Landscape Ecology vol. *5* no. 1 pp **53-64** (1990)
SPB Academic Publishing bv, The Hague

Nature and origin of stone stripes on the Columbia Plateau

George W. Cox and Jodee Hunt*
Department of Biology, San Diego State University, San Diego, CA 92187-0057, USA

Keywords: basalt weathering, Columbia Plateau, erosion, fossorial rodents, Mima mounds, stone stripes, ***Thomomys talpoides***

Abstract

Beds of size-sorted stones forming stripes perpendicular to the contour are conspicuous on hillsides of the Columbia Plateau. Stripes occur on terrain ranging from 0" to about 30" in steepness, often beginning among Mima-type mounds on mesa tops and extending downward onto steep, unmounded slopes. Four mechanisms of their origin have been hypothesized: 1) water erosion, 2) solifluction and soil creep, **3)** weathering of rock outcrops, and 4) tunneling by pocket gophers. We measured characteristics of five stripes on slopes of differing exposure and steepness. These stripes were 58–124 m long, and widths showed a maximum range of 0.55–3.70 m. Data on physical and biotic characteristics of the stripes suggest that pocket gopher tunneling is a basic mechanism of stripe formation on gentle slopes, and that this mechanism is augmented by outcrop weathering and colluvial dynamics on steeper slopes, with erosion playing a secondary role.

Introduction

Narrow beds of bare stones, sharply demarcated from adjacent well-vegetated soils and forming conspicuous stripes perpendicular to the contour, are characteristic features of hillsides of the Columbia Plateau. Within the beds, stones are size-sorted, with the largest stones predominating at the surface.

Several different hypotheses of origin of these stone stripes have been suggested. **A** number of authors have invoked erosion as the primary mechanism. Waters and Flagler (1929) gave aerial photos of such stripes and characterized them as erosion furrows in volcanic ash soils overlying weathered basaltic bedrock. Knechtel (1952) gave an aerial photo of mounds and stone stripes near Shaniko, Wasco County, Oregon, and suggested that the stripes are furrows (implicitly due to erosion) that follow joint planes in the underlying basalt. Fosberg (1963) concluded that stone nets and stripes in Idaho were the product of erosion initiated in freeze-thaw cracks formed in the original soil mantle under a periglacial climate. Wilson (1977, 1978) also supported erosion as the process forming mounds and stripes of the western Snake River Plain in Idaho.

In contrast, Sharpe (1938), who presented a photo of stripes near Yakima, Washington, concluded that they were identical to cold-climate stripes produced by solifluction. Kaatz (1959) likewise described mounds, together with sorted stone polygons and hillside stripes, on Manastash Ridge in central Washington; he attributed the features on

---

***Correspondence to*:** Dr. George W. Cox, Department of Biology, San Diego State University, San Diego, CA 92182, USA.

* ***Present address:*** Arkansas Cooperative Fish and Wildlife Research Unit, U.S. Fish and Wildlife Service, Department of Zoology, University of Arkansas, Fayetteville, AR 72701, USA.

level areas to erosion and freeze-thaw dynamics, and the stripes on steeper slopes to an extension of sorted stone polygons onto steeper slopes by solifluction and soil creep. In southwestern Idaho, Malde **(1961, 1964)** examined mounds, stone nets, and stone stripes, and noted the progressive transition of stone nets on nearly level areas (< 3" slope) to stone stripes on slopes of about 10" steepness. He also interpreted stripes as extensions of frost-sorted stone polygons onto slopes by solifluction and soil creep. Brunnschweiler **(1962)** concurred in this interpretation, providing a diagram of the transition of stone nets to stripes. Masson **(1949)** noted a similar phenomenon, consisting of linear stone beds bordering ridges in glaciofluvial outwash deposits in northern California, and interpreted these as the result of coalescence of stone rings associated with mound-and-ring units formed by freeze-thaw processes.

Pyrch **(1973)** investigated the characteristics of slope stripes on the Deschutes-Umatilla Plateau in north-central Oregon. He examined six stripes, determining basic stripe features and sampling stone characteristics in cross-sections in the upper, center, and lower thirds of each stripe. He also recorded downslope movements of marked stones over a 2-yr period. He concluded that stripes and primarily relict cold-climate features, with present-day weathering of rock outcrops contributing to some stripes. He found no evidence that water erosion contributed to stripe formation, and was unable to suggest a mechanism for origin of stripes not associated with bedrock outcrops.

In the same geographical area, Cox and Allen **(1987)** examined the sorted stone beds, nets, and stripes associated with Mima-type mounds on level uplands and gentle slopes, and concluded that these features were produced by pocket gophers. These animals tunnel into areas of thin, stony soils in search of the tubers, corms and roots of perennial plants, particularly biscuitroots of the genus ***Lomatium*** that preferentially grow in these habitats. Removal of fine soil and small stones and subsequent collapse of tunnels expose the larger stones, creating bare stone beds in areas of intense foraging activity. Cox **(1990)** later examined the patterns of mound form, mound dispersion, and stone bed structure in relation to slope aspect and steepness on gentle upper slopes (**< 10**" in steepness). He concluded that as slope increased, mounds became elongated and connected into bead-like chains perpendicular to the contour, and that the encircling stone beds seen on level areas became transformed into stripes bordering chains of mounds. These changes were interpreted as reflecting primarily the response of pocket gopher activity to moisture conditions prevailing on gentle slopes. In many instances, however, stone stripes continue onto unmounded slopes **> 10**" in steepness, or originate on moderate to steep slopes where their upslope ends are not associated with Mima-type mounds (G.W. Cox, ***personal observation).***

Thus, the origin and dynamics of stone stripes of the Columbia Plateau and nearby areas are unclear. The objective of our study was to refine the hypotheses of stripe origin and to determine if these hypotheses, individually or in combination, adequately account for the characteristics and origin of sorted stone stripes at a representative Columbia Plateau site. In the summer of **1988** we studied the physical and biotic features of **1)** stripes associated with Mima mounds on gentle slopes, **2)** steep-slope continuations of the above stripes, and **3)** stone stripes without connections to stripes on mounded slopes. With these data we test alternative hypotheses of origin of stone stripes on slopes of varying aspect and steepness.

Methods

Study area

Our studies were conducted at the Lawrence Memorial Grassland Preserve (LMGP) and on adjacent ranch land of the Priday Brothers Corporation, southern Wasco County, Oregon **(44° 57′N, 120" 48′W),** from **15** through **23** June, **1988.** The LMGP is a Registered National Landmark owned by the Nature Conservancy, and lies at an elevation of **1036–1060** m on the Shaniko Plateau, formed of Columbia River basalts. The LMGP includes mesa tops and ravines that fall steeply northward into the valley of Ward Creek, **122** m below. The climate of

Table 1. **Predictions of four hypotheses of origin of stone stripes on hillsides of the Columbia Plateau. U = upper end, M = middle, L = lower end of stripe. Predicted correlations between quantitative characteristics, and with density of pocket gopher heaps in the stripe border zone ('heaps') are indicated as positive (+) or negative (−). Predictions unique to a specific hypothesis are *italicized.***

Quantitative characteristic	Hypotheses			
	Erosion	Solifluction/soil creep	Outcrop weathering	Pocket gopher
Stripe width	U < M < L	*U > M > L*	U < M < L *Above < below outcrops*	*Correlation: Heaps (+)*
Stripe depth	*U < M > L* *Correlation: Slope (+)*	*U > M > L*	*U < M < L* *Above < below outcrops*	*Correlation: Heaps (+)*
Stone size	*U < M > L*	U = M = L	*U > M > L*	U = M = L
Stone sorting	*U < M < L*	U > M > L	U > M > L	*Correlation: Depth (+)* *U = M = L*
Angularity	U = M = L	U = M = L *Correlation: Slope (0)*	*Above < below outcrops* *Correlation: Slope (−)*	U = M = L *Correlation: Heaps (+)*
Lichen cover	*U < M > L*	Correlation: Slope (−)	*Above > below outcrops* Correlation: Slope (−)	*U = M = L* *Correlation: Heaps (+)*
Lomatium abundance				*Correlation: Heaps (+)*

the region is cold, semi-desert, with an average annual precipitation of 280 mm. The mesa tops and upper slopes of the plateau exhibit 'biscuit scabland' topography, with Mima mounds that range up to about 1 m in height and 20 m in diameter. The mound soils are Condon eolian silt loams, and the intermound soils Bakeoven residual very cobbly loams. Idaho fescue (*Festuca idahoensis*) and bluebunch wheatgrass (*Agropyron spicatum*) dominate the vegetation of mounds and deeper upland soils. Scabland sagebrush (*Artemisia rigida*), Sandberg bluegrass (*Poa scabrella*), several species of biscuitroot (*Lomatium* spp.), and bitterroot (*Lewisia rediviva*) dominate the shallow intermound soils. The northern pocket gopher (*Thomomys talpoides*) is abundant throughout the preserve. Copeland (1980) gives a comprehensive physical and biotic inventory of te LMGP. Plant names follow Hitchcock and Cronquist (1973).

Hypotheses and their predictions

The suggestions of previous authors can be grouped into four hypotheses of origin of stone stripes, the predictions of which are partially overlapping (Table 1).

I. The erosion hypothesis suggests that the stripes are simply areas from which soil has been removed by running water, and that size-sorting results from patterns of removal and deposition of smaller stones. This hypothesis corresponds to the erosion hypothesis of Washburn (1980). Being a drainage channel, its formation is postulated to begin on the steepest portion of the slope, the bed of exposed stones growing upslope and downslope to its final extent. Thus, width and depth of the zone of bare stones should be least at the head and greatest in steep, intermediate parts of the stripe, where water flow is greatest and erosion most intense. At the foot of the stripe, width should be still greater, reflecting further increase in volume of flow, but depth of the bare stone layer should be less, owing to deposition of fine materials eroded from upslope parts of the stripe. Depth should thus be positively correlated with slope steepness, since greater steepness increases vulnerability to erosion and reduces deposition tendency. Stripes should show a stronger representation of small stones at their upper end, where erosional removal is weak, and at the downslope end, where small stones eroded from the stripe mid-zone are deposited. Mean stone size should increase from the upslope end of a stripe to its middle, and then decline toward the downslope end. Vertical sorting of stones by size should thus be greatest near the lower end of the stripe, because of deposition of small stones in the deeper part of the stone bed. Angularity of stones should show no pattern with location along the stripe, since stones should have been exposed to chemical weathering in the slope soil for a similar period of time. Since formation of the stripe begins at its present mid-zone, lichen cover should be greatest near the middle of the stripe, where surface stones have been exposed for the longest period.

11. The solifluction/soil creep hypothesis states that stripes are derived from sorted stone polygons, formed by freeze-thaw processes under a Pleistocene glacial climate. The sides of these polygons are postulated to have become elongated and carried downslope by solifluction (Goldthwait **1976),** as illustrated diagrammatically by Sharpe **(1938).** This hypothesis predicts that stone stripes should show greatest width, depth, and vertical size-sorting at their upper ends, which are nearest the sorted stone polygon features from which they are derived, and are thus least deformed. The stones of the stripes should be uniformly highly weathered and rounded, because of their very long period of exposure to chemical and mechanical weathering processes. Lichen cover should be least on steep slopes, where instability of position of stones is greatest.

111. The outcrop weathering hypothesis proposes that stone stripes originate below outcrops which weather to feed rock fragments into stone beds where their rapid downslope movement is promoted by physical processes such as gravity and freeze-thaw disturbance. This hypothesis is similar to the differential mass-wasting hypothesis of Washburn **(1969, 1980).** This hypothesis predicts that stripes will occur only below rock outcrops. The hypothesis predicts a progressive decrease in mean stone size downslope, as observed by Washburn **(1969)** in stripes formed by differential mass wasting in Greenland, due to the continued fragmentation of rock fragments of increasing age as they move down the stripe. Stripe width and depth should also be greatest at the lower end of the stripe, where maximum accumulation of stones occurs. Width and depth should also show substantial increases below outcrops. Maximum sorting with depth should also be shown at the upper end of the stripe where fresh stones of varying sizes are being supplied by weathering. Angularity of stones should be greatest and lichen cover least immediately below the outcrops that contribute stones to the stripe, and since outcrops are associated with steeper slopes, indices of these variables should show negative correlations with slope steepness.

IV. The pocket gopher hypothesis suggests that stripes are formed and maintained by the soil translocation activities of pocket gophers, with this mechanism acting in recent and current ecological time. Tunneling by these animals in search of roots, corms, and other below-ground plant organs removes soil from deep layers of mixed soil and stones. Collapse of these tunnels causes a downward settling of soil and smaller rocks, concentrating and exposing the larger stones at the surface. Mature stone beds provide a substantial degree of protection against the over-exploitation of certain preferred food plants by pocket gophers, and thus become the principal habitat of these plants.

This hypothesis predicts that physical characteristics such as size, angularity of stones, and lichen cover of stones should not show progressive trends from stripe head to base, since different regions of the stripe are postulated to be nearly contemporaneous in origin, and no movement of stones downslope is assumed. Since soil depth and drainage influence pocket gopher activity, variability in soil conditions should result in positive correlations between pocket gopher activity and stripe width and depth. Shallow, unstable soil conditions that are unfavorable to pocket gopher activity should lead to positive correlations of pocket gopher activity with indices of angularity of stones and lichen cover. Vertical sorting of stones should increase with stripe depth, reflecting intensity of pocket gopher mining activity which promotes the settling of smaller stones downward through the matrix of larger stones. Pocket gopher activity should, in turn, be positively correlated with the abundance of highly preferred food plants such as ***Lomatium cous*** and ***L. minus.*** These plants are postulated to survive and grow to maturity most frequently in well-developed stone beds that give them protection against pocket gopher over-exploitation.

Sampling Procedure

Five stripes were selected for sampling. These stripes were at least 50 m in length and included the full range of aspect and steepness of slopes that exhibited stripes. Three of the stripes were selected specifically because they originated among Mina mounds on gentle upper slopes but continued onto steep, unmounded lower slopes.

We measured the total depth of each stripe and designated sampling locations at five equally spaced points. The uppermost and lowermost sampling locations were located at points 1 m from ends of the stripe. At each sampling point we measured the prevailing direction of the slope, the direction of the next sampling point down the stripe, the width of the stripe, depth of the zone of bare stones to soil or bedrock at the stripe center, and the angularity and lichen cover of surface stones in a 10-cm band crossing the stripe. Angularity was rated on a five-point scale similar to that recommended by Powers (1953): 1 – Sharply angular, 2 – angular, 3 – blunt-edged, 4 – semi-rounded, 5 – fully rounded. Lichen cover was also rated on a five-point scale: 1 – <5% covered, 2 – 5–35% covered, 3 – 35–65% covered, 4 – 65–95% covered, 5 – >95% covered. At the stripe center we tallied the sizes of stones by maximum diameter in three (shallower) or four (deeper) depth zones of equal thickness. Zones ranged from 4 to 19 cm thick, depending on total stripe depth. In each zone we tallied the sizes of the 20 stones nearest the stripe center point. Stones were tallied in five classes, according to their longest diameter: <2 cm, 2–5 cm, 5–10 cm, 10–25 cm, and >25 cm. Pocket gopher activity was assessed by counting the number of gopher heaps in a zone 1 m wide and 2 m long adjacent to the stripe on each side. We determined the density of fruiting and non-fruiting plants of *Lomatium cous* and *L. minus* in this same zone and in the corresponding 2-m section of the stripe itself. These species are two of the most highly preferred food plants of pocket gophers (Cox 1989), and possess large, fleshy corms or rootstocks. Finally, we made notes on other features of the stripe, such as its relation to mounds and rock outcrops, and whether or not the surface showed a 'stepped' pattern created by terracettes that crossed the stripe.

Statistical procedures follow Zar (1984). Product-moment correlations were calculated among variables assuming that values for different stations along individual transects were fully independent. Two-way ANOVA's were performed on replicate values of variables from five sampling locations along the five stripes. Correlation coefficients possessed 19 DF and F-values for ANOVA's 4, 16 DF unless otherwise indicated.

Results

The five stripes examined varied from 58 to 124 m in length. Stripes #1 and #2 were on south-facing slopes. Stripe #1 began in a gently sloping intermound zone, crossed a small rock outcrop, and terminated at the base of a steep slope. Stripe #2, located on the steep canyon slope of Ward Creek, began below a prominent rock outcrop and terminated at the edge of an alluvial terrace at the base of the slope. Stripes #3 and #4 were on north-facing slopes. Stripe #3 began below a small outcrop, traversed a steep slope, and terminated on the brow of a cliff above Ward Creek. Stripe #4 originated among mounds and extended across a very gentle unmounded area. Stripe #5, on an east-facing slope, originated among mounds on a gentle upper slope and continued downhill onto a moderate, unmounded slope, crossed a small rock outcrop and ended near the rim of a small canyon.

The directional axis of stripe segments was closely correlated with that of the slope, particularly on slopes greater than 5" in steepness (Table 2). On gentle, mounded slopes, such as the two uppermost sampling stations of Stripe #5, the axis of stripe segments was influenced by the microtopographic gradient created by mounds, rather than strictly following the general hillside slope.

The steepness of stripe segments between sampling points varied from 1.5 to 25.0" (Table 2). Stripes #1 and #5 showed a pattern of increase in steepness from upper to lower segments. Stripes #2 and #3 were steep throughout, with slopes of segments ranging from 18.5° to 25.0". Stripe #4 was gentle in slope throughout. A stepped configuration of the stripe surface was evident on all stripe segments over 17" in steepness, and was absent on more gentle slopes.

Stripe width ranged from 0.55 to 3.70 m at sampling stations (Table 2). The greatest width for all

Table 2. Characteristics of hillside stone stripes sampled at the Lawrence Memorial Grassland Preserve, north-central Oregon.

	Stripe #1	Stripe #2	Stripe #3	Stripe #4	Stripe #5
Slope direction (°)					
Stn. 1–2	182	154	11	328	60
2–3	168	165	6	326	54
3–4	167	179	18	326	57
4–5	166	170	16	323	55
Stripe direction (°)					
Stn. 1–2	190	154	4	334	37
2–3	178	165	4	336	32
3–4	167	179	18	326	57
4–5	171	170	17	323	55
Steepness (°)					
Stn. 1–2	8.50	20.67	22.50	4.00	1.50
2–3	11.83	20.00	19.83	4.17	5.00
3–4	16.50	24.00	19.00	3.33	6.33
4–5	17.33	25.00	18.50	2.50	10.83
Width (m)					
Stn. 1	0.60	2.85	0.80	0.87	1.00
2	0.60	1.35	0.85	1.00	1.77
3	1.04	1.60	3.55	0.95	1.50
4	1.90	2.25	2.00	1.05	1.51
5	2.55	3.70	2.18	0.55	3.20
Depth (cm)					
Stn. 1	18	34	54	20	17
2	18	42	59	19	20
3	14	23	63	27	26
4	33	38	75	24	29
5	36	83	15	18	32
Lichen index					
Stn. 1	4.0	1.0	4.0	4.0	4.0
2	4.0	1.0	4.0	4.0	4.0
3	3.0	1.0	4.0	4.0	4.0
4	1.0	1.0	4.0	4.0	4.0
5	2.0	2.0	4.0	4.0	3.0
Angularity index					
Stn. 1	3.0	1.0	2.5	4.0	3.0
2	3.0	1.0	3.0	4.5	2.5
3	2.0	2.0	3.0	3.0	3.5
4	2.0	2.0	3.5	3.5	4.5
5	2.5	1.5	3.5	4.0	3.5

stripes was at or below the middle sampling station, although the topmost station of Stripe #2, which lay just below a large rock outcrop, was the third widest value measured at any location. On Stripes #1 and #5, stripe width essentially doubled where the stripe crossed an outcrop. Stripe width was positively correlated with slope steepness ($r = 0.568$, $p < 0.01$).

Depth to soil or bedrock varied from 15 to 83 cm (Table 2). Variation in depth was significant among the five stripes ($F = 3.73$; $p < 0.05$), being greatest for Stripes #2 and #3 which occurred on the steepest

Table 3. Frequencies of stones in different size classes at sampling stations along five hillside stripes at the Lawrence Memorial Grassland Preserve, Oregon.

Stripe	Station	Size classes (cm)								Mean diameter (cm)
		<2	2–5	5–10	10–25	>25	χ^{2*}	DF	P	
#1	1	7	15	24	14	0	41.57	4	<0.001	8.08
	2	4	12	26	18	0	44.72	4	<0.001	9.27
	3	7	5	36	12	0	31.00	4	<0.001	8.41
	4	0	9	53	18	0	20.15	4	<0.001	9.30
	5	1	15	55	9	0	25.04	4	<0.001	7.79
	Total	19	56	194	71	0	36.65	12	<0.001	8.57
#2	1	0	24	30	26	0	49.62	4	<0.001	9.55
	2	0	19	42	17	2	16.12	4	<0.01	9.42
	3	5	14	36	5	0	24.94	4	<0.001	6.86
	4	3	12	24	21	0	31.64	4	<0.001	9.88
	5	3	8	49	19	1	28.43	4	<0.001	9.61
	Total	11	77	181	88	3	37.16	12	<0.001	9.14
#3	1	0	43	32	5	0	6.49	4	NS	5.98
	2	7	28	33	5	0	37.06	4	<0.001	7.03
	3	7	32	33	8	0	10.43	4	<0.05	6.33
	4	1	27	30	21	1	15.57	4	<0.01	9.07
	5	7	12	6	15	0	36.67	2	<0.001	8.91
	Total	22	142	134	61	1	53.32	12	<0.001	7.30
#4	1	3	9	33	15	0	26.61	4	<0.001	9.08
	2	10	19	25	6	0	14.81	4	<0.01	6.15
	3	4	13	21	22	0	22.12	4	<0.001	9.87
	4	5	11	31	13	0	12.07	4	<0.05	8.39
	5	2	9	29	19	1	23.80	4	<0.001	10.35
	Total	24	61	139	75	1	27.51	12	<0.01	8.77
#5	1	3	10	37	10	0	10.80	4	<0.05	9.08
	2	4	10	42	4	0	20.07	4	<0.001	7.07
	3	3	11	34	12	0	25.52	4	<0.001	8.44
	4	9	8	34	8	1	16.07	4	<0.01	7.82
	5	0	8	29	22	1	15.32	4	<0.01	11.13
	Total	19	47	176	56	2	31.77	12	<0.01	8.53

$^*\chi^2$ values for individual stations are for contingency tests of frequency of sizes versus depth at that station (data not given in table), those for stripe totals are for contingency tests of frequencies of stones in different size classes versus the five station positions for that stripe.

slopes. Depth was strongly correlated with slope steepness (Table 5), as well as with stripe width ($r = 0.692, p < 0.001$). Although maximum depths were recorded at middle to lowermost sampling stations, depth did not show significant variation among stations along stripes. Depth did not change appreciably where stripes crossed rock outcrops.

Angularity of stones varied from a scale value of 1 (sharply angular) to 4.5 (fully- to semi-rounded) and lichen cover varied from 1 (<5%) to 4 (65–95%) (Table 2). These two variables were strongly correlated ($r = 0.839, p < 0.001$). Angularity varied significantly among the five stripes ($F = 11.60, p < 0.001$) but not among stations from the top to the bottom of stripes. Angularity index was also negatively correlated with slope steepness (Table 5) and with the degree of sorting of stone sizes with depth ($r = -0.459, p < 0.05$). The mean angularity index for 16 stations above outcrop locations (including all stations on stripes

Table 4. **Biotic characteristics** of **hillside stone stripes sampled at the Lawrence Memorial Grassland Preserve, north-central Oregon.**

	Stripe #1	Stripe #2	Stripe #3	Stripe #4	Stripe #5
Pocket gopher heaps					
Stn. 1	1	1	3	11	4
2	8	0	0	6	0
3	2	0	2	22	5
4	5	1	1	15	4
5	6	1	0	9	4
Lomatium cous (m^{-2})					
Stripe bed					
Stn. 1	1.7	0	0	0	1.0
2	20.0	0	0	0	3.4
3	20.2	0.6	0	0	0
4	17.4	0	0	5.7	3.3
5	0	0	0	10.9	0.9
Stripe border					
Stn. 1	2.2	0	0	1.2	0.2
2	0.8	0	0	5.0	3.5
3	2.2	0	0	1.5	2.5
4	0	0	0	2.5	4.2
5	0.2	0	0	3.2	0.8
Lomatium minus (m^{-2})					
Stripe bed					
Stn. 1	0	0	0	17.8	2.0
2	0	0	0	10.5	8.2
3	0	0	2.2	7.9	9.0
4	0	0	0	5.2	3.9
5	0	0	0	0	0.8
Stripe border					
Stn. 1	0	0	0	0	0
2	0	0	0	0	0.2
3	0	0	0	1.5	1.0
4	1.5	0	0	0	0
5	0	0	0	0	0

without outcrops) was 3.38, whereas for 9 stations below outcrops the mean was 1.95; these values showed a highly significant difference by the Mann-Whitney U Test (Table 5).

Lichen cover varied among stripes ($F = 16.45$, $p < 0.001$) but not with location along stripe. The lichen cover index was likewise negatively correlated with slope steepness (Table 5). The mean lichen cover index for stations above outcrops (16) was 4.00, and that for stations below outcrops (9) 1.67, a difference likewise highly significant by a Mann-Whitney U Test (Table 5).

Sorting of stones by size was tested by a χ^2 contingency analysis of frequency of stones of various size classes versus depth. Size-sorting, with larger stones more abundant near the surface and smaller stones more common in deeper layers, was significant in all but 1 of the 25 locations sampled (Table 3). In general, sorting was weaker when the mean diameter of stones at the sampling site was smaller than average for the site. The intensity of sorting was not clearly related to many other variables. Sorting was negatively correlated with angularity of stones ($r = -0.459, DF = 24, p < 0.05$),

Table 5. **Results of tests of predictions of the four hypotheses of origin of stone stripes on hillsides of the Columbia Plateau, as outlined in Table 1. Predictions unique to a specific hypothesis are italicized. Symbols without parentheses indicate support of the prediction, those with parentheses indicate opposition. The symbol '+' indicates support by qualitative observations only.**

Quantitative characteristic		**Hypotheses**			
		Erosion	**Solifluction/soil creep**	**Outcrop weathering**	**Pocket gopher**
Stripe width	**U – M – L**	(NS)	*(NS)*	+	
	Outcrop			+	
	Heaps				*$(r = -0.509, p < 0.05)$*
Stripe depth	**U – M – L**	*(NS)*	*(NS)*	+	
	Slope	*$r = 0.719, p < 0.001$*			
	Outcrop			*(NS)*	
	Heaps				*$(r = -0.455, p < 0.05)$*
Stone size	**U – M – L**	*(NS)*	NS	*(NS)*	NS
Stone sorting	**U – M – L**	*(NS)*	(NS)	(NS)	*(NS)*
	Depth				*(NS)*
Angularity	**U – M – L**	NS	NS		NS
	Slope		*$(r = -0.652, p < 0.01)$*	*$r = -0.652, p < 0.01$*	
	Outcrop			*$z = 3.41, p < 0.001$*	
	Heaps				*$r = 0.494, p < 0.05$*
Lichen cover	**U – M – L**	*NS*			*NS*
	Slope		$r = -0.638, p < 0.01$	$r = -0.638, p < 0.01$	
	Outcrop			*$z = 4.08, p < 0.001$*	
	Heaps				*(NS)*
Lomatium	**Heaps**				*$r = 0.665, p < 0.01$*

and was most consistently strong on Stripes #1 and #2 on south-facing slopes (Table 3).

The distribution of stone sizes for all depths combined varied significantly among the five sampling stations for all five stripes (Table 3). The patterns contributing to these significant χ^2 contingency values differed for the individual stripes. Excesses of stones less than 5 cm in diameter at the upper three stations and excesses of stones larger than 5 cm at the lower two stations were exhibited for 16 of the 25 comparisons of individual station data with expectations. Stones greater than 5 cm in diameter were more frequent than expected at the lowermost station in four of the five stripes. The percentage of stones in the smallest size class (<2 cm diameter) was negatively correlated with slope ($r = -0.470, p < 0.05$). Stone size (mean maximum diameter) did not vary significantly among the stripes or among stations along stripes.

Pocket gopher heaps were numerous in the zone bordering Stripes #1, #4, and #5, but were scarce in the zones bordering Stripes #3 and #4, which were on steep slopes (Table 4). Numbers of heaps showed a strong negative correlation with slope steepness ($r = -0.685, p < 0.001$). Numbers of heaps also showed weak negative correlations with stripe width and depth (Table 5), and a positive correlation with angularity index of stones (Table 5). No heaps were observed within the sorted stone beds of the stripes themselves.

Lomatium cous and ***L. minus*** were almost completely absent from the stone beds and adjacent soil of Stripes #2 and #3 on steep slopes (Table 4), which were also the deepest stripes. ***Lomatium cous*** showed highly variable abundance in the other three stone stripes, and was present in low to moderate density in areas adjacent to these stripes. The abundance of ***L. cous*** in the stripes themselves showed little relation to other variables. Total numbers of plants were negatively correlated with stripe width and depth ($r = -0.456$ and -0.476, respectively; $p < 0.05$). Numbers of plants in fruit were positively correlated with the degree of sorting of stones ($r = 0.551, p < 0.05$). The abundance of ***L. cous*** in the zone bordering stripes, however, showed strong ($p < 0.001$) negative correlations with slope steepness ($r = -0.875$), angularity of stones ($r = -0.692$), and stripe depth ($r = -0.671$), a moderately strong ($p < 0.01$) positive correlation with lichen cover of stones ($r = 0.544$), and a weak ($p < 0.05$) negative correlation with stripe width ($r = -0.476$). Pocket gopher activity, as evidenced by the abundance of heaps bordering the stripe, showed no relation to the abundance of *L. cous* in the stripe itself, but was positively correlated with the abundance of non-fruiting ($r = 0.867$, $p < 0.001$) and total ($r = 0.620$, $p < 0.01$) plants in the zone bordering the stripe.

Lomatium minus occurred in abundance only in Stripes #4 and #5, and was almost completely absent from areas outside the sorted stone beds of the stripes themselves (Table 4). This species was abundant in several sampling locations from which L. *cous* was absent. When data for L. *minus* and L. *cous* were combined, the abundance of pocket gopher heaps was positively correlated with *Lomatium* abundance in both the stripe (Table 5) and stripe border zones ($r = 0.588$, $p < 0.01$).

Discussion

None of the four hypotheses of origin of the stripes was supported fully by the sampling data (Table 5).

The positive correlation between slope steepness and stripe depth supported the erosion hypothesis, but depth did not show the consistent pattern of being greatest at stations near the stripe mid-zone, as predicted by this hypothesis. Lichen cover was not less at the upper and lower ends of stripes than in the middle zone, as predicted by this hypothesis, nor was vertical sorting of stones by size greatest near the bottom of stripes. Furthermore, although small stones tended to be more abundant at upper stations in stripes, they were not more abundant at the lowest stations than near the middle of the stripe, as predicted by the erosion hypothesis.

The pattern of stripe width and depth from upper to lower end of the stripes contradicted the prediction of the solifluction/soil creep hypothesis, as did the fact that major differences in angularity of stones occurred at different sampling locations. Lichen cover was negatively correlated with slope steepness, however, as expected by this hypothesis.

The outcrop weathering hypothesis was supported by several stripe characteristics. Stripe width and depth were greatest at or below the stripe mid-elevation, and stripes increased in width below outcrops; both trends supported this hypothesis. The strong correlations of slope steepness with angularity of stones and lichen cover, along with the highly significant differences in angularity and lichen cover above and below outcrops, likewise supported this hypothesis. The predicted increase in stripe depth below outcrops was not observed. The tendency for larger stones to predominate at lowermost sampling stations of four stripes opposed this hypothesis. The lack of outcrops in association with Stripe #4 and with the upper ends of Stripes #1 and #5, in addition, indicate that this hypothesis cannot account for stripe formation in all situations.

The pocket gopher hypothesis was supported by the lack of significant trends in lichen cover, angularity, mean size and degree of vertical sorting of stones with location along stripes. The positive relation between pocket gopher activity and angularity of stones also supported this hypothesis. Pocket gopher activity, as indexed by the number of heaps adjacent to stripes, was positively correlated with abundance of food plants both in the stripe itself and in the zone bordering the stripe, as predicted by the hypothesis. The abundance of pocket gopher heaps was negatively related to stripe width and depth, however, in direct opposition to the prediction of this hypothesis.

Of the four hypotheses, the solifluction/soil creep hypothesis was not supported by any of the four predictions unique to this hypothesis. The erosion hypothesis was supported by only one of the four predictions unique to it. The outcrop weathering hypothesis, however, was partially or fully supported by five of its seven unique predictions. The pocket gopher hypothesis was supported by four of eight unique predictions. These results indicate that the origin of hillside stone stripes involves at least three of the postulated mechanisms.

We conclude that the origin of stripes on gentle upper slopes is primarily the result of pocket gopher tunneling activity. Pocket gopher activity was greatest in areas of abundance of ***Lomatium*** species, both in and adjacent to the stripes, and these areas of abundance were concentrated in narrow, shallow stripe sections on gentle slopes. Cox (1990) has shown that the orientation of bare stone beds perpendicular to the contour on mounded upper slopes can be accounted for by the influence of slope on soil translocation by pocket gophers. These stripes also serve as channels of water flow, which probably also contribute to stripe maintenance by the removal of soil fines. The pattern of soil excavation from tunnels beneath stone beds and deposition at bed margins, as noted by Cox and Allen (1987) for beds associated with Mima mounds, creates the sharp borders to these stripes. Erosion seems to be of secondary importance, however, since it does not lead to predictable patterns of concentration of the smallest stones in lower sections of the stripe.

When stripes originate below outcrops, or cross them downslope, the character of the stripe changes substantially. Stripe width increases, the angularity of stones increases, and lichen cover declines, indicating that outcrops actively feed new stones into the stripe. Although pocket gopher activity is shown in areas bordering stripes below outcrops, the abundance of ***Lomatiurn*** food plants in these locations decreases, probably because the depth of the stripes in these situations becomes too great for these plants. On the steepest slopes of Stripes #2 and #3, for example, both ***Lomatiurn*** plants and pocket gopher heaps were very scarce. The action of pocket gophers in these situations may only be to contribute to the sharply bordered edge of the stripe. Thus, with increasing slope steepness and the crossing of an outcrop, weathering of outcrops and downhill movement of stones by mass wasting becomes the dominant stripe process. Pyrch (1973) documented mean downslope rates of stone movement equal to about 9.8 mm yr–' in this same general region. With reduced importance of pocket gopher activity, erosion may play a greater role in maintaining the stripes free of soil fines.

We conclude that stripe formation and maintenance in the Columbia Plateau region involves the dominant forces of pocket gopher tunneling on upper slopes and outcrop weathering processes on lower slopes, with erosion playing a secondary role in both locations. Stripes thus appear to be formed and maintained by processes presently operating, and do not appear to be relic features of Pleistocene glacial periods. The shallow soils overlying basaltic bedrock in this region, in fact, do not permit the free convection mechanism of origin of sorted stone polygons and stripes (Ray ***et al.*** 1983; Gleason ***et*** al. 1986; Krantz ***et al.*** 1988) to operate. We suggest that pocket gopher activity is a widely important mechanism in the origin of stone nets and stripes in western North America, and that it should be considered in regard to other stripes considered to be relicts of past cold climates (***e.g.***, Krantz ***et al.*** 1988, p. 71).

Acknowledgments

We thank Annan Priday for permission to conduct much of the work on areas of the Priday Brothers Ranch adjacent to the LMGP. P.L. Abbott, **S.H.** Hurlbert, G.M. Marion, and A.L. Washburn provided valuable criticism of earlier drafts of the manuscript. Donald B. Lawrence gave advice and encouragement throughout the study. This study was supported by NSF Grant INT-8602539 and by a contract with the Oregon Chapter of the Nature Conservancy.

References

Brunnschweiler, D. 1962. The periglacial realm in North America during the Wisconsin glaciation. Biul. Peryglacjalny 11: 15–27.

Copeland, W.N. 1980. The Lawrence Memorial Grassland Preserve: A Biophysical Inventory with Management Recommendations. Unpublished report (revised 1983), Oregon Chapter, Nature Conservancy, Portland.

Cox, G.W. 1989. Early summer diet and food preferences of northern pocket gophers in north central Oregon. Northwest Science 63: 77–82.

Cox, G.W. 1990. Form and dispersion of Mima mounds in relation to slope steepness and aspect on the Columbia Plateau. Great Basin Naturalist 50: 21–31.

Cox, G.W. and Allen, D.W. 1987. Sorted stone nets and circles of the Columbia Plateau: A hypothesis. Northwest Science 61: 179–185.

Cox, G.W. and Gakahu, C.G. 1986. A latitudinal test of the fossorial rodent hypothesis of Mima mound origin in western North America. Zeitschrift fur Geomorphologie 30: 485–501.

Cox, G.W., Gakahu, C.G. and Allen, D.W. **1987.** The small stone content of Mima mounds in the Columbia Plateau and Rocky Mountain regions: Implications for mound origin. Great Basin Nat. **47: 609–619.**

Fosberg, M.A. **1963.** Genesis of some soils associated with low and big sagebrush complexes in the brown, chestnut, and chernozem-prairie zones in southcentral and southwestern Idaho. Ph.D. Dissertation, University of Wisconsin, Madison.

Gleason, K.J., Krantz, W.B., Caine, N., George, J.H. and Gunn, R.D. **1986.** Geometrical aspects of sorted patterned ground in recurrently frozen soil. Science **232: 216–220.**

Goldthwait, R.P. **1976.** Frost sorted patterned ground: a review. Quaternary Res. **6: 27–35.**

Hitchcock, C.L. and Cronquist, A. **1973.** Flora of the Pacific Northwest. University of Washington Press, Seattle.

Kaatz, M.R. **1959.** Patterned ground in central Washington: a preliminary report. Northwest Sci. **33: 145–156.**

Knechtel, M.M. **1952.** Pimpled plains of eastern Oklahoma. Bull. Geol. Soc. Amer. **63: 689–700.**

Krantz, W.B., Gleason, K.J. and Caine, N. **1988.** Patterned ground. Sci. Amer. **259(1): 69–76.**

Malde, H.E. **1961.** Patterned ground of possible solifluction origin at low altitude in the western Snake River plain, Idaho. USGS Prof. Pap. **424-B: 170–173.**

Malde, H.E. **1964.** Patterned ground in the western Snake River plain, Idaho, and its possible cold-climate origin. Geol. Soc. Amer. Bull. **75: 191–208.**

Masson, P.H. **1949.** Circular soil structures in northeastern California. Calif. Div. Mines Bull. **151: 61–71.**

Powers, M.C. **1953.** A new roundness scale for sedimentary particles. J. Sed. Petr. **23: 117–119.**

Pyrch, J.B. **1973.** The characteristics and genesis of stone stripes in north central Oregon. MS Thesis, Department of Geography, Portland State University, Portland, Oregon.

Ray, R.J., Krantz, W.B., Caine, T.N. and Gunn, R.D. **1983.** A model for sorted patterned ground regularity. J. Glaciol. **29: 317–337.**

Scheffer, V.B. **1947.** The mystery of the Mima mounds. Sci. Monthly **65: 283–294.**

Scheffer, V.B. **1958.** Do fossorial rodents originate Mima-type microrelief? Amer. Midl. Nat. **59: 505–510.**

Sharpe, C.F.S. **1938.** Landslides and related phenomena. Columbia Univ. Press, New York.

Washburn, A.L. **1969.** Weathering, frost action, and patterned ground in the Mesters Vig District, northeast Greenland. Medd. om Gronland **176: 1–303.**

Washburn, A.L. **1980.** Geocryology. John Wiley & Sons, New York.

Waters, A.C. and Flagler, C.W. **1929.** Origin of the small mounds on the Columbia River Plateau. Amer. J. Sci. **18: 209–224.**

Wilson, M.D. **1977.** Origin of patterned ground near Boise, Idaho. Geol. Soc. Amer. Abstracts with Programs **9: 775–776.**

Wilson, M.D. **1978.** Patterned ground of erosional origin, southwestern Idaho. Int. Conf. Permafrost **3: 60.**

Zar, J.H. **1984.** Biostatistical Analysis. 2nd ed. Prentice-Hall, Englewood Cliffs, New Jersey.