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Mima-type mounds in southwest Missouri: Expressions of point-centered and locally thickened biomantles

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Abstract

Mima-type mounds, formed in gravelly soils of the Diamond Grove Prairie Natural Area near Joplin, Missouri, are the focus of this study. Emphasis is on the spatial and morphological aspects of the mounds, and more particularly on the analysis of mound soils and gravel distributions as a means for shedding light on mound origins in this region. The results strongly suggest that hierarchically dominant point-centered bioturbation by small vertebrates is the mode of mound genesis. Pocket gophers (*Geomys bursarius*), aided by other biota, create mounds as they burrow in residual gravelly soils that have evolved dense, relatively impermeable claypans that perch water during wet periods. Although pocket gophers do not presently inhabit the Diamond Grove area, evidence of past occupation, along with laboratory and field data, support them as the dominant role in forming the mounds. We conclude that these mounds are expressions of point-centered and locally thickened biomantles. Various subsidiary processes such as aeolian inputs, water erosion, and physical and chemical weathering also have genetically impacted Diamond Grove mounds.

Keywords: Mima mounds; Bioturbation; Biomantles; Southwest Missouri

1. Introduction

A vexing problem for many geomorphologists, pedologists, and others interested in landscape evolution is explaining the origin of the innumerable, small landforms variously referred to as “Mima mounds,” “prairie mounds,” and “pimple mounds” that cover many areas of central and western North America. The term ‘Mima mound’ comes from Mima Prairie, a well mounded tract in the Puget Sound lowlands south of Olympia, Washington. The unusually high density of mounds in this type locality, with their strikingly hemispherical shapes, evokes awe and interest from lay people and scientists alike. Though they may bear resemblances to the type locality, Mima-type mounds elsewhere invariably differ in height, diameter, texture, internal composition and structure, and in the elevations at which they occur. Despite any similarities, one cannot assume a single and simple origin for all of them. It is more likely that one process is hierarchically dominant in producing mounded tracts, but subordinate processes also operate.

Mima-type mounds are generally found on flat or gently sloping terrain, but some also occur on moderate slopes (reviews in Cox, 1984; Washburn, 1988). Mounds on flat terrain are commonly circular in shape, while

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those on slopes are more elliptical and elongated downslope. Basic conditions that commonly lead to Mima-type mound formation include areas of thin soil that overlie bedrock, hardpan, densely bedded gravel, heavy clay (which creates periodic wetness), or areas with high water tables. The internal composition of Mima-type mounds ranges across various textures, including sandy, loamy, and/or silty soils, and if gravels are present in the parent materials, the mounds are invariably gravelly and have a basal stone-layer of coarse gravels (Cox, 1984; Johnson et al., 2002). The presence of infilled animal burrows, called krotovina (or "mound roots" by some early authors), are sometimes noted in the lower horizons or near the basal contact.

Before widespread agricultural plowing, Mima-type mounds were observed in intermittent groups or clusters in almost all states west of the Mississippi River (Washburn, 1988). They were particularly common in some pre-settlement prairies of Minnesota, Iowa, Missouri, Oklahoma, Arkansas, Louisiana, and Texas (Fowke,

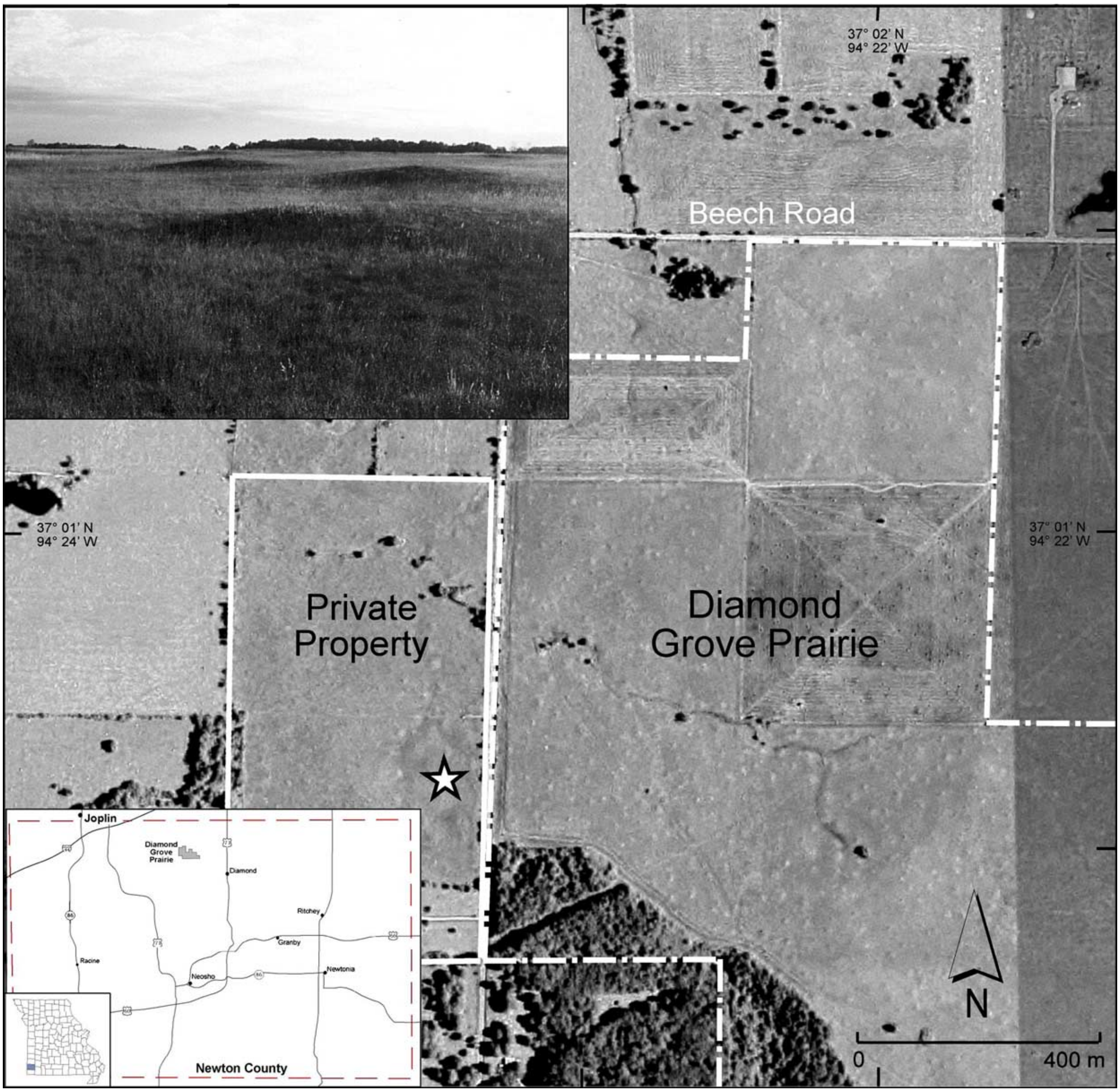


Fig. 1. Aerial photograph of the study area. Numerous mounds dot Diamond Grove Prairie and the adjacent private property. Lower inset shows the location of Diamond Grove Prairie in Newton County in southwest Missouri. Upper inset shows mounds in the study area that measure approximately 75 cm high and 15 m in diameter. Star indicates the location of the mound trenched for this study.

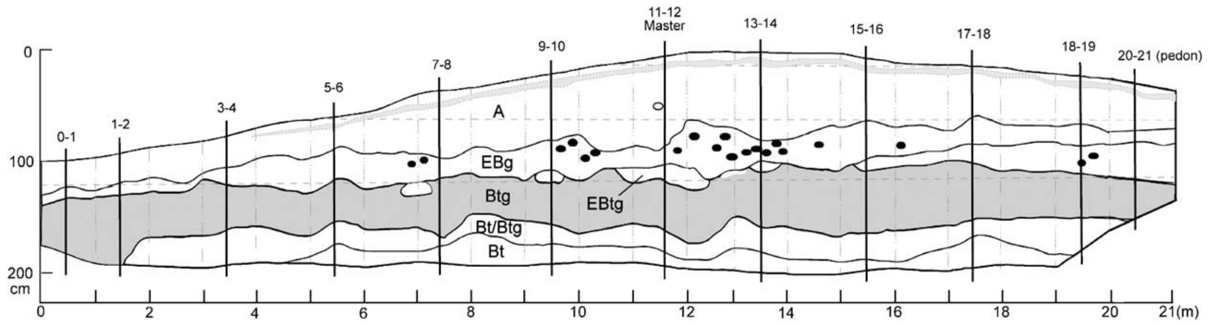
1922; Holland et al., 1952; Ross et al., 1968; Brotherson, 1982; Ricks et al., 1997). Though not well documented in the literature, we have recently noted the presence and former abundance of mounds in two states east of the Mississippi River — Illinois and Wisconsin. Many moundfields still remain in nature preserves, private land, and conservation lands, but most have been destroyed or altered by farming and other human activities.

Since William Darby (1816) first observed them in western Louisiana, more than 30 theories for the origin of Mima-type mounds have been proposed (Washburn, 1988). These can be grouped into five main genetic categories: erosional, depositional, fossorial (burrowing) animals, periglacial, and seismic origins. While scientists in various fields have studied such mounds for almost two centuries, they have yet to agree on a unifying process or processes to explain the origin (Washburn, 1988; Berg, 1990; Hallet and Sletten, 1994). Regardless of how compelling a category may seem in explaining a given mounded tract, only one — the fossorial (burrowing) animal theory proposed by Dalquest and Scheffer (1942), seems consistent with our observations at Diamond Grove Prairie, and at other midwestern mounded tracts that we visited during the course of the study. Further, essentially all of these 30 hypotheses were advanced prior to the recent formulation of the biopedological–biomantle approach – elements of which are adopted here – for explaining such point-centered and locally thickened soil mantles, and soils with stone-layers (Balek, 1995; Horwath, 2002; Johnson et al., 2002, 2003).

In this paper we present one component of a broader, ongoing study of Mima-type mounds, with a focus on Diamond Grove Prairie in southwestern Missouri. We examine the surficial morphology and spatial character of several tracts of mounds within Diamond Grove Prairie, and provide detailed soil characteristics of a representative mound. To this end, we present the results of field and laboratory studies, including measurements on the size, density, and distribution of mounds in the moundfield. Particular focus is placed on the coarse and fine fractions of soil in the mound as revealed by a trench cut through a typical mound, and by laboratory analyses of close-interval samples systematically collected from multiple pedons along the trench wall.

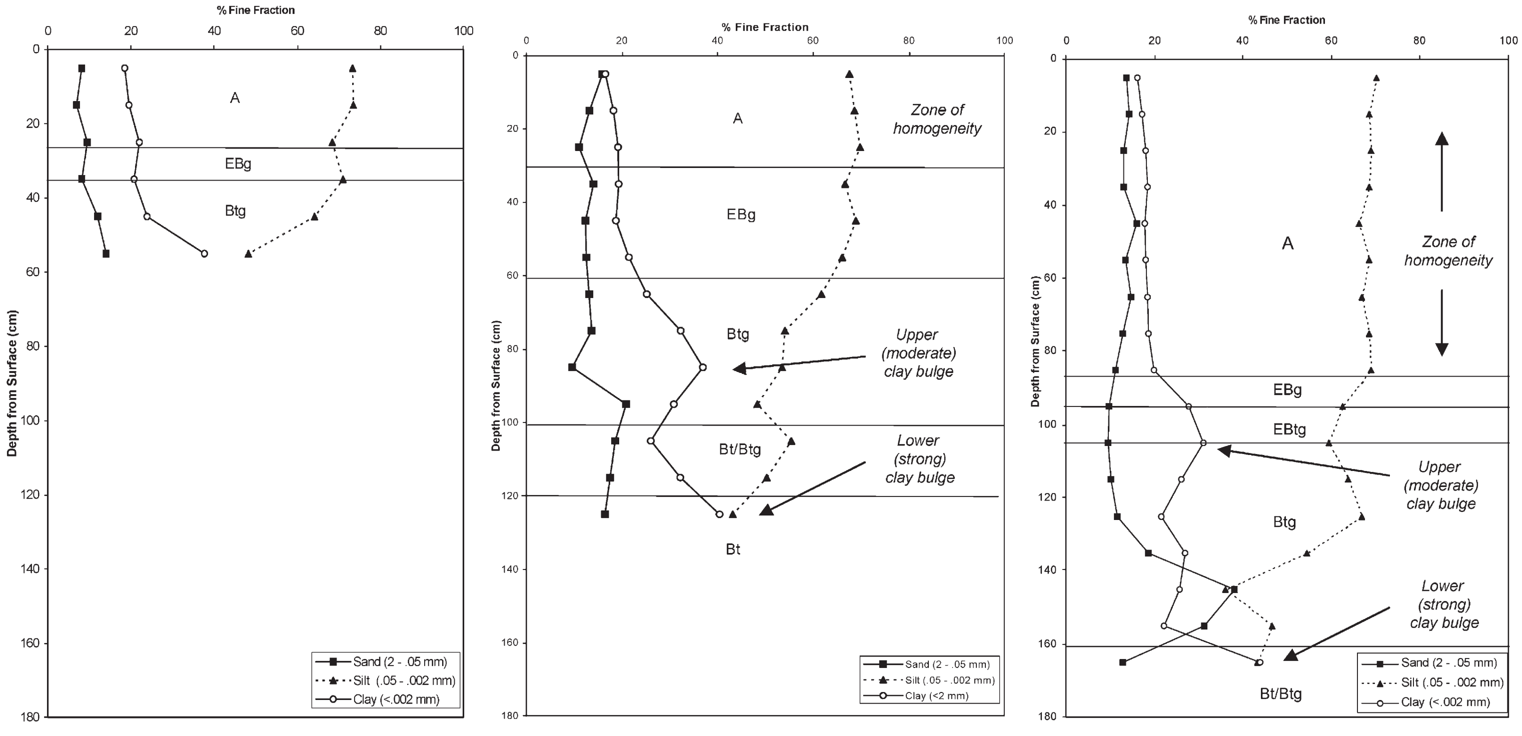
2. Study area

This study focuses on Diamond Grove Prairie Conservation Area and an adjacent private tract in Newton



A:	Silt-rich, gravelly and dark mollic epipedon, thickest in the center of the mound, thinning towards edges.
EBg:	Transitional horizon of a generally homogenous mixture of gravelly loam (sand, silt, and clay) with stronger E horizon indicators than B horizon. Many small rodent-sized krotovina (black ovals).
EBtg:	Thin transitional silt-rich gravelly layer between A and B, not continuous across all pedons.
Btg:	Continuous gravel-dominated clayey horizon present across entire mound. This horizon is a very distinct, weakly cemented stone-layer that exhibits weak fragic properties.
Bt/Btg:	Thin transitional layer that represents a gradational change from the overlying stone-layer to the underlying highly weathered, reddish, very clay-rich Bt horizon.
Bt:	Clay-rich horizon characterized by strong red colors and composed of highly weathered chert gravels (some saprolitized). This relatively impermeable horizon is responsible for the locally perched water table and evident gleying, and seasonal wetness of intermound areas of Diamond Grove Prairie.

Fig. 2. Cross-sectional profile of trenched mound showing grid network (dashed lines), horizon boundaries, and pedon sampling locations (vertical black lines). No vertical exaggeration applied. Bottom of figure represents the base of the trench as limited by perched water table. Upper thin, gray horizon approximates the location and thickness of a minor stone-layer, while lower thick gray horizon represents the main stone-layer. Black ovals represent infilled krotovina and one white oval represents an open and active burrow. Fewer horizons exist and horizons thin towards mound edge (left side). A brief description of horizon characteristics accompanies this graphic. Modified from Horwath (2002).



mound edge (pedon 0-1 m) pedon 5-6 m mound center (pedon 11-12 m)

Fig. 3. Depth function graphs of the distribution of the fine fraction (<2 mm) in three regions (pedons) of the trenched mound. Mound center (right pedon) shows a very thick, silt-rich, texturally homogeneous A horizon, and two distinct clay bulges in lower profile. The mound edge (left pedon) is fairly homogeneous from surface to depth and has a thinner A horizon. The lower clay bulge is interpreted to represent the original, pre-mound residual plateau Bt horizon over which the mounds formed, whereas the upper clay bulge is interpreted to have formed in the mounds after the dominant bioturbator (Geomys bursarius) abandoned the area. Modified from Horwath (2002).

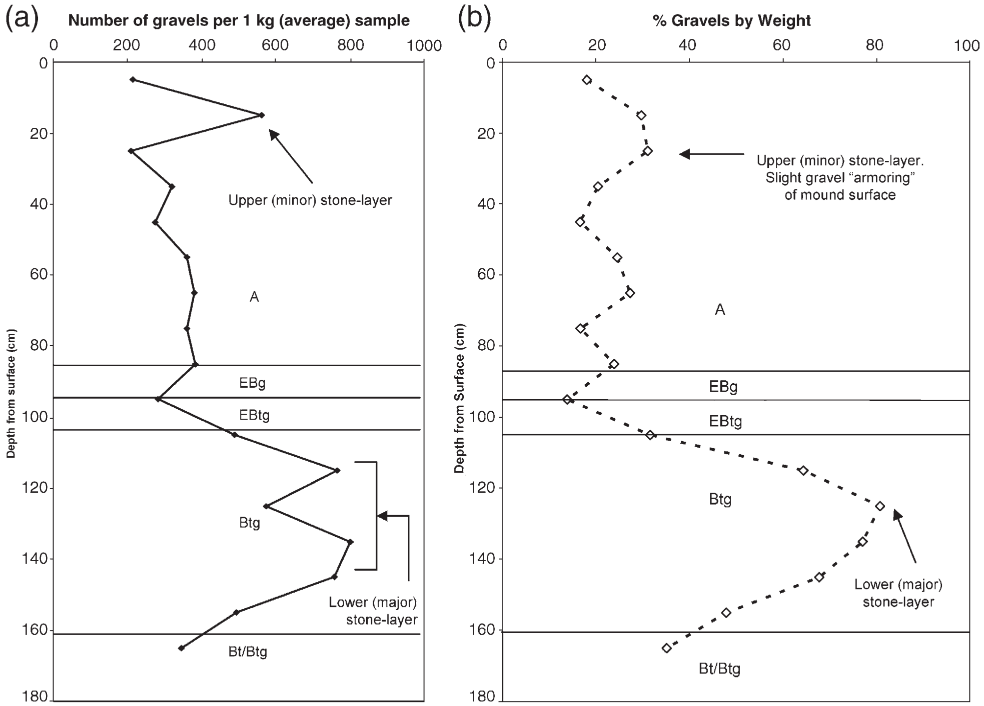


Fig. 4. Depth function graphs of coarse fraction (>2 mm) in the mound center (pedon 11–12) by number (a) and by weight percentage of total bulk sample (b). A distinct gravel bulge occurs as a lower (major) stone-layer and a smaller gravel bulge exists as an upper (minor) stone-layer. Modified from Horwath (2002).

County, near Joplin, in southwest Missouri (Fig. 1). The geology of the area consists of Mississippian-age cherty limestone (Warsaw Formation) over sandstone and dolomite (Unklesbay and Vineyard, 1992). Modern soils are developed in weathered cherty residuum that has received one or more thin additions of loess during the late Quaternary (Unklesbay and Vineyard, 1992; Robertson, 1969). The study area is approximately 200 km south of the maximum extent of midcontinent Pleistocene glaciations.

This region of southwest Missouri, referred to as the Springfield Plateau (Thom and Wilson, 1980), was historically covered with periodically wet prairie tracts that are now mostly in cultivation. Current periodic wetness in Diamond Grove Prairie is indicated by crayfish chimneys that seasonally form in intermound areas. This prairie (managed by the Missouri Department of Conservation) and the adjacent private property described in this study are used primarily for hay production. Local historians, owners, and conservationists confirm that although these tracts have long been in hay production and occasionally grazed, they have never been plowed. Consequently, the Mima-type mounds and intermound areas, and the prairie flora are relatively pristine and more or less representative of pre-settlement conditions.

3. Methods

3.1. Mound surveys and measurements

Forty-six mounds were studied on four one-hectare plots on Diamond Grove Prairie and on two one-hectare plots on the adjacent private property. The heights of the mounds, taken in four cardinal directions, were measured against intermound areas using a rod and level and averaged for total height. Diameters were measured in north–south and east–west directions using a tape measure. Edge boundaries of the mounds were visually estimated by noting changes in vegetation, surface wetness, and or slope angle. GPS coordinates were recorded for mound centers and plot corners.

3.2. Mound trench and soil horizon mapping

On private property adjacent to Diamond Grove Prairie, one Mima-type mound was trenched with a backhoe to examine, measure, and analyze its internal characteristics. The trench was 21 m in length and 2 m deep below the highest point of the mound. A sampling grid (1 m wide and 0.5 m high) was installed along the south facing trench wall to guide mapping and sampling. Soil horizons were designated and described according

Table 1
Percentages of >2 mm coarse fraction (gravels) in total bulk samples obtained in 10 cm depth increments in each of the twelve pedons

Depth (cm)	0–1 m	1–2 m	3–4 m	5–6 m	7–8 m	9–10 m	11-12 m	13-14 m	15–16 m	17–18 m	19–20 m	20–21 m
0–10	11.3	13.6	14.9	15.2	27.0	18.5	18.0	20.0	17.6	13.2	10.0	13.0
10–20	17.1	10.0	14.5	14.3	24.2	34.5	29.7	28.2	18.9	24.3	15.7	13.2
20–30	8.0	13.3	14.4	14.6	22.7	26.6	31.1	18.5	26.8	14.4	21.1	9.1
30–40	16.2	7.8	13.7	15.5	27.9	23.3	20.4	13.8	23.1	43.4	13.5	8.3
40–50	82.5	78.3	11.8	16.8	24.0	21.4	16.6	31.1	17.8	13.9	16.8	7.7
50–60	85.4	84.5	26.7	22.2	20.0	25.9	24.5	18.1	21.0	11.0	9.9	9.3
60–70	*	75.6	86.8	45.8	17.7	30.1	27.3	20.2	19.0	10.4	15.2	20.5
70–80	*	79.3	85.8	88.3	13.5	21.1	16.6	14.9	18.4	24.1	11.1	20.3
80–90	*	*	84.2	85.6	73.6	20.6	23.9	16.9	9.6	17.1	23.3	8.1
90–100	*	*	69.0	84.3	84.2	19.4	13.8	13.1	13.1	78.3	27.7	*
100–110	*	*	51.2	52.5	85.4	12.3	31.6	6.3	64.7	84.9	85.4	*
110–120	*	*	*	61.5	73.4	66.2	64.4	63.1	78.8	83.6	66.4	*
120–130	*	*	*	59.6	56.7	85.6	80.8	65.7	80.4	65.6	66.0	*
130–140	*	*	*	*	14.1	91.4	77.1	74.3	73.2	62.2	54.5	*
140–150	*	*	*	*	30.1	53.8	67.8	59.4	24.6	61.2	59.1	*
150–160	*	*	*	*	*	36.9	47.9	7.6	10.6	25.9	62.1	*
160–170	*	*	*	*	*	9.9	35.1	27.6	35.4	18.0	*	*
170–180	*	*	*	*	*	11.3	*	64.4	36.0	17.5	*	*
180–190	*	*	*	*	*	*	*	62.4	55.6	*	*	*

Asterisks indicate that no samples were obtained. Dark lines and shaded areas indicate approximate boundary and thicknesses of the two stone-layers. Modified from Horwath (2002).

to USDA-NRCS procedures (Soil Survey Staff, 1993). Bulk samples, weighing approximately 1 kg, were collected at 10 cm depth intervals from twelve pedons along the south facing trench wall from surface to base (greater depth was limited by a perched water table).

3.3. Analysis of particle size

Laboratory analysis of soil samples followed standard procedures which included sieving, all necessary pre-treatments, and analysis of particle size (Soil Survey Staff, 1996). Analysis of the fine fraction (≤2 mm) was done by pipette method to determine percentages of sand, silt, and clay. The coarse fraction (>2 mm) was analyzed by passing the bulk samples through nested sieves (31.5, 16, 8, and 4 mm). Gravels remaining on each sieve were weighed and hand counted, and long axis diameters were measured on the largest gravel from each sieved sample (detailed methodology in Horwath, 2002).

4. Results

4.1. Size, density, and distribution of mounds

A total of 46 mounds were measured in the study area. Mounds had average heights of 45 cm, average diameters of 14 m, and average densities of 7.6 ha^{-1} (Horwath, 2002). The largest mounds occur in low-lying wet areas along small watercourses in and adjacent to Diamond Grove. Larger mounds outside the study area, averaging 100 cm in height and 24 m in diameter (along a small watercourse), were observed but not included in the measured averages of this paper. The majority of mounds are circular in shape or elongate in a north–south direction, with minor exceptions of mounds along watercourses that were elongated parallel to stream flow (Horwath, 2002).

4.2. Mound morphology, horizonation, and krotovina

Six soil horizons were identified in the trenched mound; A, EBg, EBtg, Btg, Bt/Btg, and Bt horizons (Fig. 2). Horizon designations were based on field observations and supported by laboratory analyses. The horizons lie nearly horizontal, dipping very slightly downhill to the west. A brief description of the six horizons is provided in Fig. 2.

Approximately 20 krotovina, all less than 10 cm in diameter, were mapped within the EBg horizon near the center of the mound (Fig. 2). One open and presumably active burrow (~5 cm) was also observed within the A horizon. This open burrow is but a small reflection of the vast amount of active burrowing evidenced on the surface of innumerable mounds of Diamond Grove Prairie (Horwath, 2002). Most surface

Table 2
Diameter (cm) of the largest stone from each of the gravel fractions

Depth (cm)	0–1 m	1–2 m	3–4 m	5–6 m	7–8 m	9–10 m	11-12 m	13-14 m	15–16 m	17–18 m	19–20 m	20–21 m
0–10	3.5	3.2	3.2	3.3	4.5	3.5	3.7	4.9	4.5	3.3	1.9	3.0
10–20	6.0	2.9	2.7	2.5	3.1	7.2	5.4	4.2	3.5	4.7	3.8	4.0
20–30	2.5	2.8	3.5	2.9	6.0	4.6	7.2	3.4	8.2	4.9	7.1	2.4
30–40	4.0	2.0	5.0	5.2	9.3	4.0	5.2	2.5	6.0	2.9	4.3	3.2
40–50	14.0	9.0	2.4	3.2	3.7	4.5	4.4	5.3	3.9	4.3	5.2	3.1
50–60	8.3	1.0	7.3	5.5	4.1	5.5	7.7	5.2	5.8	4.0	2.7	3.9
60–70	*	8.5	15.3	8.0	4.5	6.2	5.4	3.5	5.2	4.2	6.0	5.2
70–80	*	9.5	9.5	10.8	2.5	4.4	3.6	4.2	5.7	6.6	3.5	5.0
80–90	*	*	9.3	9.1	11.2	5.3	4.5	4.5	3.0	4.4	5.3	2.7
90–100	*	*	7.1	7.5	7.5	5.3	3.5	3.5	4.5	10.8	7.5	*
100–110	*	*	5.9	6.0	6.1	2.5	5.4	2.2	9.3	9.2	12.2	*
110–120	*	*	*	8.0	7.1	7.8	6.8	8.9	8.2	10.9	5.0	*
120–130	*	*	*	7.2	10.0	6.1	10.0	9.1	6.6	6.0	6.2	*
130–140	*	*	*	*	4.1	6.8	10.0	6.5	6.0	11.0	5.8	*
140–150	*	*	*	*	*	6.0	5.4	5.3	4.6	7.0	4.8	*
150–160	*	*	*	*	*	6.2	6.3	8.7	3.3	4.9	7.0	*
160–170	*	*	*	*	*	4.2	5.9	3.0	5.1	4.7	*	*
170–180	*	*	*	*	*	3.6	*	5.5	5.7	5.0	*	*
180–190	*	*	*	*	*	*	*	10.4	8.2	*	*	*

Asterisks indicate that no samples were obtained. Dark lines and shaded areas indicate approximate boundary and thickness of the lower stone-layer. This lower stone-layer is composed of stones too large for *Geomys* to move. The stone-layer is deepest in the center of the mound. Modified from Horwath (2002).

burrows range from 0.1 to 9 cm in diameter and are attributed to insects, crayfish, box tortoises, small rodents, and larger mammals (rabbits, badgers, armadillos, coyotes, etc). At least ten small mammal species (mice, shrews, voles, etc.) have been documented on Diamond Grove Prairie as occupiers of mounds (Robbins and Hadley, 1998).

4.3. Particle size distribution of fine and coarse fractions

Depth functions of the fine fraction (≤2 mm diameter) show homogeneity in the A horizon and heterogeneity below (Fig. 3). In all pedons, the surface A horizon shows little variation in fine fraction, reflective of a fairly homogeneous upper profile. Pedons near mound edges show little vertical variation in fine fraction, indicating near homogeneity in proximity to the intermound area. Texturally, the soil trends vertically from silt or silt loam in upper horizons to silty clay loam and clay in the lower profile. The high silt content of the A horizon suggests the input of wind-blown material (loess) into the soil system. The bimodal distribution of clay is one of the more variable and interesting aspects of the fine fraction in the mound soil. An upper mid-mound clay bulge (i.e. increase in clay content) occurs in most pedons within the EBtg and Btg horizon. A basal and much larger clay bulge is present in the lower part of all pedons in or directly above the Bt horizon (Fig. 3).

A bimodal distribution of coarse fraction gravels (>2 mm) is also present in the mound (Fig. 4 and Table 1).[1] The distribution reveals a pattern of generally low percentage of gravels (by weight of total sample) in the upper profile, but with a slight concentration near or at the land surface, and a much larger gravel concentration within the Btg horizon (stone-layer) at the base of the mound. (Because this basal gravel concentration can, in places, be observed in some intermound areas of Diamond Grove, and because it was encountered during hydraulic Giddings probes of two other mounds prior to the onset of this work, it is assumed to be continuous and underlies all the mounds of Diamond Grove.) Below the basal stone-layer the percentage of cherty gravels decrease markedly, and many are partly or wholly saprolitized indicating intense weathering in this gleyed and periodically wet basal zone. The slight near surface concentration of gravel indicates a discontinuous and very weak, though distinct, stone-layer just below the surface (in some pedons

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[1] We interpret the two slight inflection points in the lower A horizon of Fig. 4b as genetically insignificant and non-diagnostic insofar as they are not present in Fig. 4a.

it becomes a surface armor; c.f. Table 1). In sum, two stone-layers are present in this mound and presumably in others at Diamond Grove: one that is weak and discontinuous near the mound surface, and another that is much more strongly developed and continuous at the mound base.

The gravels reveal interesting patterns of size distribution. Table 2 shows that in horizons *above* the basal stone-layer, the largest gravel sizes are (with few exceptions) less than 6.5 cm in long axis diameter, whereas many clasts in the basal stone-layer have long axis diameters larger than 6.5 cm. Fig. 4 shows that the transition from EBg (or EBtg in some pedons) to the Btg horizon is marked by a very abrupt increase in gravel weight and number. The increase in long axis diameter of the gravels in this horizon is shown in Table 2 (shaded area). Gravels in the Btg horizon and overlying horizons are composed of naturally fractured chert derived from the cherty Warsaw limestone. Below the basal stone-layer, a decrease in weight and long axis diameter of gravels is noted in the Bt/Btg and Bt horizons. The highly weathered nature and appearance of gravels below the stone-layer indicate advanced weathering of chert gravels, some saprolitized, that are typically mottled bright red, yellow, and white.

5. Discussion and interpretations

The uniform nature of the A horizon across all pedons, as evidenced by dark color, texture, and small gravels, strongly suggests that it has been highly bioturbated by small burrowing vertebrates in the past, and to some extent probably continues today (although the suite of bioturbating vertebrates is somewhat different now). Biological mixing clearly extended into the (currently neoformed) E horizon, as indicated by many visible (though faint) krotovina (Fig. 2), but eluvial and leaching processes in the E horizon have diminished the field evidence of this formerly intense mixing.

Sizes and distributions of gravel support a biological genesis of the mounds in Diamond Grove Prairie. As indicated, the distribution of small gravels (<6.5 cm long axis diameter) increases dramatically in size and weight at the base of the mound in the Btg horizon. This strongly developed lower stone-layer horizon is interpreted as a product of bioturbation by burrowing fauna, we believe mainly by the pocket gopher *G. bursarius* (the sole genus in Missouri) (Johnson, 1989, 1990; Horwath, 2002; Horwath et al., 2002; Johnson et al., 2002). All species of pocket gophers mix soil by moving it through burrows. Diameters of burrows vary by species, with those of adult *Geomys* averaging about 6–7 cm (Jackson, 1961; Schwartz and Schwartz, 1981; Johnson, 1989). Hence, all soil particles of this size or smaller will be mixed throughout the burrowing domain of these animals. As *Geomys* burrow centripetally outward from point-centered nesting sites they slowly move soil and small gravels (<6.5 cm diameter) back towards the, nesting sites (Cox and Allen, 1987; Cox et al., 1987; Hansen and Morris, 1968; Johnson, 1989). In areas of thin soil over an impermeable substrate or high water table, mounds will often form because of the inability of *Geomys* to burrow deeper, thereby leading to lateral soil transfer (Dalquest and Scheffer, 1942; Cox, 1984; Cox and Allen, 1987; Cox et al., 1987; Johnson et al., 2002). Dalquest and Scheffer (1942) noted that pocket gophers often burrow around stones that are too large to move. Over time, this will cause the larger clasts (>6.5 cm) to gradually “sink” to form a stone-layer at the base of burrowing. The process produces a two-layered biomantle (i.e. a relatively low gravel content biomantle and a gravel rich stone-layer below), defined by Johnson (1990) as “the differentiated zone in the upper part of soil produced largely by bioturbation aided by subsidiary processes.” The occasional presence of stones larger than 6.5 cm in diameter above the stone-layer most likely results from the predation of small mammal nests by larger mammal predators, such as badgers, coyotes, foxes. These predators commonly dig into mounds in search of food, and because of their great size and strength they bring larger gravels to the surface (Cox et al., 1987; Johnson, 1999). This process can offset the stone-layer producing propensities of *Geomys*. Whereas other fossorial species, such as moles (family Talpidae), may be suspect in the creation of these mounds, the burrowing styles and mound morphologies are distinctly different from the nest-centered centripetal burrowing style of *Geomys* (Dalquest and Scheffer, 1942; Schwartz and Schwartz, 1981).

Although pocket gophers are currently not present in Newton County, evidence for a former occurrence in the Diamond Grove area is strongly suggested by Faunmap Working Group (1994) compilations. In this document, paleontological records of *Geomys* have been gathered across the United States for time periods ranging from Late Wisconsin (10,000–40,000 ybp) to Late Holocene (500–4000 ybp). Known sites of *Geomys* fossils are located north and south of Newton County in areas of similar topography and vegetation (Faunmap Working Group, 1994). Schwartz and Schwartz (1981) indicate that the current range of pocket gophers in Missouri is not known with certainty, and that in some localities they may be abundant for 6 to 8 years, then become rare. “Frequently there are areas near active colonies that are

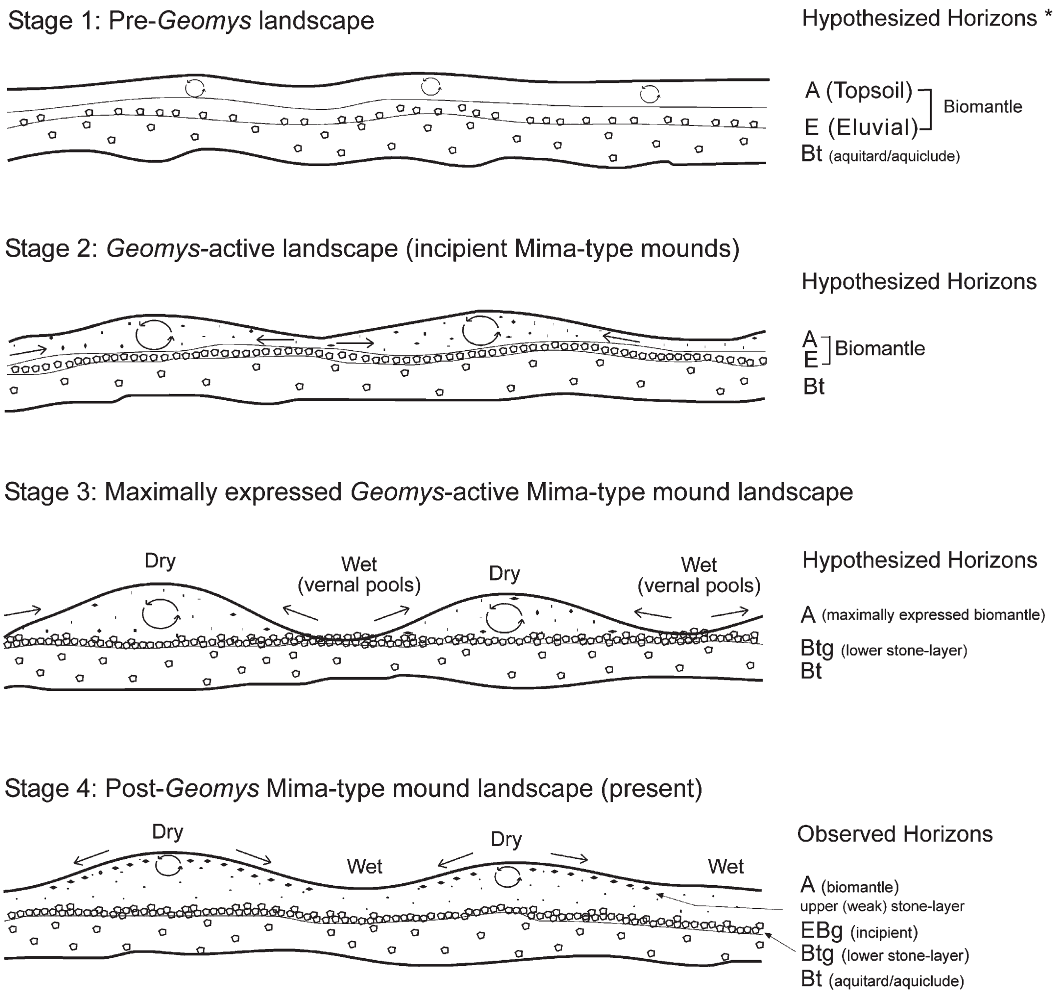

Fig. 5. Hypothetical evolution of Diamond Grove Mima-type mounds in the cherty residual soil of Springfield Plateau. Small open symbols represent larger (>6.5 cm) cherty stones, and dots represent smaller (<6.5 cm) stones mixed throughout mound by *Geomys*. Circular arrows in stages 1 and 4 indicate bioturbation dominated by soil invertebrates. Circular arrows in stages 2 and 3, on the other hand, indicate bioturbation dominated by *Geomys*. Stages 2–4 represent the Springfield Plateau landscape typified by point-centered, locally thickened Mima-type mounds and intervening shallow (periodic) vernal wet areas. *Hypothesized horizons based on observations of non-mounded Springfield Plateau soils.

unoccupied, although formerly pocket gophers inhabited them" (Schwartz and Schwartz, 1981).

The mid-mound upper clay bulge is present in most pedons, but diminishes towards the mound edges (Fig. 3). This upper "secondary" clay bulge is interpreted as having neoformed *after* the departure of *Geomys* from the Diamond Grove area. It likely reflects the average depth of wetting. A post-*Geomys* scenario of "normal" pedogenesis is proposed because if this burrower were still active in the mounds, bioturbation would almost certainly preclude the formation of a clay bulge and an E horizon, just as bioturbation precludes illuvial clay concentrations and "normal" horizonation in mounds of other midwestern moundfields where pocket gophers are active (Ricks et al., 1997). Also, because burrowing animals are not likely to penetrate the deeper, weakly cemented and very gravelly basal Btg horizon, this horizon is neither bioturbated nor reworked which has allowed the accumulation of illuvial clays expressed as a notable clay bulge.

The lower primary and much more strongly pronounced clay bulge would likely be interpreted by some as a paleosol. We do not agree with this interpretation, however, for the following reasons. First, the term paleosol as used in this study follows Johnson's (1998) usage, namely that the term be used for buried soils, not surface soils, and also follows Fenwick's (1985) admonition that, "Only when a soil has been isolated from modern processes by burial could it be truly considered paleosolic". The lower Bt horizon is, we submit, still receiving illuvial clays from above via occasional deeply penetrating wetting fronts — that is, it is not isolated. Further, this horizon also does not fit the description of "buried" or "isolated" paleosols as conceptualized by Schaetzl and Sorenson (1987). We, therefore, hypothesize that this clay-rich illuvial horizon is the former Bt horizon of the residual pre-*Geomys* (and pre-mound), Springfield Plateau soil, and is not a paleosol. This relatively impermeable horizon functions as an aquitard – and when fully wetted possibly an aquiclude – that perches groundwater at present, and most likely perched water in the pre-*Geomys* (pre-mound) landscape.

5.1. Proposed soil and mound evolution

Fig. 5 depicts our interpretation of the evolution of the mounds in the Diamond Grove Prairie area. In a pre-*Geomys* landscape (Stage 1), relatively thin A and E horizons evolve, augmented by nonpoint-centered invertebrate bioturbations (upward transfers of fine fraction) to produce a basal pedogenic stone-layer. These horizons co-evolve with a developing Bt horizon that functions as a probable aquitard when dry (some water transmission because of clay shrinkage and cracking) and as an aquiclude that perches water when wet (because of clay swelling). The pedogenic stone-layer, produced by soil infauna (sans *Geomys*), develops at the interface of the E and Bt horizons. A two-layered biomantle thus forms whose base is defined by the base of the stone-layer (Johnson, 1990).

Stage 2 represents the time when *Geomys* appears (in-migrates or evolves) in the periodically wet Diamond Grove Prairie area. Episodic surface wetness would force *Geomys* to drier high ground positions, which become incipient point centers (Fig. 5). Since *Geomyidae* are incessant and aggressively territorial burrowers, dry nesting sites would confer a survival advantage against flooding. Inasmuch as the burrowing style is centripetally outward from the nesting centers (Dalquest and Scheffer, 1942; Cox and Allen, 1987), *Geomyidae* begin to slowly "mine" and translocate the thin A and E horizon material towards the nesting sites (point centers of thicker, higher, drier soil), and, thus, ultimately create mounds. Gravels too large to be moved by *Geomys* gradually sink and begin forming a stone-layer at the base of burrowing. As they form, the mounds increasingly confer an advantage to reproductive success and predator avoidance by enabling gophers to nest more deeply to protect against natural predators and to escape periodic wetness and flooding. Successive generations of *Geomys*, as well as other opportunistic fossorial species, would continue nesting and inhabiting these "advantage conferred" mounded and point-centered locations, and, thereby, slowly increase the size and breadth of the mounds. Such mounds would also support a more luxuriant vegetation, as most do now (Horwath, 2002), serving as dust (loess) traps, which add still more bulk and breadth.

In the well-expressed *Geomys*-active landscape of stage 3 (Fig. 5), broad, seasonally wet intermound areas co-evolve, conferring an even greater advantage to soil fauna that access the mounds during wet periods. At this stage the formerly distinct A and E horizons are now essentially "blended" together as *Geomys* bioturbation is maximally expressed. This process results in a biomantle consisting of point-centered and locally thickened Mima-type mounds underlain by a well expressed stone-layer. Because the majority of the fine fraction has been "mined" from intermound areas, the large chert fragments of the stone-layer are left behind as a surface-exposed intermound "lag" deposit that is typical of most *Geomyidae*-inhabited moundfields formed in gravelly soils of western North America (Johnson et al., 2002). Stage 3 is hypothesized as representing a long period of Quaternary time, perhaps involving some or most of the late Tertiary (however long *Geomys* has inhabited this part of the Springfield Plateau).

During stage 4 (Fig. 5), hypothesized as representing the last several hundred years or so (very late Holocene), the present post-*Geomys* landscape evolves where an incipient E and Bt horizon begin to form in the absence of *Geomys* mixing. Invertebrate bioturbation (ants, worms, etc.) of fine fraction aids in forming the upper, near-surface stone-layer. Intermound areas that formerly exposed the stone-layer now begin infilling with fine material episodically washed from mounds. This episodic surface wash also results in the slow downwasting of the mound and aids in forming a near-surface gravel layer that partially "armors" the mound in some pedons (Fig. 4). The absence of regular bioturbation by *Geomys* in late Holocene time allows a new Bt horizon (modern Btg) to develop in the mounds.

6. Conclusions

Trenching and mapping of a Mima-type mound in Diamond Grove Prairie reveal a dark, locally thickened and silt-rich, A horizon that thins towards the mound edges. The homogeneity, color and texture of the A horizon of the mound soil are interpreted as reflecting a combination of two principal processes: episodic loess inputs to the Springfield Plateau prairies and, most importantly, bioturbation by past and present soil fauna (mainly small fossorial rodents (*Geomys*), other mammals, and invertebrates such as insects, ants, worms, etc.). The presence of small fossorial vertebrates in the past is indicated by relict krotovina that match those produced by modern pocket gophers. Because mounds remain above the surface water during periods of wetness, they become refuges for numerous animals, and confer a reproductive and predation avoidance advantage for the species that inhabit them. Bioturbation by these fauna would dominate the higher and drier portions of the mound, and, thus, result in a thicker A horizon at the mound center. It is hypothesized that this process reached a maximum when *Geomys* inhabited the Diamond Grove Prairie area — sometime in the late Tertiary and Quaternary, through the very late Holocene time when they locally disappeared (Faunmap Working Group, 1994).

Two bioturbationally produced stone-layers occur in the mounds: a weak, thin and discontinuous near-surface one that is presumably neoformed and composed of clasts smaller than about 6.5 cm in diameter; and a thick, strongly developed, lower one in the Btg horizon that is composed of larger clasts and is continuous across the plateau landscape. The deeper and stronger stone-layer (in the Btg horizon) is likely the result of collective bioturbation by small fossorial rodents, other small vertebrates, and by insects and other invertebrates over a long period of the late Quaternary. As they burrow into and through soils, mounded or otherwise, they may encounter stones too large to be carried through the burrows. Such large clasts are burrowed around and under, so that over time they "migrate" to lower positions, and ultimately accumulate as a stone-layer. A two-layered biomantle thus forms (Johnson, 1990).

Whereas percentages of silt and sand are fairly constant throughout the upper and middle parts of the mound soils, clay is expressed bimodally as two illuvial bulges: a higher actively forming and modestly expressed one, and a lower, less actively forming (now), but very strongly expressed and functionally significant one. The depth of the upper clay bulge may reflect the average wetting front depth, forming after the dominant bioturbator (*Geomys*) abandoned the Diamond Grove area. The lower clay bulge is likely the former main, highly polygenetic Bt horizon of the pre-mound, residual Springfield plateau soil that functioned then, as now, as a strong aquitard or effective aquiclude.

This research supports the hypothesis that the mounds of Diamond Grove Prairie and adjacent private lands in southwestern Missouri were formed *primarily* by, and continually shaped by, the burrowing activities of animals, as do comparative work by others on Mima-type mounds elsewhere in North America (Dalquest and Scheffer, 1942; Cox, 1984; Cox and Allen, 1987; Cox and Gakahu, 1986; Cox et al., 1987; Johnson, 1989). Although this research suggests bioturbation as the primary, dominant factor of mound development, important secondary processes such as episodic small inputs of loess, storm flow, rainfall erosion, and other physical and chemical weathering processes also collectively operate in producing the mounds and the evolved pedogenic horizons (stone-layers, Bt aquicludes, etc.). This suite of dynamic processes has produced the current mound–intermound morphology and topography of the otherwise more or less stable uplands of the Springfield Plateau.

Finally, numerous species and subspecies of pocket gophers are found throughout western and southeastern North America and exhibit moderate to notable differences in food preferences and other behavioral patterns and habits. Such differences are manifest, we hypothesize, in the variable sizes and morphologies of mounds in the moundfield tracts scattered across western North America.

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Erratum

Erratum to “Mima-type mounds in southwest Missouri: Expressions of point-centered and locally thickened biomantles” [Geomorphology 77 (2006) 308–319]

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The publisher regrets that in the second paragraph of Section 5, Discussion and interpretations, page 315, a few errors appeared in the text: Small gravels (<6.5 cm long axis diameter) should read: Large gravels (>6.5 cm long axis diameter). Line 1 of the right column should read 6–9 cm instead of 6–7 cm. A word *Geomys* in line 52 of the left column and in lines 4, 11, 31 and 36 of the right column should read: gophers. The whole paragraph is rewritten correctly below:

Sizes and distributions of gravel support a biological genesis of the mounds in Diamond Grove Prairie. As indicated, the distribution of large gravels (>6.5 cm long axis diameter) increases dramatically in size and weight at the base of the mound in the Btg horizon. This strongly developed lower stone-layer horizon is interpreted as a product of bioturbation by burrowing fauna, we believe mainly by the pocket gopher *G. bursarius* (the sole genus in Missouri) (Johnson, 1989, 1990; Horwath, 2002; Horwath et al., 2002; Johnson et al., 2002). All species of pocket gophers mix soil by moving it through burrows. Diameters of burrows vary by species, with those of adult gophers averaging about 6–9 cm (Jackson, 1961; Schwartz and Schwartz, 1981; Johnson, 1989). Hence, all soil particles of this size or smaller will be mixed throughout the burrowing domain of these animals. As gophers burrow centripetally outward from point-centered nesting sites they slowly move soil and small gravels (<6.5 cm diameter) back towards the nesting sites (Cox and Allen, 1987; Cox et al., 1987; Hansen and Morris, 1968; Johnson, 1989). In areas of thin soil over an impermeable substrate or high water table, mounds will often form because of the inability of gophers to burrow deeper, thereby leading to lateral soil transfer (Dalquest and Scheffer, 1942; Cox, 1984; Cox and Allen, 1987; Cox et al., 1987; Johnson et al., 2002). Dalquest and Scheffer (1942) noted that pocket gophers often burrow around stones that are too large to move. Over time, this will cause the larger clasts (>6.5 cm) to gradually “sink” to form a stone-layer at the base of burrowing. The process produces a two-layered biomantle (i.e. a relatively low gravel content biomantle and a gravel rich stone-layer below), defined by Johnson (1990) as “the differentiated zone in the upper part of soil produced largely by bioturbation aided by subsidiary processes.” The occasional presence of stones larger than 6.5 cm in diameter above the stone-layer most likely results from the predation of small mammal nests by larger mammal predators, such as badgers, coyotes, and foxes. These predators commonly dig into mounds in search of food, and because of their great size and strength they bring

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larger gravels to the surface (Cox et al., 1987; Johnson, 1999). This process can offset the stone-layer producing propensities of gophers. Whereas other fossorial species, such as moles (family Talpidae), may be suspect in the creation of these mounds, the burrowing styles and mound morphologies are distinctly different from the nest-centered centripetal burrowing style of gophers (Dalquest and Scheffer, 1942; Schwartz and Schwartz, 1981).