Small-stone content of Mima mounds of the Columbia Plateau and Rocky Mountain regions: implications for mound origin

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SMALL-STONE CONTENT OF MIMA MOUNDS OF THE COLUMBIA PLATEAU AND ROCKY MOUNTAIN REGIONS: IMPLICATIONS FOR MOUND ORIGIN

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Abstract.—Mima moundfields were investigated at the Lawrence Memorial Grassland Preserve, located on the Columbia Plateau in southern Wasco County, Oregon, and at three locations in the San Luis Valley and Sangre de Cristo Mountains, southern Colorado, to test the alternative hypotheses of mound origin by erosion, frost action, and soil translocation by geomyid pocket gophers. The concentrations of two size classes of small stones, gravel (8–15 mm diameter) and pebbles (15–50 mm diameter), were sampled along mound-to-intermound transects and at different depths within the mounds. Numbers and masses of small stones per unit soil volume increased from intermounds to mound tops at the Colorado sites and from mound edge to mound top at the Oregon site, where thin intermound soils lay directly on the weathering surface of basalt bedrock. Numbers and masses of small stones in the surface soil of mound tops were greater than or similar to concentrations in deeper layers. Mean masses of individual pebbles were greater in the intermound zone than in mound soils at the Oregon site, but did not differ along mound-intermound gradients at the Colorado sites. Ratios of gravel to pebbles varied significantly along the mound-intermound gradient at the Oregon site and at one Colorado site, being highest at mound edges or in intermounds. These observations support the hypothesis that mounds are formed by centripetal translocation of soil by geomyid pocket gophers, and are contrary to predictions based on theories assuming erosion or frost action to be the mechanism of mound formation.

In western North America, earth mounds, which reach about 25 m in diameter and 2 m in height and are commonly known as Mima mounds, occur in many locations from southern Canada to northern Mexico (Cox 1984a). The density of mounds ranges from about 1 to 3 per ha in localities in the Great Plains and to more than 50 per ha in many localities in California. The material forming these mounds consists largely of soil and small stones (up to about 50 mm in diameter) but includes few stones of larger size, although these may be abundant in intermound areas. Mounds of similar nature also have been reported in East Africa (Cox and Gakahu 1983, 1987), South Africa (Lovegrove and Siegfried 1986), and Argentina (Cox and Roig 1986).

In the interior montane region of western North America, Mima mounds occur from southern British Columbia, Canada (O. Slaymaker, personal communication), to central Sonora, Mexico (Hill 1906). They are very widespread on the Columbia Plateau of eastern Washington, north central Oregon, and southwestern Idaho (Freeman 1926, Fosberg 1965, Kaatz 1959, Malde 1961, 1964, Waters and Flagler 1929). In the Rocky Mountain region of the United States they occur in valleys and basins and on plateaus and mountain meadows from eastern Idaho and southwestern Montana south through northeastern Utah and Wyoming (R. Reider, personal communication) to Colorado (Murray 1967, Vitek 1978) and northern New Mexico (J. D. Vitek, personal communication).

Three major hypotheses have been suggested for the origin of mounds in the interior montane region of North America: (1) water erosion, (2) periglacial freeze-thaw dynamics, and (3) soil translocation by geomyid rodents.

Waters and Flagler (1929) postulated that the mounds of the Columbia Plateau resulted from the erosion of a volcanic ash layer laid down over the surface of basaltic rock, the intermound zones constituting "erosion furrows." Fosberg (1965) suggested that the stone nets often associated with Columbia Plateau mounds were formed by frost-sorting processes, and that soil material deposited over this system was eroded to leave mounds within the stone polygons. The erosional hypothesis was also supported by Knechtel (1962) and Washburn (1980).

Others have regarded the mounds, as well as the sorted stone nets often associated with them, to be a periglacial phenomenon. Kaatz

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(1959) suggested that moundfields were a thermokarst landscape, with the mounds representing the centers of former ice-wedge polygons. Malde (1961, 1964) and Brunnschweiler (1962) concluded that the mounds were formed in the late Pleistocene by processes of freeze-thaw and solifluction. In the Sangre de Cristo Mountains of southern Colorado, Frederking (1973) interpreted the mechanism of formation of mounds in lower alpine tundra areas to be frost heave, soil creep, and solifluction.

Finally, the Dalquest and Scheffer (1942) hypothesis that Mima-type mounds form by the centripetal translocation of soil resulting from outward tunneling of pocket gophers from their centers of activity has been applied to mounds of this region (Larrison 1942, Price 1949, Cox 1983a).

Cox and Gakahu (1986) derived alternative predictions of the major hypotheses of Mima mound origin. These predictions pertained to the small stone content of mound and intermound soils, and to moundfield geometry. They tested these predictions against data from four Mima moundfields in western Washington, central California, and southern California. They concluded that the results strongly supported the pocket gopher hypothesis of mound origin.

Our studies extend this test to mounds of the Columbia Plateau of eastern Oregon and to mounds of valley floors, upland mesas, and alpine tundra in southern Colorado.

PROCEDURE

Study Areas

In Oregon we investigated moundfields on and adjacent to the Lawrence Memorial Grassland Preserve (hereafter, Lawrence Preserve), a Registered National Natural Landmark owned by the Nature Conservancy, near Shaniko, southern Wasco County (44°57′N, 120°48′W). The mounded portion of this preserve is typical "biscuit scabland" (Copeland 1980) and lies at an elevation of 1,036–1,060 m on the Shaniko Plateau, formed of Columbia River basalts. The numerous Mima mounds range up to about 1 m in height and about 20 m in diameter. The mound soils are classified as Condon aeolian silt loams and the shallow intermound soils as Bakeoven residual, very cobbly loams. The climate of this region is cold and semiarid, with annual precipitation averaging 280 mm. The vegetation of the mounds is dominated by Idaho fescue (*Festuca idahoensis*) and bluebunch wheatgrass (*Agropyron spicatum*), and that of the intermounds by Sandberg bluegrass (*Poa sandbergii*), scabland sagebrush (*Artemisia rigida*), bitterroot (*Lewisia rediviva*), and several species of biscuitroot (*Lomatium* spp.). The northern pocket gopher (*Thomomys talpoides*) is abundant at this site. This area was studied between 24 and 28 May 1986.

In southern Colorado three sites, all originally investigated by Vitek (1978), were studied. These sites span a wide range of altitudinal and climatic conditions. Sampling of these sites was carried out between 30 July and 4 August 1986.

The Blanca South site (37°20′N, 105°33′W) is located on the floor of the San Luis Valley, about 13 km south of the community of Blanca, Costilla County, at an elevation of 2,375 m. These mounds range from about 8.4 to 16.8 m in diameter and from 11.4 to 42.5 cm in height, and are developed on a residual sandy loam overlying extrusive basalt bedrock. The arid climate has less than 20 cm annual precipitation and is extremely cold in winter. The vegetation of the mounds is dominated by winterfat (*Eurotia lanata*) and blue grama (*Bouteloua gracilis*), with snakeweed (*Gutierrezia sarothrae*) and globemallow (*Sphaeralcea coccinea*) increasing in importance in intermound areas. The valley pocket gopher (*Thomomys bottae*) is common at this location.

The Mosca Flats site (37°46′N, 105°23′W) is located 9 km west of Red Wing, in western Huerfano County at an elevation of 2,800 m. Mounds at this location range from 8.2 to 13.0 m in diameter and from 20 to 71 cm in height. Soils are sandy loams developed on Quaternary gravels overlying Tertiary volcanics. Mean annual precipitation is probably 20–36 cm, and the vegetation of both mound and intermound areas is dominated by blue grama and pasture sagebrush (*Artemisia frigida*). The northern pocket gopher (*T. talpoides*) is abundant at this site.

The Alpine Ridge site (37°39′N, 105°29′W) lies at an elevation of 3,615 m in a saddle of the main ridge of the Sangre de Cristo Mountains on the border of Alamosa and Huerfano counties. Mounds range from 8.4 to 16.8 m in diameter and from 11.4 to 39.4 cm in height. Soils are residual sandy loams, in this case developed on Precambrian metamorphic rocks. Precipitation at this lower alpine tundra site is probably in excess of 50 cm. The vegetation of mounds and intermounds is dominated by *Kobresia myosuroides*, with plant cover in the intermounds being sparser and richer in mosses and lichens. The northern pocket gopher is abundant at this site.

Hypotheses

Based on the analysis of mound-formation hypotheses by Cox and Gakahu (1986), we postulated the following patterns for small rock content of mound and intermound soils:

Erosion hypothesis.— The concentration of both gravel and pebbles will be greater for intermound and mound edge than for mound tops because some concentration of these erosion-resistant elements should occur as the fines are removed to reduce the intermound surface level. Because the smaller gravel fraction should be carried away more than the pebble fraction by such erosion, the gravel/pebble ratio should be lower for the intermound and mound edge than for the mound top. Mean pebble mass should be least on the mound top and greatest at the mound edge and in the intermound zone.

Frost-sorting hypothesis.—The concentration of gravel and pebbles should increase from mound centers to the center of the intermound zone because of transport of these stones to the margins of convectional cells (intermound centers). Because the larger pebbles should be moved more actively, the ratio of gravel to pebbles should be greatest on mound tops. The mean size of pebbles should also increase progressively from mound top to mound edge and intermound center.

Fossorial rodent hypothesis.—Both gravel and pebbles should be more concentrated on mound tops than at mound edges, if soil and small stones are moved moundward by animal activity and if fines are selectively returned toward the intermounds by erosion. Concentrations should also be greater at mound edges than in intermound areas, unless the intermound zone is a strong source area of weathering rock fragments. Gravel/pebble ratios should not be greatest on mound tops, however, because erosion should also tend to return more gravel than pebbles toward the intermounds. Mean pebble masses should be greater in the intermound zone than in the mounds, but values for mound edge and mound top should be similar because the major transportational bias should be exerted during movement of pebbles from intermound to mound edge.

Methods

Four (Alpine Ridge) to six (other sites) mounds were selected at each site for sampling small-stone content of mound and intermound soils. The diameters and maximum heights of these mounds were measured. These mounds were chosen because they were among the largest available and were surrounded on all sides by intermound flats. On the top of each mound, a 2-m square was marked out, with sampling locations designated at each corner. From these corner points, transects were paced outward toward the centers of the four widest intermound zones and sampling locations designated at the mound edge (0.5 m inward from the edge proper) and at a point one mound radius beyond the edge. A total of 12 locations were thus sampled for each mound. At each location, 1,980 cm^3 samples of the surface (0–10 cm) material, including stones less than 50 mm in maximum diameter, were collected. At the mound-top locations, pits were dug and similar samples taken at 30–40 cm (Colorado sites) or at 40–50 and 80–90 cm (Oregon site). Samples were dry-sieved in the field to retain all stones greater than 8 mm in minimum diameter. In the laboratory the small-stone fraction was separated into two size classes, arbitrarily termed gravel (8–15 mm) and pebbles (15–50 mm), and the numbers and masses of each of these components were determined. Because of heavy deposition of caliche in the Blanca South soil, samples of small stones were washed for 24 hr in concentrated HCl before sorting and analysis. This was done to obtain the concentration of elements influenced by the mound-forming mechanism, rather than by the pattern of caliche deposition.

At the Oregon site samples for fine textural analysis were also taken at the three sampling depths at one mound-top location on each mound. These samples were analyzed by the standard Bouyoucos technique (Cox 1985) to

TABLE 1. Characteristics of Mima mounds from which soil and small stone samples were collected in north central Oregon (southern Wasco County) and south central Colorado (San Luis Valley and Sangre de Cristo Mountains).

Location	N	Mean diameter (m)		Maximum height (m)	
		$\bar{x}$ ± SD	Range	$\bar{x}$ ± SD	Range
OREGON					
Lawrence Preserve	6	14.73 ± 2.63	11.55–17.25	0.92 ± 0.12	0.80–1.09
COLORADO					
Blanca South	6	12.21 ± 1.90	10.00–14.60	0.25 ± 0.06	0.19–0.36
Mosca Flats	6	10.24 ± 1.49	8.50–12.35	0.34 ± 0.06	0.25–0.40
Alpine Ridge	4	11.92 ± 2.05	10.00–14.75	0.56 ± 0.13	0.40–0.70

obtain percentages of sand, silt, and clay in the 2-mm soil fraction. For the Colorado sites, soil textural data for samples collected in an earlier study were supplied by J. D. Vitek. These samples were taken from 12.7-cm-depth zones from the surface to the maximum depth of the soil at six locations along a transect crossing one mound at each site. The two end locations of each transect lay in the intermound zone and the four central locations on the mound surface. The percentages of sand, silt, and clay in the 2-mm fraction of these samples were also determined by the Bouyoucos hydrometer technique.

Data on the numbers and masses of small stones were analyzed by a three-factor ANOVA, using the BMDP8V statistical procedure (Dixon and Brown 1979). In these analyses the three classification factors were size class, mound, and location (either horizontal position along the mound-intermound gradient or depth of mound-top samples). Data on fine textural composition were tested with a single-factor ANOVA.

RESULTS

The mounds sampled at the Oregon site were greater in diameter and height than those at any of the Colorado sites (Table 1). In Colorado, mounds were lowest in elevation at the arid Blanca South site and increased in height, but not in diameter, with increasing elevation and precipitation. All mounds sampled were nearly circular in outline. Circularity ratios (r_c) were calculated from the area (a) and circumference (p) by the equation

$$r_c = 4\pi a/p^2$$

and ranged from 0.95 to 1.00.

Mounds at all sites were composed of soil containing an abundance of small stones (mostly less than 50 mm in maximum diameter). Some larger stones were also present. Most of these were 5–10 cm in maximum diameter. At the Colorado sites these were often at the mouths of deep holes dug into the mounds by badgers (*Taxidea taxus*) or coyotes (*Canis latrans*). The holes dug by these animals were often deeper than the mound height, and digging thus brought to the surface large stones from the zone beneath the mound proper. In one instance, a rock fragment 24 cm long was found in the spoil heap of a presumed badger hole. In contrast, large stones, including partially exposed boulders more than 50 cm in diameter, were common in the intermound zones of all moundfields. Samples of soil and stones less than 50 mm in maximum diameter were sometimes difficult to obtain in the intermound zones because of the high density of these large stones.

At the Lawrence Preserve, Oregon, data for variables relating to small-stone content varied significantly among the mounds sampled in almost all cases. However, several consistent patterns were noted along mound-intermound and mound-top depth gradients. Both total numbers and total masses of gravel and pebbles in the surface soil varied significantly along the mound-intermound gradient ($F_{2,10}$ = 4.7 and 37.2 for number and mass, respectively; $P < .05$ and $< .001$ for number and mass, respectively), being greatest in the shallow intermound soils (Fig. 1). Between the edges and tops of mounds, however, mean values for both number and mass increased, this increase being significant for mass ($F_{1,5}$ = 13.6, $P < .05$). This increase was greater for pebbles than gravel, as indicated by a size-place interaction term ($F_{1,5}$ = 26.4, $P < .01$). Total mass of small stones also varied significantly with depth at the tops of mounds ($F_{2,10}$ = 9.4, $P < .01$), being less at the

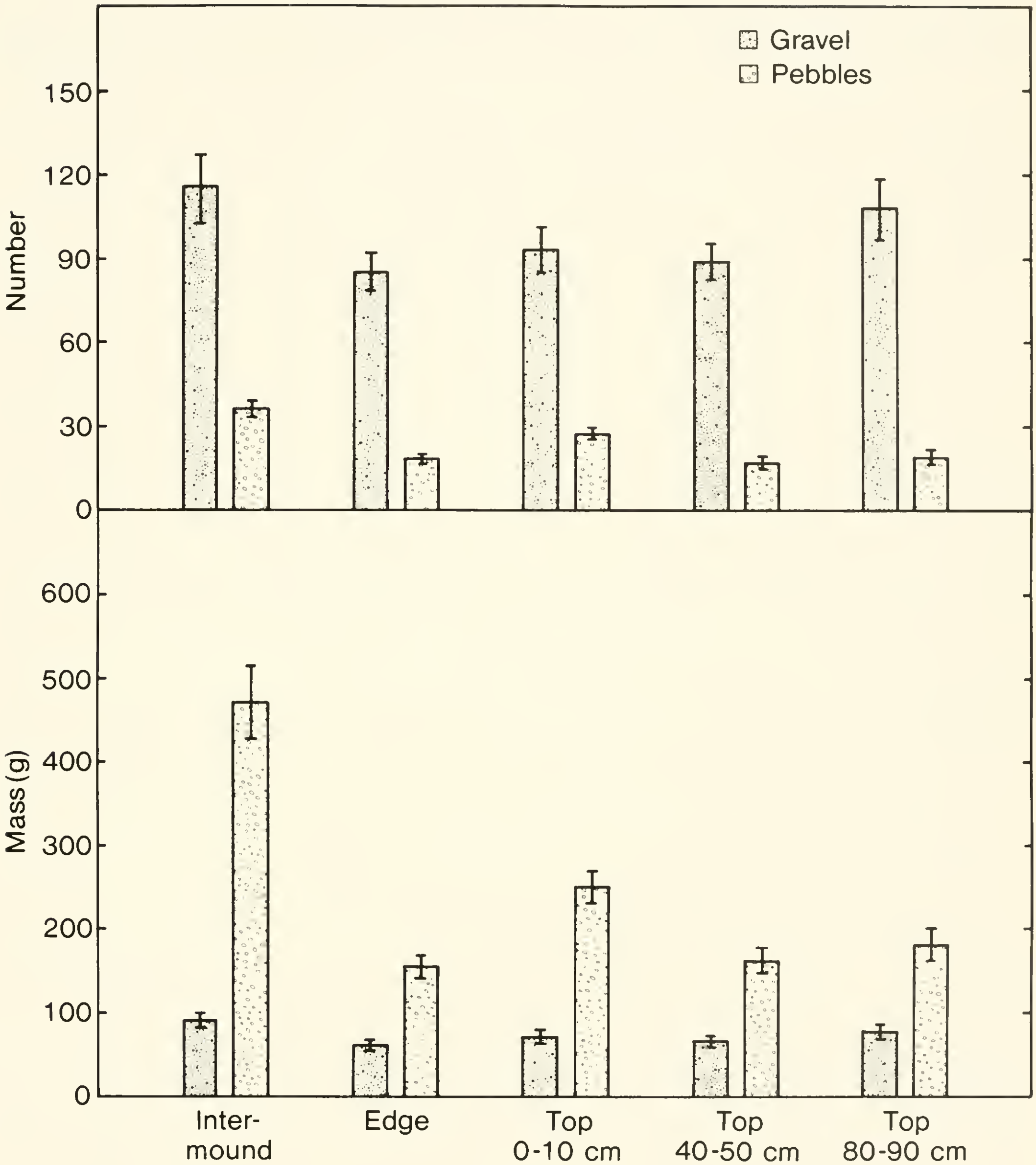

Fig. 1. Total numbers and masses of gravel and pebbles in 1,980 cm^3 soil samples from Mima mound tops (0–10, 40–50, and 80–90 cm depths), edges, and intermound zones at the Lawrence Memorial Grassland Preserve, Wasco County, Oregon. Four replicates were taken at each location on each of six mounds.

intermediate depth than at either the surface or the greatest depth. Again, this variation was more pronounced for pebbles than for gravel ($F_{2,10}$ = 18.1, P < .001), with pebbles showing more than a 1.5X increase in mass from intermediate depth to surface.

Ratios of gravel numbers and masses to pebble numbers and masses in the surface soil at Lawrence Preserve, Oregon (Table 2), varied significantly along the mound-intermound gradient ($F_{2,10}$ = 12.8 and 15.8 for numbers and masses, respectively; P < .01 and < .001, respectively), with the highest ratios being at the mound edge. Variation along the depth gradient at mound tops was significant only for ratios of masses ($F_{2,10}$ =

TABLE 2. Mean gravel/pebble ratios for numbers and masses and mean masses of individual gravel and pebble elements from mound and intermound sites at the Lawrence Memorial Grassland Preserve, Oregon (n = 24 in all cases).

Location	Depth	Gravel/pebble ratio ± SE Mass ratio	Number ratio	Mean mass (g) ± SE Gravel	Pebbles
Mound top	0–10 cm	0.316 ± 0.028	3.544 ± 0.244	0.792 ± 0.019	8.838 ± 0.517
Mound top	40–50 cm	0.499 ± 0.058	6.158 ± 0.586	0.758 ± 0.029	9.795 ± 0.556
Mound top	80–90 cm	0.564 ± 0.087	6.805 ± 0.806	0.724 ± 0.031	9.396 ± 0.597
Mound edge	0–10 cm	0.454 ± 0.036	5.232 ± 0.432	0.725 ± 0.023	8.575 ± 0.346
Intermound	0–10 cm	0.221 ± 0.021	3.340 ± 0.279	0.820 ± 0.027	12.837 ± 0.525

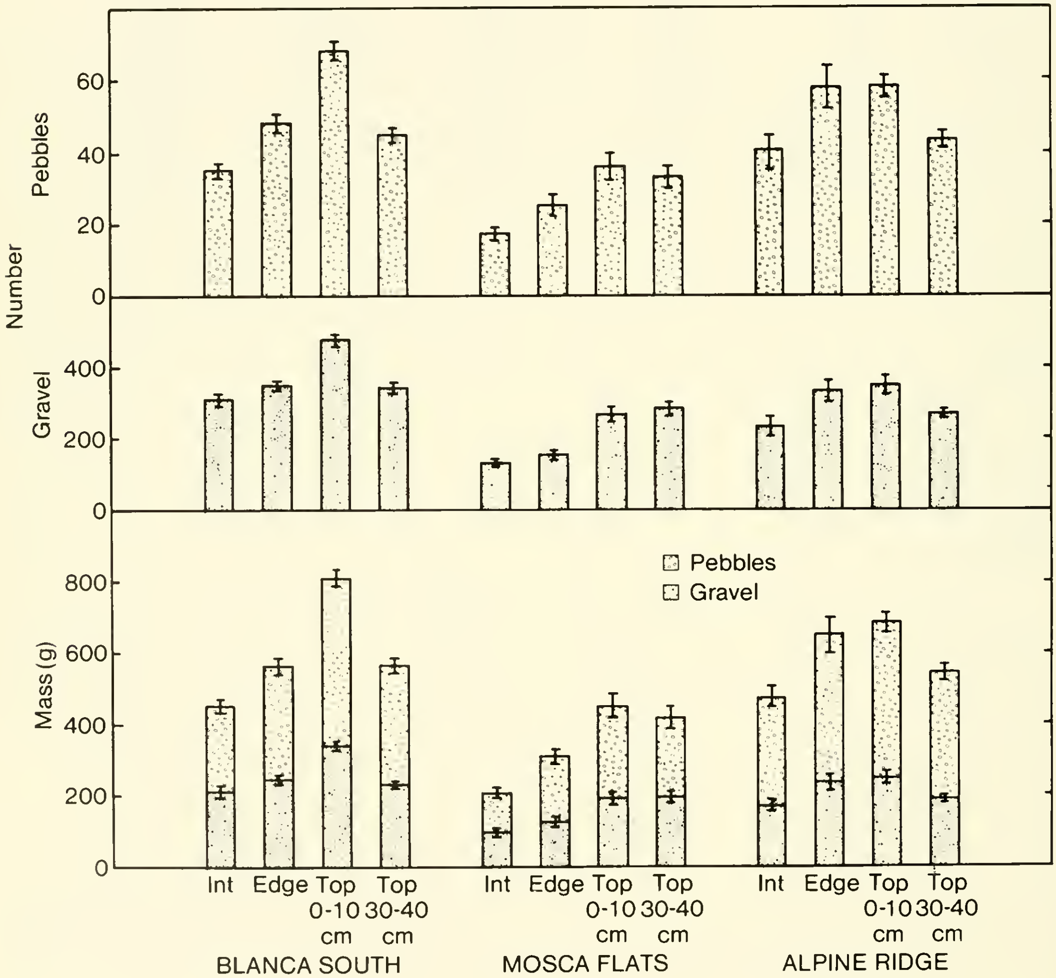

Fig. 2. Total numbers and masses of gravel and pebbles in 1,980 cm^3 soil samples from Mima mound tops (0–10 and 30–40 cm depths), edges, and intermound zones at three locations in the San Luis Valley and Sangre de Cristo Mountains of southern Colorado. Six mounds were sampled at Blanca South and Mosca Flats, four at Alpine Ridge. Four replicates were taken at each location on each mound.

6.7, $P < .05$), with the ratios being greatest at the deepest level.

At the Oregon site the mean mass of individual pebbles in the surface soil of intermound areas was about 1.4–1.5X that in mound soils ($F_{2,10}$ = 26.2, $P < .001$). No

TABLE 3. Results of ANOVA tests of variables relating to small-stone content (gravel and pebbles) of mound and intermound soils at three locations in the San Luis Valley and Sangre de Cristo Mountains, Colorado. Surface positions are mound top, mound edge, and intermound; mound-top depth positions are 0–10 and 30–40 cm. Six mounds were sampled at Blanca South and Mosca Flats, four at Alpine Ridge.

Test	Blanca South	Mosca Flats	Alpine Ridge
NUMBERS VS SURFACE POSITION			
Among places (DF = 2,10)*	$F = 28.2, P < .001$	$F = 14.3, P < .01$	$F = 9.5, P < .05$
Size X place (DF = 2,10)*	$F = 16.1, P < .001$	$F = 15.2, P < .001$	$F = 9.3, P < .05$
MASSES VS SURFACE POSITION			
Among places (DF = 2,10)*	$F = 126.9, P < .001$	$F = 12.3, P < .01$	$F = 7.8, P < .05$
Size X place (DF = 2,10)*	$F = 4.7, P < .05$	$F = 4.2, P < .05$	NS
NUMBERS VS DEPTH			
Among places (DF = 1,5)†	$F = 89.1, P < .001$	NS	NS
Size X place (DF = 1,5)†	$F = 85.5, P < .001$	NS	NS
MASSES VS DEPTH			
Among places (DF = 1,5)†	$F = 63.7, P < .001$	NS	NS
Size X place (DF = 1,5)†	NS	$F = 8.8, P < .05$	NS

*2,6 for Alpine Ridge
†1,3 for Alpine Ridge

TABLE 4. Ratios of gravel numbers and weights to pebble numbers and weights in soil samples from Mima mound tops (0–10 and 30–40 cm depths), edges, and intermound zones at three localities in the San Luis Valley and Sangre de Cristo Mountains, southern Colorado. Six mounds were sampled at Blanca South and Mosca Flats, four at Alpine Ridge. Values are derived from four replicates at each mound location.

		Gravel/pebble ratio			
Locality	Ratio type	Top (0–10 cm)	Top (30–40 cm)	Edge	Intermound
Blanca South ($n = 24$)	Number *	7.155 ± 0.310	8.043 ± 0.491	7.545 + 0.436	9.216 ± 0.577
	Weight	0.756 ± 0.038	0.752 ± 0.045	0.837 ± 0.059	1.008 ± 0.105
Mosca Flats ($n = 24$)	Number	8.352 ± 0.672	9.482 ± 0.486	7.438 ± 0.412	8.749 ± 0.721
	Weight	0.950 ± 0.100	1.081 ± 0.088	0.799 ± 0.066	1.094 ± 0.116
Alpine Ridge ($n = 16$)	Number	5.922 ± 0.216	8.017 ± 1.082	5.972 ± 0.437	5.894 ± 0.566
	Weight	0.564 ± 0.024	0.553 ± 0.030	0.619 ± 0.052	0.630 ± 0.068

*DF = 3, 15, F = 2.43, P < .05

significant variation was noted with depth, however. Mean mass of individual gravel elements did not vary greatly among sampling locations.

For the Colorado sites, data on small-stone content also varied significantly among the mounds sampled for almost all variables, although less often for the Alpine Ridge site, where only four mounds were sampled. Nevertheless, clear patterns of increase in the concentration of both gravel and pebbles in the surface soil from intermound to mound top were evident at all sites, both for numbers and mass (Fig. 2). These trends were significant in all cases (Table 3) but were much stronger for the Blanca South and Mosca Flats sites than for Alpine Ridge, especially for the pebble component. Gravel and pebbles differed significantly in the strength of this trend (size × place interaction, Table 3) in all but one case (mass data, Alpine Ridge), the tendency being for pebbles to show a greater overall increase in concentration.

With only two exceptions (number and mass of gravel at Mosca Flats), mean values for concentration of gravel and pebbles were greater in the surface soil of mound tops than at a depth of 30–40 cm (Fig. 2). This tendency was significant only for Blanca South, however (Table 3).

Little significant variation of gravel/pebble ratios was noted for the Colorado sites (Table 4). Ratios of gravel and pebble numbers at Blanca South were greater in the intermounds

TABLE 5. Mean masses of individual gravel and pebbles in soil samples from Mima mound tops (0–10 and 30–40 cm depths), edges, and intermound zones at three localities in the San Luis Valley and Sangre de Cristo Mountains, southern Colorado. Six mounds were sampled at Blanca South and Mosca Flats, four at Alpine ridge. Values are derived from four replicate samples from each mound location.

		Mean mass (g) ± SE			
Locality	Rock component	Top (0–10 cm)	Top (30–40 cm)	Edge	Intermound
Blanca South ($n = 24$)	Gravel *	0.714 ± 0.008	0.684 ± 0.009	0.706 ± 0.010	0.677 ± 0.010
	Pebbles	6.866 ± 0.198	7.460 ± 0.292	6.544 ± 0.238	6.683 ± 0.330
Mosca Flats ($n = 24$)	Gravel	0.752 ± 0.056	0.684 ± 0.009	0.711 ± 0.008	0.728 ± 0.012
	Pebbles	6.673 ± 0.310	6.420 ± 0.312	7.156 ± 0.355	6.355 ± 0.347
Alpine Ridge ($n = 16$)	Gravel	0.707 ± 0.013	0.715 ± 0.009	0.718 ± 0.015	0.758 ± 0.026
	Pebbles	7.490 ± 0.205	8.084 ± 0.290	7.117 ± 0.360	7.269 ± 0.317

*DF = 3,15, F = 3.56, P < .05

TABLE 6. Soil textural data for mound depth profiles at the Lawrence Memorial Grassland Preserve, Oregon, and for mound and intermound locations at three sites in the San Luis Valley and Sangre de Cristo Mountains, southern Colorado.

		Percent of 2-mm fraction ± SE		
Location	N	Sand	Silt	Clay
LAWRENCE PRESERVE, OR				
Mound top, 0–10 cm	6	34.2 ± 3.1	43.8 ± 3.3	22.0 ± 0.3
Mound top, 30–50 cm	6	34.6 ± 3.2	41.9 ± 3.5	23.6 ± 0.5
Mound top, 80–90 cm	6	31.8 ± 3.6	45.5 ± 4.2	22.7 ± 0.8
BLANCA SOUTH, CO				
Intermound, 0–25.4 cm	4	63.6 ± 2.0	21.0 ± 1.8	15.4 ± 0.3
Mound, 0–25.4 cm	8	62.5 ± 0.6	22.2 ± 0.6	15.2 ± 0.2
Mound, 25.4–50.8 cm	6	64.3 ± 1.1	20.9 ± 1.0	14.6 ± 0.5
MOSCA FLATS, CO				
Intermound, 0–25.4 cm	2	62.5 ± 0.1	21.3 ± 1.1	16.2 ± 1.0
Mound, 0–25.4 cm	8	61.7 ± 0.6	20.3 ± 1.1	18.0 ± 0.7
Mound, 25.4–50.8 cm	4	58.8 ± 1.1	18.6 ± 0.6	22.5 ± 1.5
ALPINE RIDGE, CO				
Intermound, 0–25.4 cm	4	63.8 ± 2.0	26.0 ± 1.6	10.2 ± 0.5
Mound, 0–25.4 cm	8	75.2 ± 1.4	14.2 ± 1.3	10.7 ± 0.2
Mound, 25.4–50.8 cm	3	71.3 ± 0.6	17.9 ± 0.8	10.9 ± 0.3

and in the deep zone of the mound top than in the surface soil of the mounds. Trends in mean values of gravel/pebble ratios were generally similar for Mosca Flats and Alpine Ridge, but these patterns were not statistically significant. Mean masses of individual gravel and pebble elements showed very little variation with sampling location at any of the sites (Table 5).

Soil textural data from mound profiles at the Lawrence Preserve, Oregon, showed no consistent change with depth (Table 6), the texture being that of a loam at all levels. At the Blanca South site in Colorado no clear pattern of mound-intermound or depth variation in texture was noted. Although both mound and intermound soils were sandy loams, samples from the upslope side of the mound and the adjacent intermound were significantly sandier ($n = 8$, $\bar{x} = 64.85\%$) than samples from the downslope portion of the mound ($n = 12$, $\bar{x} = 61.22\%$; $t = 4.65$, $P < .001$). At Mosca Flats the concentration of clay in the soil varied significantly (DF = 2,11; $F = 6.74$, $P < .025$) among sampling locations, being greatest in the deeper layers of the mound. Surface soil texture at this site was also a sandy loam. At Alpine Ridge texture also varied significantly among sampling locations (DF = 2,12; $F = 13.52$, $P < .001$ for sand), the intermound soil having the highest concentration of silt and the surface soil of the mound the highest concentration of sand.

Discussion

With respect to predictions of the three hypotheses of mound origin, the trends of increase in total concentrations of gravel and pebbles from mound edge to mound top at all locations support the fossorial rodent hypothesis. The low concentrations of gravel and pebbles in intermound areas at the three Colorado sites also support this hypothesis. The very high concentrations of small rocks in the intermound areas at the Oregon site reflect only the shallowness of these soils over the weathering surface of the basalt bedrock.

The increases in small-stone concentration from deep to surface layers of the mounds at the Colorado locations likewise support the fossorial rodent hypothesis, as does the increase in mass of small rocks from intermediate depth to the surface of mounds at the Oregon site. The high surface concentrations of small stones suggest that movement of soil and small stones to the tops of mounds is being offset by erosional removal of soil fines. Thus, erosion now appears to be an agent of mound destruction.

The significantly greater change in concentration of pebbles than of gravel along the mound-intermound gradient at Lawrence Preserve, Blanca South, and Mosca Flats, together with the significant variation in the gravel/pebble number ratio at Lawrence Preserve, also supports the fossorial rodent hypothesis. In no instance, as predicted by the erosion and frost-sorting hypotheses, did the highest values of this ratio occur at mound tops. The trend of mean pebble mass at Lawrence Preserve also agrees with the prediction of the fossorial rodent hypothesis. In no case was a significant difference in mean pebble mass noted between mound top and mound edge, as predicted by the erosion and frost-sorting hypotheses.

Soil textural data from Lawrence Preserve indicate that the mound soils are very high in silt and clay content, which reflects the high loess component of the mound parent material. The lack of strong textural sorting with depth suggests that the mound soils are kept well mixed by the activities of burrowing animals. However, an argillic B horizon is evident in at least some mounds of this region (R. Reider, personal communication). Our data are very similar to those obtained by Johnson (1982) at this same site. Johnson (1982), however, noted that the intermound soils were somewhat sandier than those of the mounds. The texture of the intermound soil probably reflects the contribution of coarser components by weathering of the basaltic bedrock. At the Colorado sites texture was quite similar for both intermounds and mounds. The higher concentration of sand in mound-top soils at Alpine Ridge and the higher concentration of clay in the deeper mound soils at Mosca Flats, however, suggest that some differential removal of the finer textures occurs by wind and water erosion from the mounds.

Thus, many of the observed patterns of small-rock composition support the fossorial rodent hypothesis, and none supports the erosion or frost-sorting hypothesis. Both small-stone concentration and soil textural patterns are also consistent with the hypothesis that erosion is presently a mechanism of mound degradation rather than development.

Other evidence also argues strongly against freeze-thaw dynamics as a cause of mound formation. The suggestion that mounds may be remnant centers of ancient ice-wedge polygons (Kaatz 1959) is not supported by evidence of former permafrost, such as ice-wedge casts, from the vicinity of any present moundfield (Washburn 1980). The hypothesis that Mima mounds represent some sort of frost-sorting phenomenon is likewise not well supported by observations in any present-day periglacial environments. Most active sorted polygons lack central mounds of appreciable height and are less than 4 m in diameter (Washburn 1980). The largest sorted stone nets may reach 5–20 m in diameter and have a mounded center up to 1 m above the bordering gutter, but such nets require that the common large clasts in the soil system be 0.5–3.0 m in diameter (Goldthwaite 1976). Even these net dimensions are exceeded commonly in Mima mound fields, even though clasts of such size are rarely present. Recent models of the development of sorted polygons (Gleason et al. 1986), as well, suggest that the width of such polygons should be about 3.6X the depth of the active layer of the soil. For the very shallow soils of most Mima moundfields, this relationship does not permit the formation of mound-intermound units of the order of 20–30 m or more in diameter. Finally, even the large sorted stone circles and nets associated with Mima mounds on the Columbia Plateau have recently been attributed to the soil-mining activities of pocket gophers (Cox and Allen 1987). Thus, we conclude that periglacial hypotheses of Mima mound origin are conclusively falsified.

Data on small-stone concentrations in mound and intermound soils at these Columbia Plateau and Rocky Mountain sites are similar to those of Cox and Gakahu (1986) for sites on the Pacific Coast from southern California to the Puget Lowlands of Washington. In all, data from eight Mima mound sites, spanning a wide range of climatic and geological settings, show a consistent pattern of concentration of the small-stone fraction in mound soils. In addition, all of these sites are consistent in showing highest gravel/pebble ratios at intermound or mound edge locations, rather than on mound tops, as predicted by physical hypotheses of mound origin.

Data for the Colorado sites differ from those of the Pacific Coast sites (Cox and Gakahu 1986) and our Oregon site in showing no variation in mean pebble mass along the mound-intermound gradient. This apparently reflects the deficiency of heavy rock fragments with maximum diameters less than 50 mm in the intermound soils at the Colorado sites. Mean masses of pebbles at these locations ranged from 6.4 to 7.3 g (Table 5), compared to values of roughly 9–14 g for intermound soils at other sites.

The impetus for formation of Mima mounds by pocket gopher activity at Lawrence Preserve and Alpine Ridge sites is probably waterlogging of the shallow intermound soils during wet periods of the year. Intermound soils at these locations are shallow, and precipitation levels are high enough that wet conditions are frequent, especially in spring. In these locations, as well, water erosion probably exceeds wind erosion and may be the primary physical factor limiting height development of the mounds. Selective erosional transport of silt and clay fractions from mounds to intermounds probably accounts for the sandier texture of mound-top soils at Alpine Ridge.

The impetus for Mima mound formation at Blanca South, and perhaps Mosca Flats, must be somewhat different, however. Blanca South is the driest site at which Mima mounds have been recorded in North America. Although the mounds at this location are the lowest of those at the three Colorado sites examined in this study, they are as sharply defined and numerous as those at other Colorado sites. This suggests that the impetus for their formation is strong, but that their development in height is limited more severely by erosion. Wind erosion appears to be intense at this site, as suggested by the difference in sandiness of the upslope and downslope sides of the mound from which texture samples were obtained (Table 6).

It is unlikely that waterlogged conditions are prevalent for significant periods at the Blanca South site, which receives less than 20 cm of precipitation annually. This site possesses a thick, shallow caliche layer. In two intermound pits the surface of this layer lay at 29–36 cm. On unmounded alluvial flats immediately below the study area, rock-free, friable soil extended to a depth of 60 cm in a single test pit. Similarly, at Mosca Flats low annual precipitation and good drainage probably prevent prolonged waterlogging of the soil (J. D. Vitek, personal communication). Shallowness of the surface soil, per se, seems to favor the formation of Mima mounds at these sites. The shallowness of intermound soils may expose pocket gophers to high predation risk by animals such as badgers and coyotes, or to exposure to severe winter cold, which characterizes the San Luis Valley. Because Mima mounds are absent from shallow desert soils within the range of pocket gophers in much of the Southwest, we suggest that the primary advantage of mounds at sites on the floor of the San Luis Valley is reduction in exposure of pocket gophers to cold. In the deeper soils of mounds, these animals can locate their nests at deeper, more insulated levels.

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