do on adjacent prairies, but this is hardly proof that gophers built the mounds. Gophers could have adopted them as their home because there is where the food supply was and tunnelling and nest building were possible—a possible reversal of cause and effect as noted by Melton (1954, p. 111) and Zedler and Ebert (1979, p. 34), among others.

4. Evidence (4) is weakened by the inverse argument that gophers are widely distributed in the Puget Lowland, yet despite apparently similar soil conditions mounds are absent in nearby areas where gophers would be expectable. This argument is derived from Ritchie's (1953, p. 47, see also p. 41-43) observations that

   "1. The Mima-type mound is restricted to the outwash valleys of the Vashon glacier but is limited to those valleys that could receive floodwater from the north.

   "2. Well-developed mounds occur in topographic positions where they could have been eroded by a flood river. Although high-level terraces adjacent to the outwash valleys have a mantle of pebbly-silt material, they are unmounded."

   Both evidence (4) and the inverse argument merit extensive further research.

5. Evidence (5) relating to habits of fossorial rodents has been disputed. Thus some investigators have argued that tunnelling activities tend to accelerate mound erosion rather than build large mounds (Hubbs, 1957, p. 15, citing W. F. Blair [pers. commun.]; Nikiforoff, 1941, p. 29; Paeth, 1967, p. 27-28); or more generally that the inferred rodent activity lacks direct evidence and that the "strongest argument in favor of the gopher hypothesis is a negative one", based on the unproved absence of alternative explanations (Zedler and Ebert, 1979, p. 27-29). In a reply to criticisms by Grant (1948), Scheffer (1948, p. 231) frankly admitted

   > "...that our evidence is indirect; that we have not seen gophers building a giant mound; that we do not know whether mound building is a contemporary or a historic process; and that we do not know whether the stimulus for mound building is a hardpan or a high water table or both."

   Despite research in the more than 40 years since Dalquest and Scheffer's (1942) paper, the fact remains that no mounds as large as some Mima mounds and of comparable pattern have yet been demonstrated to be of fossorial-rodent origin. Perhaps the proof will come with further investigations of the 2-m-high mounds that Cox and Gakahu (1984) have been studying in the Kenya highlands.

6. Evidence (6) may reflect the nature of the material involved. As noted above, the fact that gophers occupied the mounds is not proof they built them.
7. Evidence (7) was admittedly extraneous to the Puget prairies and to most mound areas of California.
8. Evidence (8) cites an important observation but is subject to alternative interpretations, including comparative ease of erosion.
9. Evidence (9) is a consistency criterion only, based on the assumption that fossorial rodents are in fact responsible for the mounds.
10. Evidence (10) that Mimalike mounds as seen from the air are unoriented is misleading, although to a person on the ground the initial impression certainly suggests random distribution. A lineation was subsequently recognized by Scheffer (1958, p. 508) when he noted that in places the mounds form "...irregular rows paralleling the line of a stream, terrace, rock outcrop, or other confining border." Striking nonrandom patterns of Oklahoma "prairie mounds" have been illustrated by Branson (1966, p. 263-273). Moreover, as noted in the description of Mima, Rock, and Violet Prairies, the alignment and elongation of some Mima mounds conforms to a drainage pattern that does not necessarily mandate a confining border. If rodents built the mounds, they must have done so after the pattern was established, perhaps utilizing slight elevation differences in the drainage pattern. Alternatively, there is nothing in the pattern to negate the possibility that the mounds were segmented from more or less continuous linear rises by erosion between vegetation-protected spots, as discussed later, and were subsequently occupied by fossorial rodents. In either case, the mound alignment and occasional elongation parallel to channels does not argue for the view that "If mounds are the product of long term patterns of pocket gopher activity, their dispersion should tend toward uniformity, regardless of the dispersion pattern of initially favorable sites in the original landscape" (Cox, 1984c, p. 40). However, the argument has also been made that

    "Alignment of mounds in the manner described above (and some elongation of shape) are not inconsistent with a significant degree of uniformity of dispersion. All of the mound fields analyzed to date in North America show significant uniformity. The cells in a honeycomb—the ultimate of hexagonal uniform packing—are aligned in rows, for example" (G. W. Cox, written commun., 1986).

11. Evidence (11) is countered in part by the drainage pattern noted above. Closed intermound depressions are uncommon and only a few centimeters deep where present on the Puget prairies. Their origin is uncertain but is perhaps postmound and related to downward eluviation of fines (Holdredge and Wood, 1947).
12. Evidence (12) is mainly a summary and has no other significance if gophers inhabited the mounds but did not build them.
13. Evidence (13) refers in the first case to low mounds of uncertain height; the apparent lack of similar observations from elsewhere weakens it. The second case is based on a statement made to Bailey (1923, p. 23), who made no conclusion as to cause, although he considered several hypotheses. That the mound was gopher related is inference only; other possibilities exist. More eyewitness accounts of sizeable mound-building operations should be available to provide convincing evidence that fossorial rodents have in fact built sizeable mounds such as those of the Puget prairies. Murray (1967) found no such eyewitness reports in the literature, and although he supported the fossorial-rodent hypothesis, he was forced to admit that "the pocket gophers could be effect rather than cause" (Murray, 1967, p. 105).
14. Evidence (14) is a necessary consequence of the fossorial-rodent hypothesis but is also consistent with development of a black A-horizon color on pre-existing mounds, with rodents merely occupying them. Rodent activity would contribute to an existing prairie soil by accumulation of vegetal matter and animal refuse and remains. Extensive bioturbation, especially by rodent activity throughout the mound, would result in the appearance of an abnormally thick prairie soil. All the ways in which fossorial rodents can contribute to development of prairie soils as described by Mielke (1977) would apply.
15. Evidence (15) is indeed consistent with the fossorial-rodent hypothesis, but the method of calculation involves some assumptions about the shape of the excavated intermound areas for which confirmatory data are lacking. Moreover, the analysis does not consider the possibility of intermound material having been removed by erosion. The fact that similar mounds at somewhat lower altitude are known to be the work of termites as recognized by the authors (Cox and Gakahu, 1984, p. 149; Gakahu and Cox, 1984, p. 32-33) also sug-

gests the possible role of a climatic or other environmental change unless it can be demonstrated that such changes have not influenced ecological boundaries. Should building of 2-m-high mounds by mound rats in Kenya be accepted, it would be an important "first" and significantly strengthen but not prove the validity of the fossorial-rodent hypothesis for such regions as the Puget prairies.

16. Evidence (16) is certainly consistent with the fossorial-rodent hypothesis but, again, does not negate the possibility that fossorial rodents merely occupied mounds that were already present.
17. Evidence (17) would not apply if the grain-size distribution of the mound soil were originally distinct from that of lower lying intermound soil, or if erosion and deposition of fines from the mounds had modified the original grain-size distribution of intermound soil.
18. Evidence (18) is apparently contradicted for sites in the Puget prairies by Ritchie's (1953, p. 44) report that "...the wider the intermound area, the smaller the mounds". This report is clearly inconsistent with the hypothesis that fossorial rodents collected most of the mound soil from intermound areas, but the opposite intermound-mound relationship was reported for a Mima Prairie and three California localities by Cox and Gakahu (1986, p. 495, 498). Further observations are needed, at least for the Puget prairies.
19. Evidence (19) provides interesting statistical data consistent with the fossorial-rodent hypothesis but not necessarily proof of it. Thus data (a) to (c) might be consistent with a different origin if the mounds had been merely occupied rather than built by gophers. Other weaknesses are introduced by the possibility of an originally different grain-size distribution at different mound levels, and/or by gravity movements of soil from mound slopes to intermound areas. For the Puget prairies, the amount of gravel (USDA classification) in mounds exceeds that in intermound areas in some analyses (Table 5), and is the inverse in others (Table 6). The premise (d) that mound dispersion is random to only slightly uniform for the erosion and wind deposition hypotheses, compared to strongly uniform dispersion for the fossorial-rodent hypothesis, is questionable to the extent that the distribution and hence the anchoring effect of vegetation might be uniform. Table 15 shows the possibility of a direct relation for (e) and indirect for (f) data for all Table-15 hypotheses except frost sorting; the differences between the hypotheses are of degree only.
20. Evidence (20) is subject to a number of uncertainties. As suggested earlier in the discussion of the Puget prairies (see section on Pollen Profiles and Vegetation), these include decomposition of earlier organic matter, destruction by fire, and nondeposition because of pollen (and other fine organic matter) being carried past the area. Other potential errors include leaching, bioturbation, and rejuvenation within the rooting zone. The rejuvenation effect alone can decrease the true age of a soil since the beginning of humus formation by some 50 percent, with the beginning of humus formation itself in regolith being undatable (Geyh and others, 1971; Scharpenseel, 1971). In general, in the absence of much more detailed soil dating work than is presently available for the Puget prairies, the available soil dates must be regarded as minimum only.
21. The fact that low mounds (Fig. 10) less than 30 cm (<1 ft) high (Dalquest and Scheffer, 1942, p. 69) exist in some intermound flats of the Puget prairies suggests they are erosional remnants. Newcomb (1952, p. 468) remarked that mounds of such small size could hardly serve as gopher homes. If originally larger, they are clearly evidence of erosion, which is consistent with the view that the general uniformity in height of the larger mounds in any one part of a prairie represents erosion of a deposit of uniform thickness (McFaul, 1979, p. 42; see also Newcomb, 1952, p. 470).[16]
22. Zedler (1987, p. 33), calling for more fieldwork, argued that Mimalike mounds may be limited to extensive alluvial areas but, if so, there is no apparent reason why favorable conditions for the fossorial-rodent hypothesis should be restricted to such areas.

[16] Several further objections were cited by Newcomb (1952, p. 467-469), including "pronged depressions" and "ringed mounds", but their significance is uncertain. Unfortunately, the present writer could not relocate either of these features. The pronged depressions were reported from Frost Prairie, where human activity has considerably modified the surface since Newcomb's observations. As described, they would fit possible thermokarst depressions left by thawing ice wedges, but as discussed in connection with the erosion/permafrost-cracking hypothesis, other evidence is against former frost cracking in the Puget Lowland. The ringed mounds were described by Bretz (1913, p. 90) as "mound-and-saucer arrangements", with the saucer rim commonly broken. The location given by Bretz was the south slope of a till ridge south of Muck Post Office. Muck is no longer on the maps, but its former location is reported to lie about 6.4 km (4 mi) northeast of Roy and within the Fort Lewis Military Reservation. This area was checked for ringed mounds without success. Conceivably the low areas between the mounds and rims could have been channels around a bar as in a braided stream or perhaps related to thermokarst. Bretz described the ringed mounds as of "outwash development". In any event the significance of the pronged depressions and ringed mounds is problematical.

23. Some mounds occur at the sides and bottom of a Mima Prairie kettle hole (Fig. 9) that was formed as underlying glacier ice melted out (Bretz, 1913, plate 4, fig. 2 and p. 89; see also McFaul, 1979, p. 42-43; Washburn, 1979, p. 170). Newcomb (1952, p. 468) and Ritchie (1953, p. 45) also mentioned occurrences of this kind in the Puget Lowland but without specifying their location. The Mima Prairie kettle hole now nearly fills with water during the wet season. In this particular case the filling may be mainly due to runoff diversion as evidenced by recent channelling, but other kettle holes in the Lowland also tend to accumulate water, and some of the largest are sites of lakes. Generally, kettle holes would hardly seem to be appropriate home sites for fossorial rodents when immediately adjacent, better-drained surfaces were also available, even though Hypsithermal conditions would have promoted drier conditions. Alternatively, it has been argued that the kettle holes may have formed after the mounds had been built and the mounds were let down into them as the ice melted, as suggested by the imperfect appearance of the mounds (Newcomb, 1952, p. 468; Ritchie, 1953, p. 45). This requires that the gophers were constructing mounds while sizeable masses of buried glacier ice were still present, but it is highly unlikely that rodents invaded the area so early prior to establishment of the prairies, their ecological niche.

24. Since fossorial rodents could hardly have inhabited an active outwash plain and undertaken mound building there, and they are prairie rather than forest dwellers, they would have had to await the advent of the prairies and prairie vegetation (Dalquest and Scheffer, 1944, p. 313-314, 317, 322; Scheffer, 1958, p. 506). This was not until after the disappearance of the forest that occupied the site of the prairies until some 10,000 years ago, as reviewed in the section "Pollen Profiles and Vegetation". By this time the outwash streams would have long since abandoned the prairies, yet the mounds show evidence of fluvial shaping in their elliptical form and occasional, relatively blunt upslope ends and downslope tails.[17] That this shaping could have occurred after the prairies were established seems unlikely, because the mounds are well preserved and the prairie terraces carry no modern streams except in isolated instances where roadside or other drainage has been diverted to the terraces, resulting in minor but obvious channelling quite different from the smooth intermound surfaces. Thus the evidence favors a pre-prairie and therefore pre-rodent origin for these mounds.

[17] Evidence consistent with fluvial action is also present in the gravel pedestals on which some mounds rest. Ritchie (1953, p. 48) cited such occurrences as indicative of erosion below the surface of the outwash gravel, but Price (1949, p. 9) suggested that large stones could accumulate at the base of a mound by animal activity. The presence or absence of bedding in the gravel and the shape of the pedestal could be diagnostic, but diagnostic exposures remain to be described, and the question remains open.

Erosion Hypotheses

General

A large number of hypotheses exist, based on erosion being a primary formative process, either acting alone or in combination with other processes. As with deposition, vegetation has been deemed to be a controlling factor in places.

Runoff Erosion

According to the runoff-erosion hypothesis, the mounds to which it has been applied are simply the result of runoff processes alone. Some proponents stress fluvial erosion (including runoff from glaciers), subject to certain site conditions, others include slopewash and related unorganized drainage. Since such drainage can initiate mound development by erosion along crack patterns, and can contribute to further mound development, the inclusive term runoff erosion is adopted here.

The runoff hypothesis was adopted by Hilgard (1884c, p. 676-677) for the hogwallows of the Central Valley of California, and was regarded by Nikiforoff (1941, p. 36-37) as

> "...especially clear on gentle slopes of the lower foothills adjacent to the basin (fig. 16).
>
> "Another example is the hog-wallow microrelief on the lava and basalt beds southeast of Chico.... Still another example is furnished by hog wallows in certain areas of the Redding soil complex."

(The above localities are also cited in discussion of Evidence (1) for the fossorial-rodent hypothesis.)

The efficacy of fluvial erosion alone was strongly advocated by Waters and Flagler (1929) for the soil mounds of the Columbia Plateau of eastern Washington. For the most part the relationships they described also fit those observable on air photos and observed in the field by the present writer on the plateau's Manastash Ridge. The mounds here were well described by Bruunschweiler (1962, p. 19-23) and Kaatz (1959) but were attributed by them to frost action. Waters and Flagler (1929, p. 223) noted that

> "The symmetrical development of this drainage system may be influenced by the columnar jointing of the ash. The importance of this factor is problematical, however."

Very similar mounds but overlying various lithologies occur on the Snake River Plain of Idaho. Although ascribed to frost action by Malde (1964), Wilson and Slupetzky (1977) and Wilson (1978) regarded them as due to erosion by running water. The evidence they cited includes:

Evidence against the role of frost action

1. The large size of the forms (5-15 m across) would require a more severe climate than is expectable.
2. Lack of features supportive of severe frost action, such as periglacial landforms, involutions, frost-shattered rocks, ice-wedge casts.

Evidence favoring fluvial erosion

[1.] "...alignment of mound rows down slope;

[2.] uniform widths but varying lengths of mounds within each row;

[3.] stone borders which trend down slope but are discontinuous across slope;

[4.] well rounded cobbles and boulders; and

[5.] an argillic B soil horizon with its upper surface being a subdued reflection of mound microrelief" (Wilson, 1978, p. 60).

The runoff-erosion hypothesis was adopted and argued by Melton (1929, 1935, 1954) for a number of mounds in Arkansas, California, Louisiana, Texas, and Washington. He believed that

> "The time honored objections that the individual mounds are (1) too symmetrical in outline and profile, (2) that they are too uniformly spaced, and (3) that they are 'due to processes not now in operation in the region'...are largely due to preconceived notions about the erosional patterns that ought to result from gullying in very weak soil supported by a more resistant sub-soil" (Melton, 1929, p. 128).

Subsequently, Melton (1935; 1954, p. 109-110) added the erosional influence of wind and slopewash and suggested that vegetational anchoring might also be a factor in places. As examples, Melton cited slight accumulations of windblown sand and silt in clumps of vegetation on erosional mounds, some dune migration, and the effect of clump vegetation alone (Coppice dunes) without fluvial erosion.

Holdredge and Wood (1947) also supported the erosion hypothesis for the "mound and depression topography" of the Central Valley of California, but without citing supporting evidence. In their view this topography occurs in areas of old soils.

> "In all occurrences seen by the authors, the mounds and depressions are so similar that similar origins seem certain.... [Similarities include]
>
> "(1) Surface erosion by water under conditions of exterior drainage on relatively gentle slopes, which are underlain by a thin layer of soft material, below which there is a more resistant layer.
>
> "(2) Surface erosion under conditions of interior drainage on flat or gently sloping areas, which are underlain by relatively thin layers of soft material, below which are substrata of more resistant permeable materials. These substrata must be sufficiently thick and permeable to permit downward seepage of rain water carrying in suspension particles entrained at the surface."

More recently, Zedler and Ebert (1979, p. 34-35) held that runoff erosion was important but not the only factor in the origin of the vernal pool topography of Kearny Mesa in San Diego County, California.

Criticisms of the runoff-erosion hypothesis, *in isolation*, include the following:

1. The frequently cited, "time-honored" objection that Mimalike mounds are too regular to be explained by the runoff-erosion hypothesis, Melton's (1929, p. 128) views to the contrary (Paeth, 1967, p. 34; Rich, 1934, p. 578).
2. "...the microrelief of the San Joaquin and similar soil complexes....[in the Central Valley of California] is formed by a combination of the mounds and depressions. Practically all the depressions are separated from each other by the divides (or intermound passes); none of them has an outlet, and water does not run between the mounds except in rare instances of overflow of some particular ponds" (Nikiforoff, 1941, p. 37-38).
3. Although mounds show some relationship to slope, the lack of a consistent relationship "...constitutes an important refutation of the dominance of water erosion as the causal agency...on the Columbia Plateau" (Kaatz, 1959, p. 152). However, Kaatz's (1959, p. 152) suspicion "...that mounds are less governed by flatness of surface than they are by conditions of mantle thickness and subdrainage" makes an important point that might well explain the inconsistent slope relationship he described.
4. Intermound erosion should leave more lag gravel than is found (Paeth, 1967, p. 31, 34). This objection is difficult to evaluate, since information is lacking on the competency of streams and other conditions at the time the mounds developed. Conceivably, any streams responsible for mound erosion might have also carried away small mound gravel. Also, if subsequent mound runoff contributed small grain sizes to intermound areas as Paeth (1967, p. 27-29) also argued, this could mask lag gravel. Although Objection 4. deserves serious consideration, its general applicability

remains to be established (see also discussion of Puget prairie mounds).

5. In the Miramar Mounds National Landmark in San Diego

   > "Per cubic foot, there were about 1.8 times as many rocks in the mounds as in the soil between them. This concentration of small rocks in the mounds contradicts the erosion hypothesis, which suggests that large rocks should be in the mounds too...." (Cox, 1984a, p. 44).

   However, this objection is greatly weakened to the extent that the Puget-prairie Mima mounds, and perhaps many Mimalike mounds elsewhere, were already poor in large stones when originally deposited, as shown by comparative data for the unmounded Spanaway gravelly sandy loam (Ness, 1958, p. 53-55).

6. The criticisms raised by Cox and Gakahu (1986) in defending the fossorial-rodent hypothesis (point 19 and Table 15). The discussion of point 19 questions some of the criticisms but not as applied to runoff erosion acting alone independently of soil anchoring.

7. In the Puget Lowland

   > "A certain amount of surface runoff can occur in low-lying mounded areas, but none could occur in the well-mounded highest terrace level of Weir Prairie where the water table is deep and the percolation rate is high" (Noble and Molenaar, 1965, p. 65).

   However, this problem disappears if the mounds were formed during the period when drainage across Weir Prairie was still active, as would be the case during the early phases of glacier withdrawal.

8. The fact that the dark-brown to black mound soil of the Puget prairies is much thicker than would be normal for prairie soils favors mound building as opposed to erosion. This objection is reviewed under Point 14 in discussion of the fossorial-rodent hypothesis. Mound-focused, concentrated biologic activity was suggested as a possible alternative to mound building in accounting for the abnormally thick A horizon.

Runoff Erosion/Polygonal Cracking

Knechtel (1952) advanced a hypothesis combining erosion with polygonal jointing of bedrock, or polygonal cracking of soils as the result of frost action or desiccation. The variants are best considered individually.

Bedrock Jointing

Knechtel (1952, p. 692-693) suggested that bedrock jointing on the Columbia Plateau of Washington and Oregon and in southeastern and south-central Oklahoma may be genetically associated with mounds in these regions. Johnson (1982, p. 39) reported that "Extremely long mounds have a common orientation that appears to be related to regional joint systems in the underlying Columbia River Basalt." The implication is that erosion along the joints may be a co-factor.

That bedrock joints may be an important genetic factor in the Columbia Plateau occurrences is indeed a possibility in areas visited by the present writer, but frost action along the joints may also be involved. Bedrock jointing can be excluded for the Puget prairie occurrences.

Permafrost Cracking

Several variants of the hypothesis exist, each calling for polygonal permafrost cracking (thermal-contraction cracking of soil in a permafrost environment), with the growth of ice wedges in the cracks and subsequent thawing of the wedges leading to a mound relief. The variants differ in that Newcomb (1940; 1952, p. 470-471), who first elaborated the hypothesis (following a note by Eakin, 1932), stressed mounding of inter-ice-wedge areas by the lateral growth of the wedges followed by melting of the ice wedges, whereas Péwé (1948) relied mainly on the melting of the ice to provide the mound relief. The Péwé variant, in which lateral pressure as the cause of mounding is not required and is rarely observed on the scale suggested, was attractive because the surface topography of the mounds is essentially identical to that left by thawing ice wedges in thawing permafrost today as noted by Péwé (1948, fig. 2, p. 294) and illustrated by Rockie (1942, fig. 2, p. 12). The hypothesis has been supported by Hubbs (1957, p. 15-16).

Ritchie (1953), apparently independently of Knechtel, advanced a combination hypothesis of frost cracking and erosion, which he applied to Mima Prairie and the Puget prairies generally. This hypothesis is cited in some detail in the following because his observations are important, although they can also be interpreted as supporting the desiccation-cracking variant.

> "The [Mima] mounds were formed by running water that flowed across partially thawed, polygonally fissured ice fields.... Where the erosion was more vigorous, the intermound areas were scoured below the lag cobble surface, giving the mounds a pedestal base of submound gravel. Conversely, where the erosion was slight, the mounds are close set and may be nearly connected on all sides by part of the original pebbly-silt mantle. The size of the intermound areas is a function of the degree of erosion that formed the mounds" (Ritchie, 1953, p. 45).

As evidence Ritchie (1953, p. 46-48) reported on Frost Prairie a hexagonal network of trenches where mounds were poorly developed. The present writer searched the area but was unable to confirm this observation. However, there has been considerable building on Frost Prairie in the last 30 years. Ritchie also cited the arguments that

"1. The Mima-type mound is restricted to the outwash valleys of the Vashon glacier but is limited to those valleys that could receive floodwater from the north.

"2. Well-developed mounds occur in topographic positions where they could have been eroded by a flood river. Although high-level terraces adjacent to the outwash valleys have a mantle of pebbly-silt material, they are unmounded.

"3. ...Because polygonal ground ice is restricted to fine sediments or material having a high percentage of fine sediments, it is natural to find that the mounds occur only within the pebbly-silt mantle of the region and not in the glacial outwash gravel lacking this silt....

"4. Mounds occur on topographic features comparable to those where polygonal ground ice is forming today.

"5. Mounds in any one area have a uniform maximum height, indicating that they were carved from a common mantle locally of a uniform thickness.

"6. The mounds have pronounced curved down-gradient alignment and are rather uniformly spaced. These features require a mechanical control such as polygonal-fissure ice to form them. However, much of the alignment is due to the eroding effect of the water, which tended to flow in direct courses and thus to cause increased erosion on the pebbly silt in the path of a stream.

"7. Some intermound areas were swept clean of all mound material, leaving a clean cobble surface. Other areas were eroded below the cobble surface, which is the base of the mounds, thus leaving a pedestal of sub-mound gravel beneath the mounds. In other areas, where erosion was slight, intermound areas still carry some mound material.

"8. Where mounds are widely spaced, there is evidence of extensive erosion, such as low and subdued mounds compared to their neighbors, as well as 'blanks' in the regularity of spacing of the mounds.

"9. The double or triple-tied [incompletely separated] mounds are evidence of the imperfect development of fissure ice in the pebbly-silt mantle.

"10. Mounds are commonly absent in the lowest prairie channels, but in their place occur a few bars of segregated mound material. This indicates the actual removal and redeposition of mound material by running water.

"11. Mounds locally show one asymmetrically developed steep side and a pronounced parallel elongation to one another, regardless of minor topographic differences in occurrence. The one steep side of the mounds faces up-gradient, a feature common to other material similarly eroded...."[18]

"12. Cobbles and small boulders exist between and on the mounds. Most of them are found on the steep up-gradient side, as if floating ice containing erratics lodged against the mounds and dropped their load on that side....

"13. Erosion of a frozen mantle unaffected by polygonal-fissure ice but surrounded by mound fields seems recorded by the differential stripping of this mantle from a knoll of frozen submound gravel. Such a knoll lies near the center of a prairie channel, 30 feet above the channel floor (see pl. 1, C)."

The present writer can confirm most of the cited observations but believes they can be better explained by alternative possibilities because of the serious objections to the hypothesis as applied to the Puget prairies. These objections include

1. The hypothesis would not apply to apparently similar mounds described from regions where present or former temperatures would be quite inconsistent with frost cracking. Hubbs' (1957, p. 15-16) arguments for the necessary cold lowland temperatures were somewhat speculative when made and are not supported by the evidence available today.
2. Direct evidence of permafrost cracking such as ice-wedge casts (traces of former ice wedges in permafrost) are unknown from the Puget Lowland or other lowland areas farther south to which the hypothesis has been applied, whether on the Pacific Coast or the Gulf Coast.

[18] McFaul's (1979, p. 55-56) measurements of mound slopes on Rock Prairie do not support steeper up-gradient than down-gradient slopes. However, on Mima Prairie, the upslope-facing sides of 24 out of 26 mounds in a former outwash channel were steeper than those facing downslope by an average of 2.4°. (See Table 4 and discussion of Mima Prairie.)

3. Temperature reconstructions strongly suggest that the low temperatures needed for permafrost cracking and growth of ice wedges did not occur in the Puget Lowland following the deposition of the Vashon outwash.

   "Rather, there is clear evidence to the contrary. The estimated mean annual temperature reduction in the Cascade Range at the maximum of the last glaciation, based on the glaciation threshold, is $4.2° \pm 1°$ (Porter, 1977, 115 [not 155 as in original]). The present mean annual temperature at Olympia, near Mima Prairie, is 10.4° (50.8°F) ([U.S.] National Oceanic and Atmospheric Administration, 1974, 951), which accords very well with the projected temperature of 10°-11° for lowland areas, based on the present glaciation threshold (Porter, 1977, 109, Figure 4). Thus the $4.2° \pm 1°$ reduction for the Cascades also appears to be a reasonable estimate for the lowlands, and is supported by an estimated August sea-surface temperature of 12°-13° for the nearby Pacific Ocean 18 000 years ago (CLIMAP [Project Members], 1976, 1132, Figure 1), a temperature only 3°-4° less than today's 16.2° (61.2°F) (J. H. Johnson, 1961, 14).[16] If these estimated reductions even approach reality, ice-wedge polygons in the Olympia area would have been impossible, since permafrost would have required a temperature reduction of at least 10°, and ice-wedge polygons even more" (Washburn, 1979, p. 169-170).

   This conclusion is supported by the work of Tsukada and others (1981, p. 734), who cited a July temperature depression of 5°-6°C lower than today for the period 15,000 to 12,000 (or 12,500) years ago, based on pollen analysis of a core from Mineral Lake in the Puget Lowland and the inferred lowering of treeline. The present mean annual and July temperatures of the Mineral Lake area are 9.4° and 17°C, respectively (Matsuo Tsukada, oral commun., 1982). The inferred July temperature depression of 5°-6°C implies a former July temperature of 11°-12°C and, if the lowering of mean annual temperature was at all comparable, a climate much too warm to permit permafrost cracking and development of ice-wedge polygons.

"[16] The 13° July-August terrestrial temperature increase since 18 000 BP indicated in the model presented by Gates (1976, 1142, Figure 7) is misleading for the lowlands considered, since the increase is based on a quadrat that encompasses the State of Washington both east and west of the Cascades."

It should be noted that former frost action as a possible factor in the origin of mounds on the Columbia Plateau (Brunnschweiler, 1962, p. 19-23; Kaatz, 1959) and the Snake River Plain in Idaho (Fosberg, 1963; Malde, 1961, 1964) is not excluded by the above objections. According to geomorphic relationships and radiocarbon dating, the Columbia Plateau mounds were apparently formed some 8,000-12,000 years ago when suitable climatic conditions may well have existed there (Roald Fryxell, Washington State Univ., written commun., 1964; Mack and others, 1976, p. 394).

Although the role of former frost action in the origin of the Columbia Plateau mounds is more defensible than for Mima mounds, the evidence for erosion is impressive, as previously discussed under Erosional Hypotheses (Runoff Erosion), and is possibly the most important process in the origin of the Columbia Plateau mounds, in combination with vegetation anchoring and, perhaps, frost or desiccation cracking. The arguments presented by Cox and Allen (1987b) for fossorial rodents being responsible for the Columbia Plateau mounds are quite consistent with the erosion hypothesis (Waters and Flagler, 1929) if the pocket gophers now present had merely occupied pre-existing mounds. Frost action may also have contributed to some of the features attributed to gophers.

Neither is the influence of frost action excluded in still other environments where the relief of originally nonmounded cold-climate patterned-ground features might have become increased. Perhaps this was the case with the California features described by Masson (1949) from the forefront of former glaciers. However, most cold-climate patterned ground is not likely to be confused with Mimalike mounds.

Seasonal Frost Cracking

Conceivably, a possible explanation for the Puget prairie Mima mounds would be a combination of seasonal frost cracking and erosion in the absence of permafrost and ice wedges, since this would not require the low mean annual temperatures demanded by a permafrost climate. However, even seasonal frost cracking has serious objections.

1. Seasonal frost cracking on the scale required does not yet seem to have been reported.
2. Often-repeated seasonal frost cracking in non-permafrost environments might be expected to leave evidence in the form of soil wedges (see also Washburn, 1979, p. 114-115), which have not yet been reported from the Puget Lowland.
3. Frost cracking would not apply to many areas of Mimalike mounds where present or former temperatures would be quite inconsistent with such frost cracking on the scale required.

Desiccation Cracking

In discussing his overall hypothesis, Knechtel (1952) favored the view that the "pimpled plains" of eastern Oklahoma were probably due to desiccation cracking followed by erosion, rather than being initiated by other types of cracking. As supporting evidence he cited desiccation polygons of comparable dimensions elsewhere in North America and the world, including the Australian gilgai. Obviously, the desiccation variant of the runoff-erosion/polygonal cracking hypothesis could also be a variant of the gilgai hypothesis discussed earlier, except for the absence of pressure effects as in traditional gilgai, or wind erosion as in some variants of the hypothesis.

Runoff-erosion/desiccation cracking warrants consideration as an explanation for the mounds of the Puget prairies because the following points favor or are consistent with it.

1. The evidence cited by Knechtel of large desiccation polygons elsewhere.
2. Much of the evidence cited by Ritchie (1953) as reviewed in connection with runoff erosion/permafrost cracking, including the evidence of mound-related drainage (Fig. 13) and mound erosion (Fig. 10).
3. The presence of mounds in some Puget Lowland kettle holes is consistent with the hypothesis if cracking and erosion occurred while buried glacier ice was still present. Kettle holes in outwash plains are common, and the fact that buried glacier ice can last for some 2,000 years or more (Porter and Carson, 1971) gives enough time for decreasing glacial drainage and wind to have deposited a layer of stony fines over the outwash gravels before kettle holes developed.
4. The discontinuity between mound fines and underlying gravel provides a common level that would tend to control mound height. The Vashon outwash is porous, and once erosion had cut down to this level, drainage would tend to dissipate, thereby promoting mound preservation.
5. The hypothesis is capable of wide application to other areas where soils are subject to wetting and drying, especially where a pronounced discontinuity exists between mound soil and underlying material. In this respect it has the same advantage as the fossorial-rodent hypothesis.

Nevertheless, the following are serious objections to its application to the Mima mounds of the Puget prairies.

1. The Spanaway soil has a low content of expandable clays, as noted by McFaul (1979, p. 55, see also p. 45) in arguing against the mounds of Rocky Prairie being gilgai features, which are characterized by a high content of expandable clays (≥ 50% montmorillonite clays in South Dakota; White and Agnew, 1968, p. 943). Weber's shrinkage tests of Spanaway soil showed very low values, as noted in the discussion of Mima Prairie.
2. A crude experiment by the present writer involving placement of a 10-cm layer of Mima mound soil in a 1-m^2 box and subjecting the soil to repeated wetting and drying produced largely negative results. Initially a few cracks tended to join and become slightly discontinuous cracks as much as 60 cm long and 3 mm wide at a maximum. However, with continued wetting and drying most of the cracks disappeared, leaving only a few faint traces as much as 5 cm long and to 1 mm wide at a maximum.
3. All the desiccation-cracked areas of Mima-mound soil observed in the field by the present writer were small and involved only a thin layer of puddled soil several centimeters thick. It might be argued that repeated cracking of thicker layers should lead to larger-scale cracks, and it is known that polygon diameter can vary directly with soil thickness, also with lack of cohesion at the base of a given soil (as would probably be applicable to the noncohesive gravels beneath the mound soil) (Corte and Higashi, 1964, p. 1-27). On the other hand, crack depth and polygon diameter and pattern depend on many variables in addition to soil depth, including grain size, degree and depth of saturation, and rate of desiccation. Whether these and any other pertinent parameters would quantitatively support the hypothesis for the Puget prairies is unknown but seems unlikely in view of the nature of the soil.

Runoff Erosion/Vegetation Anchoring

Probably the first published proposal of erosion combined with patterning by vegetation anchoring as a basic process in the erosion of Mimalike mounds was by Gibbs (1854a, p. 488-489; 1854b, p. 510), who applied the hypothesis to both the Puget prairies and the Snake River Plain of the Columbia Plateau. He thus anticipated and met the "time-honored objection" to runoff erosion being a reasonable explanation.

> "It is on these gravelly prairies lying between Olympia and the Skookum Chuck that the mounds occur mentioned by Captain Wilkes, and which he ascribes to an artificial origin. Without commenting upon the improbability of any savage race covering with these monuments so extensive a tract of country, it may be proper to mention that, after a very careful examination, I have failed to discover any regularity in their arrangement, as he imagined, and that the supposed pavement appears to consist merely of the larger stones left by water-courses. It is, indeed, difficult to account for the occurrence,

over so large a tract of country, of mounds so uniform in shape and size, and so equally distributed; but the same appearance upon a smaller scale is noticeable elsewhere, and the explanation I believe to be the protection afforded by scattered bushes, roots, or grass to the particular spots constituting their summits, while the adjacent ground has gradually been washed away. In a soil so loose and easily abraded as these prairies, such an effect is not unusual; and I have seen the process going on with individual mounds. A plant fully capable of producing the result is the wild cucumber vine, whose root, sometimes reaching the size of a flour-barrel, would constitute no small nucleus of itself" (Gibbs, 1854a, p. 488-489).

Apparently arriving at the same hypothesis independently, LeConte (1873, p. 219-220; 1874, p. 365-367; 1877) applied it to occurrences on the Pacific Slope, including the Puget prairies. As controlling conditions LeConte (1874, p. 366) cited

"...a *treeless country* and a *drift-soil*, consisting of two layers, a finer and more movable one above and a coarser and less movable one below.* Surface-erosion cuts through the finer superficial layer into the pebble-layer beneath, leaving, however, portions of the superficial layer as mounds. The *size* of the mounds depends upon the *thickness* of the superficial layer; the *shape* of the mounds depends much upon the *slope* of the surface. The process once started, small shrubs and weeds take possession of the mounds as the *better soil*, and hold them by their roots, and thus increase their size by preventing or retarding erosion in these spots." [Original author's emphases.]

The runoff-erosion/vegetation-anchoring hypothesis was supported in part by Shaw (1937) and strongly by Holland (1952, p. 59-62), who cited both clump vegetation and trees as anchoring agents that could provide spot protection against erosion, subject to certain site conditions. Holland applied the hypothesis to Gulf Coast mounds in Louisiana, especially in Beauregard and Allen Parishes.

"Observational facts support the thesis that pimple mounds are the result of erosion. The minutely adjusted, well integrated drainage patterns exhibited by pimple mound areas and the relationship of the mounds to these streams is almost proof in itself that they were formed through erosion. Mounds occur on areas where the slope is very slight. If there is no slope they have not developed, and if the slope increases those that have developed are destroyed. Near the headwaters of small, intermittent streams the mounds are low and poorly developed. Usually, each individual mound is surrounded on all sides by small drainage channels. Farther down the slope these mounds are higher and better developed; contiguous mounds down slope tend to merge, becoming connected by a low saddle. Farther downstream, or where the slope is steeper, mounds no longer are present but are replaced by elongated ridges. This is due to the greater erosive power of rivulets running parallel to the slope. These rivulets cut down more rapidly than the transverse rivulets and, eventually, as relief is increased, the stage is reached where transverse streams no longer connect the main consequent streams. Thus the mounds, which existed as isolated elevations at first, gradually become connected with adjacent mounds down slope and finally cease to exist as separate mounds but, rather, become a continuous ridge on the divide between two closely spaced streams.

"The intermound areas tend to be flat or only slightly concave. It may be that, locally, the height of the mounds is controlled by the depth to the "B" horizon of the soil. These small streams can very easily remove the loose, friable soils of the "A" horizon, but erosion is more difficult in the underlying "B" horizon. Consequently, when the streams cut down to this more compact soil, they tend to widen their valleys, thus producing the flat bottoms so characteristic of such streams.

"It is quite apparent that some other factor must have entered in to initiate the formation of mounds. Erosion could not, by itself, produce such features. Once differential erosion was started, however, normal degradational processes would tend to accentuate the initial differences. Some type of clump vegetation may very well have played the dominant role in protecting certain areas from the more direct effects of erosion. Even larger trees could have protected the areas beneath them from the direct impact of rain drops and thus caused initial differences in relief which later became pimple mounds.

"If the soil were granular, the impact of rain drops would tend to break up and disperse the granules and thus produce a tight, less pervious surface that would be even less easy to erode

* The necessary condition, I believe, is the greater movableness of the surface soil, as compared with the subsoil, whatever may be the cause of the greater movableness. In Oregon and Washington, the cause is *pebble-subsoil*; in other places mentioned below, the cause may be different. [Original author's emphasis.]

than the soil of the protected areas. The soil in the pimple mound areas, however, is a sandy silt that consists primarily of individual grains. The impact of rain drops on this soil where it is not protected by vegetation thus tends to facilitate erosion. The particular type of vegetation responsible for the starting of differential erosion is not known. It must have been limited eastward by the Mississippi River because no pimple mounds occur east of this line.

"Thus, according to the hypothesis presented in this paper (which is not new but was presented in its essential form as far back as 1874 by Le Conte), the following combination of factors is responsible for the formation of pimple mounds: (1) a sandy or silty soil with a low percentage of colloidal clay, (2) an initial surface of very low relief, (3) sufficient rainfall to cause erosion, and (4) some type of vegetation peculiar to the pimple mound areas" (Holland, 1952, p. 59-60).

Holland's views on erosion were supported by Goodarzi (1978, p. 35-42) for Cameron Parish, Louisiana, on the basis of detailed soil-profile studies, except she was uncertain whether an additional control such as vegetation was necessarily required.

As discussed earlier in discussing depositional hypotheses, Gangmark and Sanford (1963) regarded vegetation and the interaction of fluvial deposition and erosion during floods as the origin of mounds near Red Bluff, California. The mounds were similar to Mima mounds in consisting of silt, sand, and scattered stones, in resting on gravel, in having an elliptical shape, and in having blunt ends directed upstream. One well-developed mound, measuring 1 m (3 ft) high and having diameters of 4 m (13 ft) and 6 m (20 ft), approximated the size of some, but not the largest, Mima mounds. The hypothesis offered by Gangmark and Sanford differs from the one under discussion in mandating that the mounds originated as depositional forms downstream from vegetation, whereas the present hypothesis stresses erosion of a pre-existing, essentially uniform layer of sediment differentially protected by vegetation. Both hypotheses require confirmation, but the Red Bluff mounds provide convincing support for the involvement of fluvial processes in shaping the mounds and, to this extent, also for the runoff-erosion/vegetation-anchoring hypothesis.

Cain (1974) called on "pedestal" trees as anchoring agents, and applied the hypothesis to mounds in Morehouse Parish, Louisiana. The mounds, ranging in height from 30 to 143 cm (1-4.7 ft) and in diameter from 10 to 27 m (33-90 ft), were slightly elongated downslope. He stressed that

1. A drainage-related pattern was a common feature of mound assemblages.
2. Mound spacing was similar to that of trees in a mature forest.
3. Mound diameters spanned the breadth of tree crowns.

He admitted his conclusions were based on limited field observations. Collins (1975) stressed the role of clump vegetation in combining vegetation anchoring and erosion for mounds in northern Texas.

The hypothesis merits careful consideration with respect to the Puget prairies and Mimalike mounds generally because:

1. Many Mimalike mound occurrences are confined to extensive alluvial areas (see also Zedler, 1987, p. 33). For the Puget prairie Mima mounds the association is general and there is clear evidence of a genetic or modifying relationship between mounds and drainage pattern as described for Mima, Rocky, and Violet Prairies.
2. The fact that the mounds of the Puget prairies are apparently confined to terrace levels of outwash streams from the last glaciation in the Puget Lowland strongly suggests a temporal as well as physical relationship. This would be consistent with the anchoring effect of vegetation and development of the mounds by erosion during floods, including probably repeated flooding from valleys normally draining into the Puget Lowland but dammed by the Puget Lobe of the Vashon ice (Booth, 1986). In this event, mounds would date from the interval between culmination of the Vashon Stade some 14,000 ± 500 radiocarbon years ago and ice withdrawal to north of Seattle by about 13,000 years ago (Porter and Carson, 1971, p. 411; S. C. Porter, oral commun., 1987), or their development could have continued for perhaps 1,000 years longer depending on how long the Cascade drainage from some of the valleys was dammed by stagnant ice, as is known to have occurred before ice melting permitted through drainage with extensive flooding (S. C. Porter, oral commun., 1987). Thus approximate maximum and minimum age spans, respectively, for flooding of Vashon recessional outwash routes in the Puget Lowland would span the intervals of 12,000 to 14,500 and 13,000 to 13,500 years ago. Mounds of such age ranges would be consistent with their presence and collapsed appearance in some kettle holes, although proof of this temporal association is lacking.
3. Favorable stratigraphic conditions exist for preservation of mounds despite appreciable age.
4. A former forest existed and could have served as anchoring vegetation, judging from pollen analyses of lake cores from the Puget Lowland, although confirming biologic evidence from the

mounded and unmounded prairies themselves is apparently lacking (see 3.- 4. below). However, some of the mound "roots" and central depressions beneath mounds ("biconvex mounds") may be physical evidence of former trees as suggested in the discussion of Mima Prairie. Other types of anchoring are not excluded.

The runoff-erosion/vegetation-anchoring hypothesis is attractive because, like the fossorial-rodent and erosion/desiccation hypotheses, it has the potential of wide geographic applicability. Nevertheless, it suffers from several weaknesses.

1. Special site and, possibly, age conditions must apply, otherwise Mimalike mounds would be much more widespread.
2. Conceivably, the special site conditions enumerated for the fossorial-rodent hypothesis (generally a thin, erodible soil overlying a horizon more resistant to erosion) might suffice, but it is not clear that these conditions exist at all the various places to which the hypothesis has been applied.
3. Statistical data advanced by Cox and Gakahu (1986) (see review of the fossorial-rodent hypothesis, point 19 and Table 15, and the accompanying discussion that questions some of the data as applied to the Puget prairies).
4. The apparent lack of late-glacial arboreal pollen in the mounds (Fig. 3B), and the report by Leopold and others (1982) that lignin compositions of a sediment core from Lake Washington suggest a treeless source region for the central Puget Lowland prior to about 11,000 years ago.

   These points are weakened by (1) the presence of cedars on the west slope of the Cascades about 50 km east of Lake Washington at least as early as 13,570 ± 130 yr B.P., based on the presence of a cedar fragment of that age in lake sediments, together with (2) the discovery in the Puget Lowland, at a site about 40 km northwest of Mima Prairie, of cedar logs dated at 12,430 ± 160 to 12,700 ± 200 yr B.P. and interpreted as derived from a forest that grew on glacial drift while underlying ice was still present (Porter and Carson, 1971, p. 411), (3) macrofossils of early postglacial trees by at least 11,800 yr B.P. in a sediment core from Kirk Lake on the western flank of the Cascade Range at lat. 48°15′ N.; long. 121°37′ W. (L. C. Cwynar, Univ. of Toronto, oral commun., 1987), and (4) the fact that conifers are known to be early invaders of glacial outwash as noted by Barnosky (1983, p. 61; 1985). (See also the section on Pollen Profiles and Vegetation in discussion of Puget prairies.) Possible explanations for the apparent lack of late-glacial arboreal pollen in the mounds include decomposition, fire, and by-passing of grains during original deposition of the fines overlying the outwash gravel. (See also the above-cited section on Pollen Profiles and Vegetation.)
5. It might be argued that the lack of early radiocarbon dates from the mounds (Tables 2A and 2B) is inconsistent with an early age for the mound sediment, a point noted earlier in discussing evidence (20) relating to the fossorial-rodent hypothesis.

   This point is weakened by (a) the general acceptance that the fine sediment overlying the outwash gravel was originally deposited in late-glacial time, however much it was subsequently reworked; and (b) the discussion of evidence (20) above.

DISCUSSION AND CONCLUSIONS

Puget Prairie Mima Mounds

General

It is here assumed that all the Puget prairie Mima mounds are of similar origin, because of their geographic proximity to each other and because of their similar appearance, constitution, and occurrence.

Any acceptable hypothesis must explain a number of mound characteristics as described in the discussion of the Puget prairies.

The presence of the following mound aspects seems especially critical.

1. Generally uniform size and pattern in any one area.
2. Curvilinear mound groups commonly reflecting a braided drainage pattern.
3. Many elliptical mounds parallel to former drainage lines.
4. Upslope side of mounds commonly steepest.
5. Some very low mounds amid larger mounds, or low moundlike patches in intermound areas.
6. Submound gravel pedestals.
7. Occupation by fossorial rodents.
8. Cobbles and boulders in, and on, some mounds.
9. Lack of expandable clays.
10. Nonsorted (probably bioturbated) soil.
11. Mounds in a kettle hole.
12. Environmental chronology of mound areas, involving rapid development of forest in the Puget Lowland while flooding consequent on retreat of Vashon Stade glacial lobes was still possible, later retreat of the forests some 10,000 years ago, followed by prairie development, thus making dating of mound development a crucial element in any hypothesis of mound origin.

Table 16. Comparison of Mima mound characteristics and hypotheses, Puget prairies. (+) indicates characteristics favoring, and (−) characteristics opposing a hypothesis. Blanks indicate neutral characteristics.

	HYPOTHESES							
MOUND CHARACTERISTICS	Gilgai	Fluvial deposition alone	Fluvial deposition/ vegetation anchoring	Fossorial rodents	Runoff erosion alone	Runoff erosion/ frost cracking	Runoff erosion/ desiccation cracking	Runoff erosion/ vegetation anchoring
1. Generally uniform size and pattern	+	−	−	+	−	+	+	+
2. Braided-stream elements		+	+	−	+			+
3. Elliptical forms commonly parallel to drainage		+	+	−	+			+
4. Upslope side commonly steepest	−		+	−	+	+	+	+
5. Low forms 30 cm or less high amid higher forms				−	+	+	+	+
6. Submound gravel pedestals	−	−		+	−	+	+	+
7. Presence of fossorial rodents				+				
8. Cobbles and boulders in some mounds				−				
9. Lack of expandable clays	−						−	
10. Nonsorted soil (bioturbation)				+				
11. Mounds in a kettle hole				−				+
12. Environmental chronology				−		−		
TOTALS +	1	2	3	4	4	4	4	7
−	3	2	1	7	2	1	1	0

Working Hypotheses

Table 16 shows the main hypotheses discussed, arranged with reference to the foregoing list of mound characteristics. The hypotheses have been compared by assigning positive (+), negative (-), and neutral (blank) ratings as indicated, based on the evidence discussed and reasonable arguments—for instance, the possibility that although fossorial rodents inhabited the mounds and contributed to their bioturbation, they did not build them. Thus the nonsorted nature of the soil is given a positive rating for the fossorial-rodent hypothesis only and neutral ratings for the others.

The ratings are admittedly subjective. Nevertheless, the available evidence indicates that runoff erosion has been an important process in shaping the mounds and, if so, that the runoff-erosion/vegetation-anchoring hypothesis is the most probable explanation for Mima mounds—that is, the mounds of the Puget prairies. Table 16 is also notable for the number of negative ratings given the fossorial-rodent hypothesis, but no claim is made that this hypothesis is invalidated. However, it faces a number of difficulties as applied to the Puget prairies. That the various hypotheses should involve depositional as well as erosional explanations is a commentary on the ambiguous and confusing nature of much of the evidence and the need for more research.

General Implications for Mimalike Mounds

As discussed earlier, some investigators believe that because Mimalike mounds (that is, mounds apparently similar to the Mima mounds of the Puget prairies but occurring elsewhere) are very widespread, they call for a unifying hypothesis. The basic question is the extent to which widely separated but similar mounds are really of comparable origin.

The regions in which most Mimalike mounds occur today are reported to have a number of common features, including

1. Mimalike mounds.
2. Treeless, at least partially vegetated environment.
3. A comparatively thin unconsolidated deposit overlying a strikingly different material characterized by a commonly coarser, but in places finer grain size, a hardpan, or bedrock. It has been held by proponents of the fossorial-rodent hypothesis that a high water table can take the place of any of these different underlying horizons.
4. A land surface of considerable age, usually thousands of years old rather than hundreds.
5. A former or present nonpermafrost climate. This last characteristic, applicable to most regions where Mimalike mounds have been reported, significantly reduces the generality of any process dependent on frost action. It should be stressed that most contemporary or fossil occurrences of patterned ground that are commonly accepted as of periglacial origin are excluded from this review.

In the strictest sense of an overall hypothesis that includes the Puget prairies, whatever explanation best applies to them is the primary candidate for such a hypothesis. Although the foregoing discussion then leads to the view that the runoff-erosion/vegetation-anchoring explanation best fits the evidence, it is highly improbable that all Mimalike mounds have the same origin.

Only future research will prove beyond doubt if any of the hypotheses discussed explain the Mima mounds or have wide applicability elsewhere.

SUMMARY

The presently available evidence based on literature review and examination of Mima mounds (that is, those confined to the Puget prairies) and Mimalike mounds (apparently similar mounds elsewhere) indicates that

For the Puget prairies

1. Mima mounds have a common origin.

2. The gilgai hypothesis and runoff erosion combined with frost or desiccation cracking are improbable explanations.

3. Fossorial rodents presently occupy or have occupied the Mima mounds, but the fossorial-rodent hypothesis for mound origin is subject to a number of serious objections.

4. Runoff erosion combined with vegetation anchoring may best explain Mima mounds.

For Mimalike mounds generally

1. No single overall explanation is mandated by the presently available evidence; multiple explanations are probable.

2. Among the following hypotheses

   (1) Runoff erosion combined with permafrost cracking is important in explaining some Mimalike mounds in present or former permafrost environments but is inapplicable to most Mimalike mounds.

   (2) (a) Erosion combined with seasonal frost cracking or bedrock jointing, and (b) eolian or fluvial deposition combined with vegetation anchoring are hypotheses of limited applicability to Mimalike mounds, but should be investigated further with respect to their possible local importance.

   (3) Runoff erosion combined with desiccation cracking is a reasonable hypothesis in places.

   (4) Gilgai formation is a leading hypothesis where there are expandable clays subject to wetting and drying.

   (5) Both the fossorial-rodent hypothesis and runoff erosion combined with vegetation anchoring are potentially widely applicable hypotheses, but they remain to be proved.

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