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Introduction: Overview of concepts, definitions, and principles of soil mound studies

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Where controversy exists, science never rests.—Kruckeberg (1991, p. 296)

VOLUME BACKGROUND AND PURPOSE

This volume grew out of a symposium titled: "The origin of Mima mounds and similar micro-relief features: Multidisciplinary perspectives," and an associated similarly themed field trip, both held at the Geological Society of America Annual Meetings, Houston, Texas, 4–9 October 2008. Five of the eight papers in that symposium were expanded for inclusion in this volume; with one nonsymposium paper added later (Johnson and Johnson, Chapter 6). The volume was invited and encouraged by the editors of GSA Special Papers to be one of their series. In regard to soil mounds, the symposium was timely for several reasons.

The first was, among the innumerable theories on how mounds form, evidence has gradually accumulated which confirms that burrowing animals are involved. Involvements would seem to include (1) animals initiating the mounds themselves, where they begin as "activity centers" for basic living purposes (denning, reproduction, food storage, safety, etc.), which are actively bioturbated; (2) where landscape microhighs created by some physical or biological process, or both (e.g., coppicing), become occupied by animals for "activity centers," then augmented through bioturbation to create "hybrid mounds"; or (3) occupy soil-filled joints and fissures in otherwise thin soil or eroded bedrock areas.[1] In any of these three conditions we are concerned with the question: Would activity centers evolve into mounds, and perhaps persist wherever the centers confer living-survival-reproductive advantages to the animals that inhabit them? Since we examine mounds *after* they form, how can we tell, beyond theorizing, what the initial conditions were that led to mound formation? A purpose of the symposium, and this volume, was to revisit and examine these and other soil mound issues and questions, especially the role of life in landscape evolution.

A second reason is the recent availabilities of useful analytical tools, such as LIDAR (light detection and ranging) and Google Earth technologies, allow new and different light to be shed on soil mound matters. In fact, they are revolutionizing studies of mounded landscapes.

Third, bioturbation- and biomantle-related ideas and formulations on pedogenesis have appeared that are spawning different genetic understandings on how soils form and landscapes evolve (Humphreys and Mitchell, 1988; Johnson et al., 2002, 2003, 2005a, 2005b, 1999; Paton et al., 1995; Schaetzl and Anderson, 2005; Horwath and Johnson, 2006, 2008; Johnson and Lin, 2008; Johnson and Johnson, 2010; Wilkinson et al., 2009; Fey, 2010). These views and models are leading to new questions being asked by Quaternary geologists, geomorphologists, pedologists, and archaeologists, not only about soil mounds but also about the fundamental principles we draw upon to explain soils and landscapes, and to accurately assess archaeological sites. It should be noted that the term "site formation processes," as used by archaeologists and geoarchaeologists, equates to "pedogenesis," as used here, and generally by pedologists and geologists (cf. Finney, this volume, Chapter 5). Contributors to this volume are asking fundamental questions about the role of animals in creating *subaerial* landscapes that ichnologists and marine geologists—whose fields gave us the term "bioturbation" and associated

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[1] Good examples of fracture trace Mima-type mounds are Upper Table Rock near Medford, Oregon (42° 28′ 29″ N, 122° 54′ 05″ W) and North Table Mountain near Oroville, California (39° 34′ 57″ N, 121° 33′ 42″ W); cf. also Shlemon et al. (1973).

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concepts and principles—once asked about the role of animals in *subaqueous* terrains (Ekdale et al., 1984). Such biodynamic principles are now central to the explanatory-operating-process paradigms of these fields (cf. Bromley, 1996).

The fourth and last reason, in light of these fundamental queries, new technologies, and conceptual advances, and because they seem likely to illuminate prairie-Mima-pimple mound issues that have produced nearly 200 years of lively and spirited genetic discourse, it seemed timely and useful to bring them to bear on the historically sticky issues surrounding the nature and origin of these mounds.

For earth science students, teachers, and other readers who may have somehow escaped familiarity with the subject, or its depth and contentious nature, perusals of end-volume appendices (A–F) coupled with the timeline quotes below, should convey that the above statements "lively and spirited genetic discourse" and "historically sticky issues" are rather mild understatements:

> Few subjects have of late years more engaged the minds of scientific antiquaries than the mounds in the valley of the Mississippi . . . there have already been too many wild speculations respecting them throughout this vast region. (Taylor, 1843)

> There is a class of mounds west of the Mississippi delta and extending from the Gulf to Arkansas and above, and westward, to the Colorado in Texas, that are to me, after thirty years' familiarity with them, entirely inexplicable. . . . In utter desperation I cease to trouble myself about their origin, and call them "inexplicable mounds." (Forshey, 1851–1852, cited in Foster, 1973, and Veatch, 1906)

> These mounds are so uniform in appearance [near Maysville, Arkansas] that they convey the idea of an artificial origin. (Owen, 1858)

> The origin of these "peculiar structures" [in Iowa] is a mystery to most people; they believing them to be "Indian mounds" or even "ancient muskrat houses." (Webster, 1897)

> They are not confined to any deposit or to any hypsometric level [in Louisiana]. Entirely absent in one locality they are quite abundant in another. (Harris and Veatch, 1899)

> The probable origin of these mounds [Mississippi Valley] has been a source of contention since the time they were brought to the attention of the scientific world. (Rice and Griswold, 1904)

> It is altogether probable that the mounds which have been noted in various parts of the country are not exactly similar and have not had a common origin. . . . (Campbell, 1906)

> The small flat mounds beginning in the Iron Mountain neighborhood in Missouri, and extending southward into Texas and Louisiana, are inexplicable in our present state of knowledge. (Fowke, 1910)

> The small, low, flattened mounds of the lower Mississippi Valley are a problem for archaeologists. (Fowke, 1922)

> Probably no landform of similar size [in Oregon, Washington, regionally] has occupied such a conspicuous place in geological controversy. (Waters and Flagler, 1929)

> [T]he enigmatic origin of these mounds [Mima Prairie] constitutes a continuous embarrassment and a challenge to geological science. (Newcomb, 1952)

> The struggle of ideas concerning pimpled plains leans either to physical processes or to biological activity and is tempered by an observer's experience and prejudice. (Malde, 1964)

> The literature on their origin is vast and confusing [in Texas-Louisiana Gulf Coast] . . . and the debate seems endless. (Aronow, 1978)

> They are a mystery that has been discussed for over 150 years and . . . have generated a greater variety of hypotheses than any other geologic feature. (Higgins, 1990)

> [I]f there is a truly perplexing, enigmatic aspect of lower Mississippi Valley Quaternary geomorphology that has defied concerted efforts at explanation and for which there is no consensus [it is] the origin of [pimple] mounds. . . . (Saucier, 1994)

VOLUME JUSTIFICATION

The editors, in sum, firmly believe that any scientific subject or theme, like Mima mounds, with a contentious explanatory history that has covered nearly two centuries—and considered by many to be still contentious—deserves another look.

TERMS AND DEFINITIONS

Mima, Pimple, Prairie, and Natural Mounds

The *Glossary of Geology: Fifth Edition* (Neuendorf et al., 2005), the reference "bible" for earth scientists, has entries for "Mima mound" and "pimple mound" but not "prairie mound" nor "natural mound." "Mima mound" and "pimple mound" once carried regional connotations, "Mima" linked to the Pacific Northwestern states, and "pimple" to the Mississippi Valley–Gulf Coast region. Both terms, along with "prairie mounds" and "natural mounds," are now viewed as synonyms without regional linkages. Entries in the *Glossary* change and evolve as earth sciences evolve. *Glossary* entries for both Mima and pimple mound are presented here, though slightly modified and updated to match our current understandings.[2] Regional connotations of "Mima" and "pimple" remain because they provide a historic context.

Mima mound (Mi'-ma [my'-ma]): A term originally and historically used in the NW U.S., but now also elsewhere, for one of hundreds of thousands, possibly millions of low, roughly circular or elliptical domes, sometimes with flat tops, or low shield-like mounds composed of loose, unstratified, often gravelly silt or loamy soil material, formed on a wide array of soil and landform types, geologic substrates, and ecological environments, from sea level to alpine tree line; basal diameters vary from 1 m to > 30 m, and heights from about 10 cm to more than 2 m. Named after Mima Prairie in western Washington state. Cf: *pimple mound*. Sp: *monticulo de Mima*.

Pimple mound: A term historically used along the Gulf Coast of Texas and SW Louisiana, the lower and upper Mississippi Valley, and more recently in the prairie provinces of Canada for one of hundreds of thousands, and possibly millions of low, roughly circular or elliptical domes or shield-like mounds, often with flat tops, composed of unstratified sandy loam soil coarser than, and distinct from, the surrounding less coarse, often more clayey soil; basal diameters range from 1 m to more than 30 m, and heights from about 10 cm to more than 2 m. Cf: *Mima mound*. Syn: *pimple*.

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[2] Editors will formally recommend to *Glossary* editor-compilers that current entries be replaced with versions presented here.

Two key descriptors in these definitions are "unstratified" and "coarser." Both are clarified and explained by the role of animals in soil and landscape evolution in sections covered below. The expression "Mima mound," coined by J Harlen Bretz (1913), derives from a small village at the south end of Mima Prairie, which no longer exists. The term was given wide attention by the landmark mound studies of Dalquest and Scheffer (1942, 1944), and by Scheffer's subsequent contributions, and various responses by others to them. Other names have been coined or used for similar microrelief elsewhere (Appendix C), with "prairie mounds" and "pimple mounds" being the more common, and "natural mounds" less so.

Origin of the expression "pimple mound" is uncertain, but dates back at least to Hopkins (1870) who used the term for the "pimpled prairies" of southwestern Louisiana. (It may have been a local term specific to that area.) McMillan and Day (2010), citing previous work (Cross, 1964, and others), applied the term to organism-modified dunes on Virginia's barrier islands, features that might be kindred to "hybrid mounds" (see below). The expression "prairie mound" appears to predate all these terms, and is the more general expression. The terms Mima, natural, pimple, prairie, and soil mounds are used interchangeably in this volume (all are used in chapter titles). Regardless of terminology, all mounds are simply variations on a biodynamic and polygenetic process theme. As defined, all animal-produced mounds in North America which fall within the size dimensions indicated are Mima-pimple mounds.

Clarification of "Mima-Type" and "Mima-Like" Mounds

A clarifying discussion of the difference between "Mima-type" and "Mima-like" mounds is detailed in Chapters 4 and 6 (Burnham et al., this volume; Johnson and Johnson, this volume). Both kinds of Mima mounds are viewed as bioturbated *activity centers* of burrowing animals that represent end members of a microtopographic spectrum of mounds, with all soil mounds falling somewhere on the spectrum. Other things equal, Mima-type mounds are relatively long lasting and "fixed" because they confer some survival-reproductive advantage to the animals that inhabit them. Mima-like mounds are relatively ephemeral and "unfixed" because such advantages are either absent or neutral.

We suppose that "survival-reproductive advantages" for any burrowing animal species may not always be obvious to human investigators and observers. Moreover, the boundary between Mima-type and Mima-like mounds on the microtopographic spectrum is unspecified. Both issues may be unsettling to those who seek limits and boundaries for complex natural phenomena, and brings to mind the Aristotelian postulate: "It is the mark of an instructed mind to rest satisfied with the degree of precision which the nature of the subject permits and not to seek an exactness where only an approximation of the truth is possible." (Cf. *GSA Today,* June 1998, p. 16.) The postulate, in some ways, also relates to the concept of "hybrid Mima mounds."

Hybrid Mima Mounds[3]

The term "hybrid mound" refers to a preexisting microhigh formed by any physical (freeze-thaw, dune) or biological (tree-uprooting) process, or combination (coppices), which becomes inhabited by soil animals (pocket gophers, ground squirrels, badgers and other predators, moles, ants, termites, other insects, etc.) and modified in form and shape to become "Mima mound-like." After some period of habitation the final biogenetic-polygenetic outcome can be a coarser textured mound than surrounding soil. Examples of preexisting microhighs on which Mima mounds commonly form are: low ridges on old meander scrolls; shrink-swell (gilgai) microhighs; small first- or second-order floodplain high-spots and/or their stream levees; low rill divides on slopes; bumps on a terrace; small dunes; knolls; boles of uprooted trees; coppice accumulations; or any small rise. If the rise or microhigh confers a survival-reproduction-dwelling advantage over the surrounding area to any soil animal that occupies it—commonly against wetness—it becomes occupied, destratified, and accordingly rounded-up and modified via the animals' life activities. The rise is now a Mima-type "hybrid mound." Many, perhaps most, hybrid mounds are Mima-type, although reasonably distinguishing them from Mima-like hybrids evokes Aristotelian uncertainties.

The hybrid mound concept embeds notions of polygenesis—multiple processes of formation—and notions of equifinality where different processes produce similar landforms, in this case forms that might resemble Mima mounds but by definition are not (lava blisters, small pingos, microhighs on partially thawed permafrost, small stratified dunes-lunettes-coppices, etc.). The concept is restated with different language in the Introduction to Chapter 4 (Burnham et al., this volume). The editors believe that an *absence* of a formal hybrid mound concept is at least partly, if not largely, responsible for the historic proliferation of mound hypotheses and theories, and for the general confusion about mounds and unsettled views on their genesis.

Hybrid Mima mounds can be either geologically old (Pleistocene) or historically formed. North American examples of historic hybrid Mima mounds are many and notable. One is the extensive and now largely rodent-insect-predator destratified and bioturbated small coppice mounds crossed by Interstate-10 and U.S. Highway 54 in the El Paso-Las Cruces regions of west Texas and New Mexico (Gile, 1966; Hall et al., 2010; Johnson, 1997; personal observations). Another example is the hybrid, partly coppiced, "grassy sand mounds" mapped as Padre and Madre soils on pocket gopher–inhabited North Padre Island, Texas (Brezina, 2007; personal observations), particularly near the National Seashore entrance kiosk. Notable, and genetically telling, is that while Mima (hybrid) mounds and pocket gophers are plentiful on North Padre Island, both are absent on dune-covered South Padre Island.

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[3] This term was coined and the concept formulated for inclusion in the field guide for the field trip held in conjunction with the 2008 Houston GSA Symposium that led to this volume (Johnson and Johnson, 2008).

Other examples are the Mima-like hybrid mounds in Fernley Sink, Nevada, crossed by Interstate-80. They are rodent-bioturbationally destratified, lake-basin–derived clay- and carbonate-enriched coppice dunes. Similarly bioturbated, lake-basin eolian-produced hybrid mounds exist on the east side of Laguna del Perro crossed by Highway 60 near Silio, New Mexico (cf. Allen and Anderson, 2000; Anderson et al., 2002). Such mounds also occupy portions of the floor of Pleistocene Lake Bonneville (Great Salt Lake), as along much of the western fringe of Logan, Utah, and near its airport (Campbell, 1906; personal observations; Janis Boettinger, 2011, personal commun.). Interstate-15 intersects a similar moundfield formed on low terraces of the Bear River several kilometers north of Brigham City, Utah (personal observations).

Hogwallows (Hog Wallows) and Vernal Pools

The term "hogwallows," used to describe Mima-type moundfields in California and Texas, is misleading. "Wallows" refers to the depressions between mounds, or to vernal pools, not the mounds themselves. Buckman Hogwallows Preserve in California, shown in Figure 1 and discussed below, is an example. Further, the term "hogwallows" originally carried an image of clayey shrink-swell grumusol-Vertisol–type landscapes, as in the Mississippi valley and Gulf Coast, for seasonally cracking soils that often displayed gilgai microrelief. Contrary to what some pedologists suppose, sandy Mima-type mounds or "sand spots" were once fairly common on Gulf Coast gilgai microhighs, and in several places still are, and had likewise formed in some California Vertisols that lacked gilgai (Retzer, 1946). A careful reading of the literature, plus personal field observations in these regions, confirm this fact (e.g., Carter and Patrick, 1919; Foster and Moran, 1935; Smith and Marshall, 1938; Watson and Cosby, 1924; Retzer, 1946; McGuff, 1973; Fields et al., 1986; Heinrich, 1986; Ensor et al., 1990). How sandy, largely biogenically produced Mima-type mounds could form on otherwise clay-rich gilgaied or nongilgaied soils is indicated both in the 1975 Soil Taxonomy (Soil Survey Staff, 1975, p. 21) and in Van Duyne and Byers (1915, p. 1078). The process involves a combination of animal bioturbations at activity centers and episodic rainwash (fine particle elutriations) over time. Such processes produce point-centered locally thickened and coarse textured biomantles relative to surrounding soil (cf. Johnson et al., 2003).

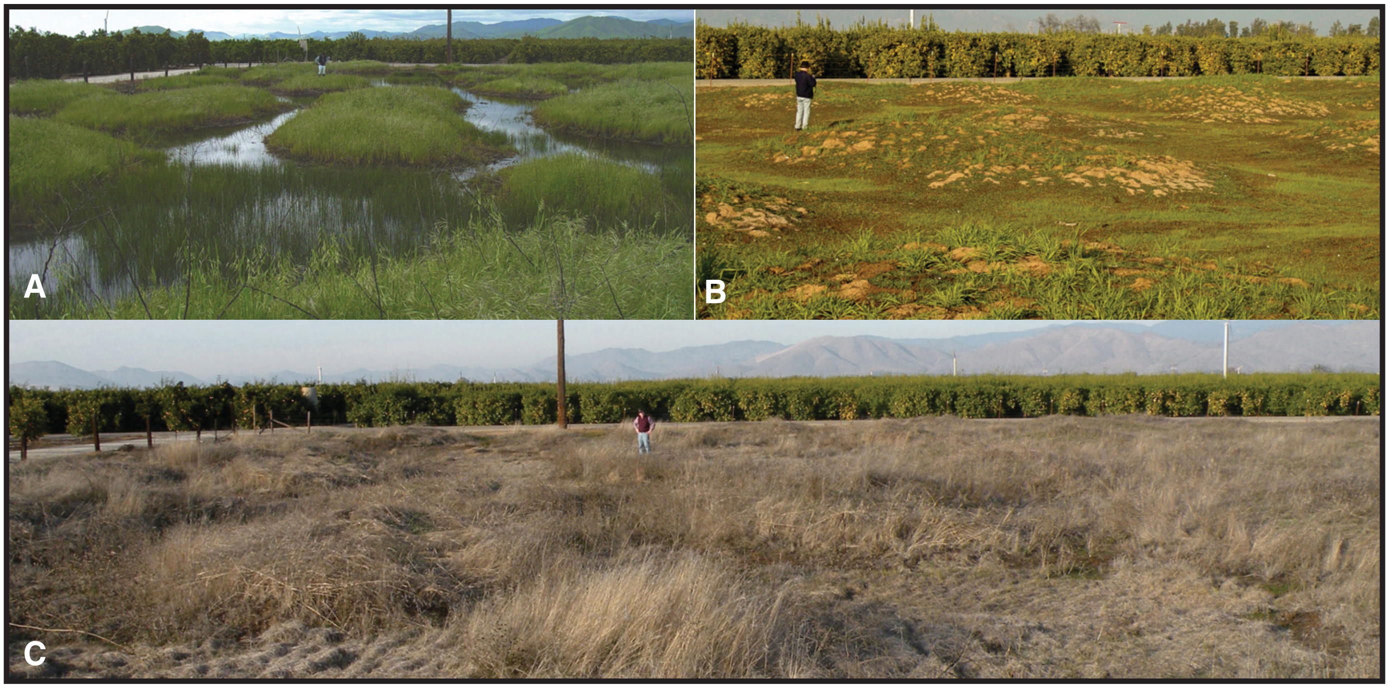

Figure 1. Three seasonally different views of Buckman Hogwallows Preserve, a small 4.1 ha (10 acre) low slope (~1%) Mima-type moundfield in hardpan soils that escaped the plow at the eastern edge of San Joaquin Valley, near Visalia, California (36° 21′ 26.58″ N, 119° 05′ 02.33″ W). The tiny preserve is now entirely surrounded by citrus groves (in order to plant trees hardpans were not uncommonly broken with dynamite; cf. Amundson, 1998). The notably domed Mima-type mounds here formed on relict alluvial fans on footslopes of the Sierra Nevada Mountains. Photo A was taken April 2006 after a wet winter. Photo B was taken January 2009 following a burn, several showers, and beginning of regrowth. Myriad surface heaps of the Botta pocket gopher (*Thomomys bottae*) attest to the effective landscape "rounding," mound making, and soil moving role that this seldom seen animal performs on this and many other moundfields. Photo C was taken January 2012 at the end of the dry season. View of photos is north, each taken at slightly different zoom levels from the same 1.8 m high mound. This moundfield, managed by the Tulare County Historical Society, provides a window into how this part of California looked before the plow and dynamite arrived (cf. Reed and Amundson, this volume, Chapter 1). The photos show that one's impressions of mounds and moundfields are strongly colored by the season observed. Photos courtesy D.N. Johnson.

Most vernal pools in Pacific Coast states occur where slopes are low and drainage restricted, often by the presence of Mima-type mounds. Larger vernal ponds and lakes are usually owed to more general geologic processes, such as warping, dune formation, or uneven igneous (basalt) extrusions (cf. Alexander and Schlising, 2000; Holland, 2000b). Such processes, however, are altogether different from, and independent of, the biogenic processes that create Mima mounds. Vernal pools constitute rainy season "hogwallows" of Mima-type mounds. The mound-vernal pool system is usually underlain by an aquiclude, such as hardpan, as is the case with many California moundfields.

An example is Buckman Hogwallow Preserve (Fig. 1), populated presently with one major mound maker, the Botta pocket gopher (*Thomomys bottae*). Here pools exist only because mounds and hardpan impede surface drainage (personal observations). Vernal pools at Buckman, like those in California generally, are typically shallow and seasonally disappear under high evaporation rates in late spring and early summer (Jain and Moyle, 1984; Holland, 2000a). As slopes steepen, as along ravine slopes in the Merced moundfields described in Chapter 1 (Reed and Amundson, this volume), pools become rills, with mounds invariably arrayed paternoster-like on rill divides.

Pixley Vernal Pools, another hardpan moundfield some 44 km south-southwest of Buckman Hogwallows, and four times larger (16.4 versus 4.1 ha), is another low slope Mima-mounded preserve, also in Tulare County (35° 59′ 03.99″ N, 119° 12′ 45.80″ W). In addition to the Botta pocket gopher, Pixley soils include two additional major bioturbators and mound makers, the California ground squirrel (*Spermophilus beecheyi*) and the American badger (*Taxidea taxus*). Other predators, coyotes, weasels, etc. are also likely present. Wild pigs likewise bioturbationally impact this moundfield (personal observations). As a consequence of this collective suite of different bioturbators, instead of smooth dome-shaped gopher-mediated mounds that characterize Buckman Preserve, Pixley mounds are irregular in outline, have hummocky and bumpy surfaces, and are heavily pock-marked by squirrels and badgers.

Environmental emphases and justification for preservation of both these Mima-mounded prairies is invariably on the pools and their often endemic, scientifically valuable, and commonly aesthetically showy and appealing flowers. Ironically, little attention is paid to the animals—primarily pocket gophers—that created the mounds, and by doing so created the pools. The long-term back-transfers of soil to nesting centers by these various animals, especially pocket gophers, during burrow-foraging activities (Dalquest-Scheffer-Cox [DSC] model, see Dedication and sections below) is what creates the mounds—and hence the depressions that hold the pools.

Polygenesis and Mound Complexity

Because all soils and landforms are polygenetic process-wise, so likewise are Mima mounds (cf. hybrid mounds, above). Mima mounds are of *polygenetic* and *complex* origin, but where bioturbation is the common process denominator. Polygenesis as used here[4] refers, literally, to the myriad and innumerable abiotic-biotic conditions, factors, and processes that impact soils and landforms at the many and varied elevations and diverse ecological environments in which Mima mounds are known to occur. Another perspective on polygenesis is that multiple organisms (animals, plants, fungi, protoctists, microbes), in various combinations, inhabit *every* soil and soil mound that exists. These life-forms all move, wriggle, and bioturbate, and in the process impart key biochemical signatures that trigger a cascade of transformations to soils and soil mounds.

Mounds are *complex* because the relative effect of each process and/or condition waxes and wanes with time, and some may be minimal, overprinted, or absent when studied. Because polygenesis and complexity must vary between mounds and moundfields, local and regional contrasts invariably fuel explanatory controversy (cf. Isaacson and Johnson, 1996).

LIDAR AND GOOGLE EARTH TECHNOLOGIES

LIDAR

LIDAR (light detection and ranging) is an active remote sensing technology that uses a pulsating laser sensor to scan the Earth's surface. The reflected pulses, up to 100,000 per second, are detected by instruments that record their location in three dimensions, which can then be used to create topographic resolution of the land surface at decimeter scales (Heidemann, 2012). The technique is excellent for accurately assessing Mima mound sizes, numbers, densities per unit area, estimating mound heights, and other measures. The authors of Chapter 1 (Reed and Amundson, this volume), for example, used LIDAR-produced mound data with other information to very conservatively calculate that 4.4 trillion metric tons of soil were moved by one species of burrowing animal, the Botta pocket gopher (*T. bottae*) in building mounds in an area equivalent to ~10% of California. As the authors note, and if their estimates are close, a small, seldom seen and nondescript burrowing rodent that is passionately detested by home-owners, greens-keepers, and gardeners alike, may be responsible for moving 350 times the annual sediment discharge of all the world's rivers!

While opening new opportunities for gaining high-resolution data on bioturbated and translocated soil and mound formation, LIDAR studies are also annually expanding our view of just how many Mima mounds might actually still exist. In fact, the numbers of mounds and moundfields being discovered with the technique by some volume contributors are attaining surprising levels in spite of several centuries of human landscape modification.

In addition to the LIDAR study in Chapter 1 (Reed and Amundson, this volume), another example of its usefulness in soil mound studies comes from Vandenberg Air Force Base in Santa Barbara County, California. Two volume contributors

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[4] Polygenesis in this volume varies significantly from how Price (1950, p. 359) used it, which was in place of the much more appropriate current term "equifinality," not then in the lexicon of earth sciences.

(Johnson and Johnson) have, for several decades, been intermittently monitoring a number of Mima-mounded tracts on Vandenberg selected in the 1980s for long-term observations. The base has a diversity of burrowing animals, which in order of most importance are the Botta pocket gopher (*T. bottae*) and California ground squirrel (*Spermophilous beecheyi*). Site selections were based on multiyear airphoto coverage and base-wide mound observations (Johnson, 1988, 1990; Johnson et al., 1991). Yet, when LIDAR became available, the number of known mounds increased exponentially. Indeed, owing to vegetation masking and subtle relief, mounds not seen in the field nor on airphotos were made instantly obvious on LIDAR, as exemplified by Figure 2. The figure shows mounded and nonmounded areas with subtle intergrades.

Irregular bumps at Sites A on Figure 2 are slightly coppiced but unmounded sage vegetation. The largest and most distinct mounds occupy low, seasonally wet swales and depressions that occasionally flood. At such sites soil material is available in sufficient quantity for making large mounds, as at Sites 4 and 7. Fines washed or blown into depressions are back-transferred to mounds by gophers during forage burrowing (DSC model). Comparatively smaller mounds occur: (1) where water accumulates only infrequently or (2) where shallow soils over hardpan slope into gullies and reentrants. Where soil biomantles are thick (>1 m) and water does not accumulate, Mima-type mounds do not form. Mounds in the depression at Site 3 range in height from ~20 cm to ~1 m, and in diameter from ~1 to 10 m, with exposed, virtually soil-free hardpan between. Arrows at Site 4 (inset) identify low (~10–20 cm), broad (~10 m) nascent mounds now forming at sinused perimeters. These evolve from erosionally thinned and centripetally bioturbated perimeter activity centers, and were unobserved before LIDAR. Depression floors receive fines from the surrounding biomantle during storms, which provides new soil material for biogenic growth of mounds; tiny bumps on depression floor are gopher heaps produced during forage runs. Seasonal sediment influxes fuel growth of large mounds as at Site 7. Many mounds are predator-impacted, especially by badgers, whose holes on mounds are quickly filled by gopher bioturbations. Nearby Sites 1 and 2, just off this image along Tangair Road, consist of large, sinus-edged, mound-dotted depressions in which gopher-inhabited mounds become islands during wet winters, as do mounds in depression Sites 3, 4, and 6.

Google Earth

Google Earth, like LIDAR, is also a relatively new research tool, and likewise has revolutionized Earth surface and soil studies, particularly soil mound studies. It draws on and applies satellite imagery, airphotos, topographic and shaded relief maps, and various other resources. Users can rapidly zoom laterally and vertically to any point on Earth, and then quickly determine cursor-point elevations (m, km), locations (latitude-longitude), and scaled distance measures (m, km). Spatial-lateral scanning allows rapid examination of large areas over short periods of time. For mound studies, the Historical Imagery application is particularly useful because a moundfield that is not apparent on one, two, or three airphotos of the same area covering different years may yet be visible on a fourth, fifth, or eighth.

LIDAR and Google Earth Combined

The volume contributors who were monitoring Vandenberg soil mounds (Johnson and Johnson) also initiated a systematic field examination of many documented (published) moundfields in former grassland or open forest tracts of Arkansas, Louisiana (west of the Mississippi), and eastern Texas (e.g., Aronow, 1988; Seifert et al., 2009; Archeuleta, 1980; Holland et al., 1952; Bragg, 2003; Cain, 1974; Owen, 1860; Frye and Leonard, 1963). Field examinations were based on locations and maps of published studies, and on airphoto analysis. While somewhat successful, the work proved to be disproportionately time-consuming, expensive, and complicated due to increased forest cover and human development, and to private property access issues.

Recent LIDAR imagery for some of these earlier examined areas, however, display an astonishingly far greater number, detail, and resolution of mounds and moundfields than had been reported, or expected, especially in light of historic human modifications. Moreover, owing to increases in forest cover, few mounds and moundfields were detected in such areas on Google Earth images. In fact, LIDAR demonstrates that in some areas almost every landscape segment is studded over with mounds, sometimes in surprising densities and detail. This is particularly true for some coastal areas, as at Hackberry Island and the Houston Ridge in Cameron-Calcasieu Parishes (cf. Aronow, 1988; Heinrich, 2007). It is also true for sublevels of the Deweyville and other terraces of the Sabine and Red Rivers (Alford and Holmes, 1985; Frye and Leonard, 1963), and on old terraces along the major rivers of this broad region (e.g., Red, Trinity, Neches, Sabine, Calcasieu, Mermentau, Arkansas, Saline, Little, Tensas, Ouachita, White, and Mississippi). Mounds are absent, as predicted, on floodplains of all these big rivers, at least those that overbank most years (most burrowing animals do not survive deep annual floods).

Figure 3 shows a comparison of LIDAR coverage matched with the best airphoto coverage in the Historical Imagery application of Google Earth. The images clearly demonstrate that LIDAR is unmatched in its effectiveness for identifying mounds in forested areas.

SOME BIOGENIC PRINCIPLES OF SOIL MOUND FORMATION

Expanded DSC Model of Soil Mound Formation

The Dalquest-Scheffer-Cox (DSC) model, which embeds biogenesis as its central concept, is that soil animals—those that spend part of their lives burrowing and living in soil or

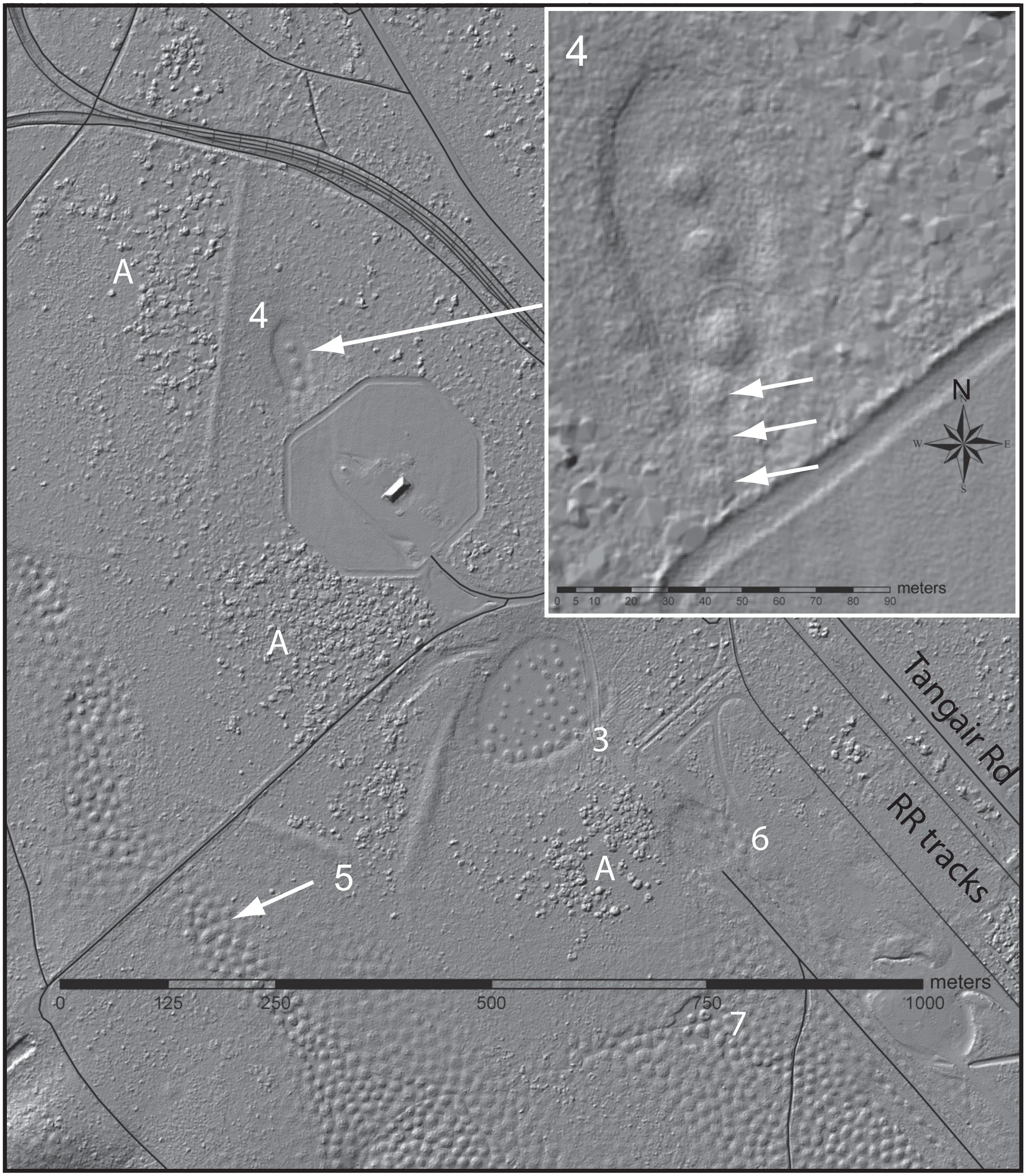

Figure 2. LIDAR imagery reveals a multitude of Mima-type mounds in sharp detail on Burton Mesa, a broad uplifted early Pleistocene and duripan-armored marine terrace, Vandenberg Air Force Base, California. LIDAR imagery helped expand the number of known mounded tracts on the base by several orders of magnitude. Burrowing animals, primarily the Botta pocket gopher (*T. bottae*), are predominantly responsible for producing the mounds, aided by local soil, slope, and runoff conditions and processes. As predicted by the expanded DSC model, mounds form where the biomantle is thin (<1 m) above a dense substrate, in this case silica-cemented hardpan. See text for explanation of numbered and lettered sites. LIDAR courtesy of James Carucci and Environmental Group, Vandenberg Air Force Base, Vandenberg, California.

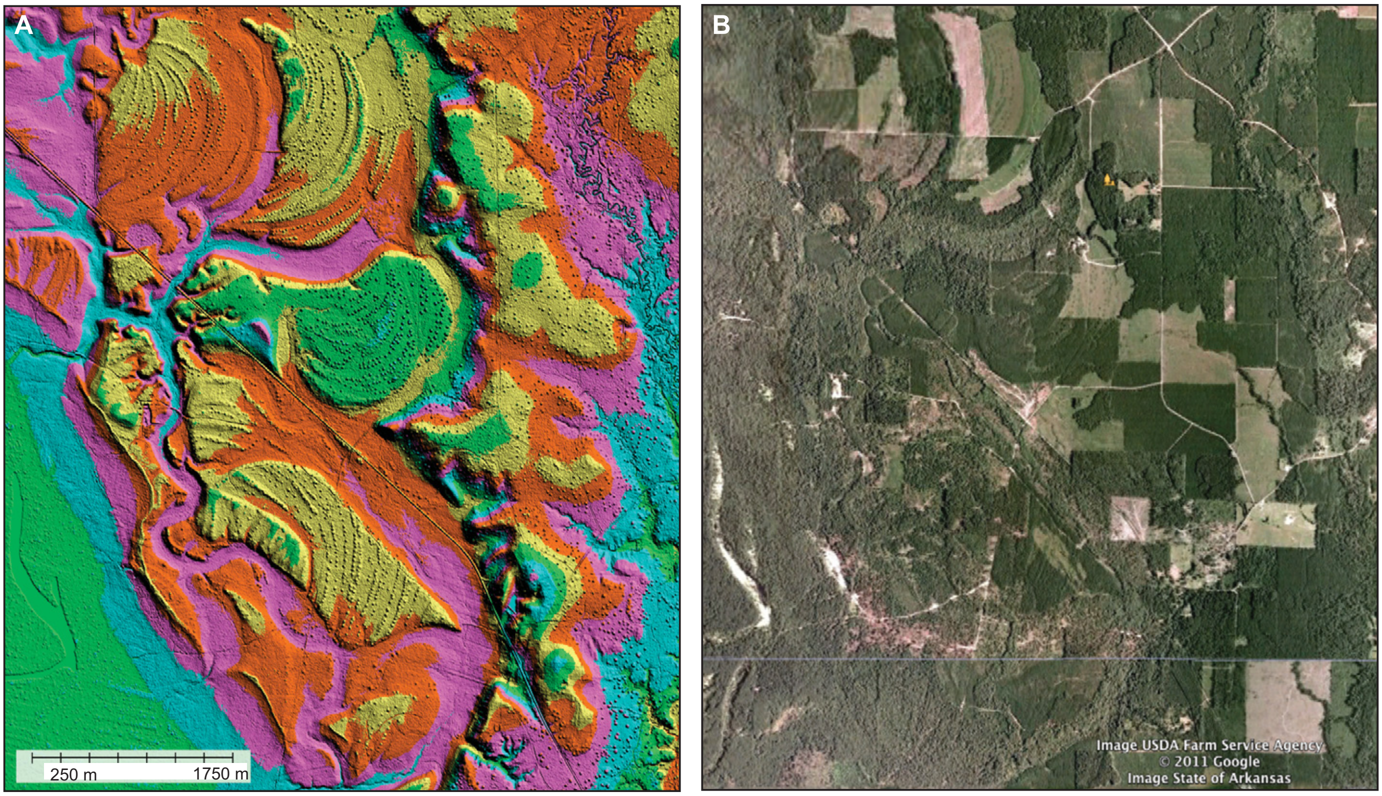

Figure 3. LIDAR image (A) and Google Earth airphoto (B) of the same semiforested border region of Ashley County, Arkansas, and Morehouse Parish, Louisiana. Image center-point is 33° 01′ 42″ N, 92° 00′ 53″ W, ~28 m elevation. The region is the lower confluence area of Saline and Ouachita Rivers. The Ouachita floodplain, on left side of images, ~20 m elevation, lacks mounds because of frequent "big river" overbank flooding. Mima-type (pimple, hybrid) "fixed" mounds occupy the higher and drier spots of very low-relief meander scrolls on two low terraces, at 25 and 28 m, of late Pleistocene Deweyville Allogroup. Mounds are arrayed in arcuate paternoster patterns, like festooned "beads on a necklace." But, on much older and higher ground nearby to the east, they are seemingly randomly distributed in a nearest-neighbor–like pattern. Mounds also dot higher spots of the small stream basin on the right side of images. These high spots afford greater survival opportunities against wetness for animals that live on them, which leads to mound formation. LIDAR courtesy Paul V. Heinrich, Louisiana Geological Survey, Baton Rouge, Louisiana. *Note:* Each color contour increases 1.524 m (5 ft) elevation; e.g., green = 20 m, blue = 21.524 m, purple = 23.048 m, etc.

sediment, which actually includes most animals—invariably establish activity centers for living, specifically for nesting-reproduction, burrowing, denning, food storage, overwintering, estivation, hibernation, and or safety. Any outward burrowing from these centers must include a lateral component where some amount of soil is centripetally back-transferred to the center (see Centripetal "Law" of Soil Movement to Animal Mounds, next section).

The *expanded* DSC model includes the proviso that all other soil-geomorphic processes, such as water-wind erosions, eolian infall, vegetation growth, mass wasting, shrink-swell, freeze-thaw, earthquakes, and other processes that can impact any landscape may, proportionately, also impact mounds, while they form, after they have formed, and while they are wasting. The collective processes, fast-forwarded, create the complex of soil mounds and mounded landscapes we observe today. DSC processes dominate over all others in low slope, level, or nearly level landscape positions.

Centripetal "Law" of Soil Movement to Animal Mounds

When animals burrow in soil or sediment in establishing activity (nesting) centers, which ultimately leads to mound formation, burrowing is never always vertically straight downward. There is invariably a lateral or centripetal component in burrowing from any nesting center. The nature of mound making would logically involve the slow radial and centripetal-lateral movement of some soil to activity centers from below and surrounding areas. The massive and robust termite and ant mounds that dot the tropics and subtropics, and their smaller mid-latitude equivalents, must be partly, if not largely, composed of such soil, mined and biotransferred from surrounding areas. The same must be true of those animals that play roles in producing Mima mounds in North America, most especially pocket gophers, and to some extent ground squirrels and prairie dogs, but also especially town ants (*A. texana*). Hence, areas surrounding some animal mounds must be topographically slightly lower, and thus wetter. Where

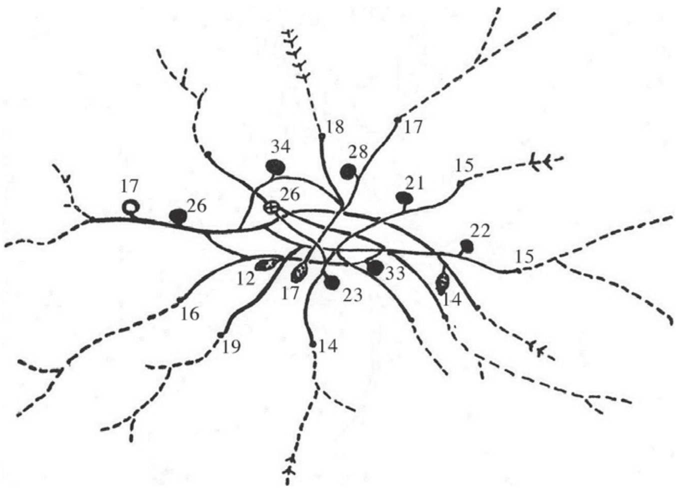

Figure 4. Plan view of pocket gopher (*T. talpoides*) reproductive–food-storage–living center that has outward radiating forage tunnels. (Original diagram unscaled but ~3 m in diameter is a reasonable estimate.) Rounded projections are nests; the one with the cross had three young; those in black were abandoned. Ovate projections, cross hatched, are food-storage chambers. (Defecation chambers not illustrated.) Numbers denote depths (inches) at which features were found (after Criddle, 1930).

Mima mounds are directly associated with, and genetically linked to, vernal pools, this fact becomes obvious. The process in this case is more or less as Price (1949) had described.

Basal Concavities of Some Soil Mounds, and Breaks and/or Depressions in Subsoils of Others

Dalquest and Scheffer (1942) noted that mounds near Olympia, Washington, commonly display concave bases in soil profile (see cover photo). Other workers have noted similar basal concavities (Holliday, 1987), including breaks or holes in hardpans and claypans into subjacent soil parent materials. The concavity, hole, or break—"dimples" as Price called them—often are found below the thickest part of the mound (cf. Nikiforoff, 1941; Retzer, 1946; Price, 1949; Arkley and Brown, 1954). Such features would be expected, if not almost predicted, by mounds predominantly made by burrowing animals. In the case of hardpan holes, it suggests that the animals were present, and bioturbation active, when the hardpans initially began developing and during subsequent formation. It also suggests that activity centers were established during early stages of soil formation, and that bioturbation rates were consistently greater than, or at least as great as, rates of pan formation.

The Principal Mound-Making Animals of North America

The five principle mound-making animals are: pocket gophers, which comprise some 40 species; kangaroo rats (k-rats) with some 21 species; ground squirrels and prairie dogs, with ~40 species; one notable ant, the Town ant (*Atta texana*) of Texas and Louisiana; and the American badger. Here, of necessity, we selectively focus on the two that most link to Mima mound formation: pocket gophers and k-rats. A brief sketch is also provided on the role of badgers, tremendous soil movers and mound-makers in their own right. The focus draws on the literature, and the coeditors' personal observations.

As a prefatory comment, it is instructive to emphasize, strongly, that of the main mound-makers in North America, pocket gophers and k-rats are behaviorally *cryptic*—respectively fossorial and nocturnal—hence rarely if ever observed on, or visually associated with, their mounds. Seldom seen badgers, to a large extent, fall into this category. Uncertainties about who made the mounds invariably arise. Conversely, ground squirrels, prairie dogs, and Town (Atta) ants are *noncryptic*, and thus commonly observed on their mounds, or seen to be immediately associated with them. Hence, observers normally do not question who made such mounds. We submit that these cryptic, noncryptic issues have historically and fundamentally significantly blurred our perceptions of Mima mound genesis in North America. They have, we believe, played a major role in shaping the genetic controversy surrounding the subject.

Pocket Gophers

Information on pocket gopher burrowing is deep and extensive, but two papers that graphically convey burrowing particulars are instructive. Figure 4 is a plan view of a gopher activity center excavated by hand on 14 June 1927 in Manitoba, Canada. The activity center is, of course, the central area of bioturbation. The continuous lines are deep open tunnels; dashed lines are foraging tunnels, some plugged, others extending out unseen into surrounding food-harvesting areas. Every radial foraging event records some soil being back-transferred to the center. The process builds mounds. Because gopher species have short lives, 2–3 years at most, where sites confer living-survival advantages over surrounding areas they become "fixed" and occupied by multiple generations of gophers. Large volume Mima-type mounds can then form.

Figure 5 shows both plan (A) and cross-sectional (B) views of another hand-excavated gopher activity center; with associated forage tunnels (in this case the species, location, and excavation date are unspecified by the author). Here the active nest was tunneled into the subsoil, confirming that this horizon does not limit vertical burrowing. It also suggests that no particular living advantage is likely conferred at this site over any other in this soil. While information is lacking to say for certain, it is possible that the very low, shield-like mound that is forming above the activity center in B will not grow into a much larger mound, and that it is likely a Mima-like mound, and thus will be ephemeral. If it does grow, the site must offer some living-survival advantage, and the biomantle will become locally thickened at the expense of the subsoil, and likely surrounding soil, and thus become a fixed point-centered biomantle (cf. Johnson et al., 2003). (Aristotle's postulate might be pondered here.)

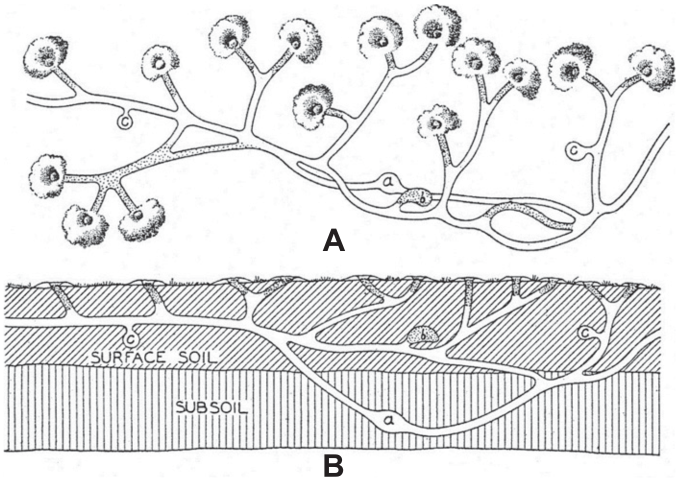

Figure 5. Plan view (A) and cross section (B) of a pocket gopher reproductive–food-storage center with lateral forage tunnels (original diagram unscaled). Surface soil is the biomantle. Symbols: a—active nest chamber; b—abandoned soil-filled nest; c—food-storage chambers (after Crouch, 1933).

Figure 6. Photo of a Mima-like mound "precinct," with multiple ~10-cm-diameter entrance holes, produced by one banner-tailed kangaroo rat (k-rat; *D. spectabilis*) on north side right-of-way of U.S. Highway 60, ~40 km west of Socorro, New Mexico. Many widely distributed k-rat mounds dot the broad, low-slope alluvial fans here that emanate from the Magdalena Mountains. Mounds, which can reach 1+ m high and up to 5+ m in diameter, are built over several years by individual k-rats, normally one animal per mound, except during breeding season. Photo courtesy D.N. Johnson.

Kangaroo Rats

Best (1972) recorded stages in the formation of two "characteristic" banner-tailed kangaroo rat, or k-rat (*D. spectabilis*), mounds in New Mexico, by two adults. One mound was formed in disturbed soil, and the other in undisturbed pastureland. In the disturbed soil, a circular mound 3.1 m in diameter and 36 cm high was developed in 23 months. In the pastureland, an ovate mound 3.7 by 2.2 m in diameter and 41 cm high formed in 30 months. An average of 3–5 entrance holes appeared in the mounds during their constructions. Each mound was constructed and inhabited by one adult k-rat, a male and a female. Figure 6 is an example of a mound built by this species, also in New Mexico.

Best's study shows the rapidity with which this species can create mounds. There are 20 other species of k-rats, and each has its own burrowing/mound-making behaviors and styles. One k-rat, the largest, may possibly challenge the pocket gopher for honors in mound-making propensities and speed, as demonstrated in the Carrizo Plain region of California.

American Badgers

The American badger, *Taxidea taxus*, is a major bioturbator of North American soils and Mima mounds in essentially *every* moundfield that co-editors and several contributors have examined—wherever rodents, a major prey of badgers, live. Ironically, badgers are notably absent, at least presently, in the one region considered by some to be the Mima mound type locality—the Olympia, Washington area (cover photos). As mentioned, the badger is also a major mound-maker in its own right.

Co-editor Johnson was introduced to the tremendous soil volumes, and large cobbles and boulders, that are regularly bioturbated and moved about by this animal while engaged in landscape evolution studies in the Tularosa Basin-Otero Mesa regions of southern New Mexico and West Texas (Johnson, 1997, 1999). This chief predator of rodents, most notably pocket gophers and ground squirrels, has impacted many, if not most, Saskatchewan mounds discussed by the Chapter 2 authors (Irvine and Dale, this volume). Badgers doubtless have done likewise to most moundfields discussed in other chapters. Some idea of soil volumes bioturbated and moved by this superburrower while rodent foraging, which could be anywhere in western North America, are summarized for a part of Idaho by Eldridge (2004):

> In the western United States, American badgers (*Taxidea taxus*) excavate large volumes of soil and create fan-shaped mounds while foraging for fossorial rodents. Densities of 790 mounds/ha were recorded on the Snake River Plain, west-central Idaho. . . . Mounds and diggings occupied an average of 5–8% of the landscape and the mass of mounded soil averaged 33.8 kg, equivalent to 26 t/ha. The surface cover of plants, cryptogams, and litter increased, and bare ground decreased, as mounds aged. Excavation holes were present at 96% of active and crusted mounds compared with 31% of older recovering mounds. Sites with a greater density of shrubs tended to have a greater density of both badger mounds and ground squirrel diggings. Additionally, increased density of badger mounds was associated with increases in the density of ground squirrel holes and scratchings. These results indicate that badger mounds are a significant landscape structure and that badger activity is likely to have major impacts on soil and ecosystem processes. . . .

Figure 7 shows a badger, with his burrow and tailings, caught in the act of either (1) co-opting a Mima-type mound for making a den (called a "sett"); or (2) preying on the rodent (gopher) occupant of the mound; or (3) perhaps both. The chief badger

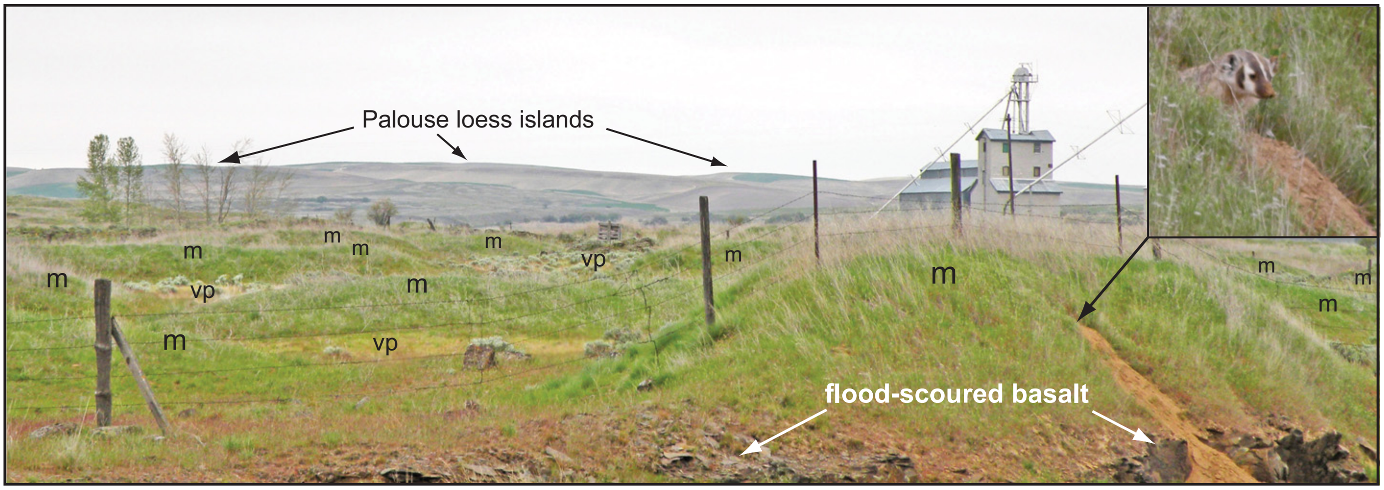

Figure 7. Photo of Mima-type moundfield developed in thin, loess-ash-rich soil above Missoula flood-scoured basalt in Channeled Scablands, Whitman County, Washington. Letter m's identify mounds, and vp's identify intermound swales-vernal pools. The photo of badger (inset) peering from mound on right was taken immediately after the first. Both photos courtesy D.N. Johnson.

prey here is the abundant Northern pocket gopher (*T. talpoides*), a major mound-maker widespread across the Pacific Northwest region (cf. Johnson and Johnson, this volume).

Rapidity with Which Mounds Form and Re-Form

Figure 8 is a photo looking east from the northbound shoulder of Interstate-5 north of Weed, California taken shortly after snowmelt. It displays many principles of the expanded DSC model. Mima-type mounds here, most dotted with abundant fresh and old gopher heaps, are formed in thin soil over hardpan—a duripan, an effective aquiclude developed on glacial outwash. Intermound pools form in very low slope areas where mounds interfere with surface run-off. Mounds are in quasi-dynamic denudation equilibrium, where any erosional removals (negligible) are offset by biogenic mound formation, or in this case re-formation (Johnson et al., 2011). The farm road over which mounds have re-formed was bulldozed sometime after 1928, the date when bulldozers were invented, and before being used as a footpath. The road fell into disuse when blocked by I-5 construction in 1965, and the mounds have re-formed in the 47 years since. Another instance where mounds re-formed over a road, "an old wagon trail," is near Boulder, Colorado, as noted by Branson et al. (1965, p. 318; cf. also Murray, 1967).

The rapidity (decades) with which Mima mounds can be formed by pocket gophers has been documented by a number of workers (e.g., Koons, 1926, 1948; Brown, *in* Arkley and Brown, 1954, p. 197; Johnson et al., 1999). Personal observations have documented mounds having formed recently, and still forming, along a number of highway right-of-ways. Examples are on both

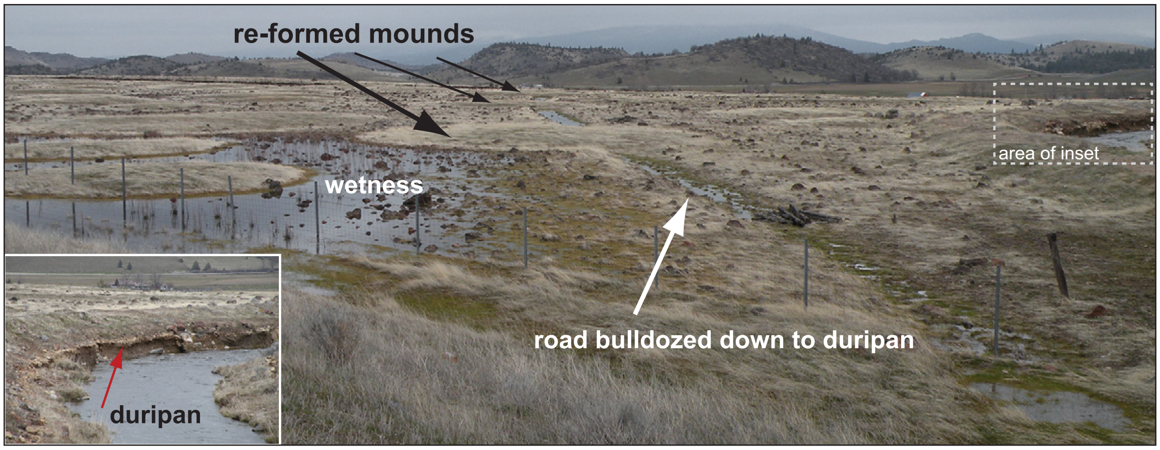

Figure 8. Shasta Valley, Siskiyou County, California. The ranch road, bulldozed down to the duripan sometime after 1928 and used into the 1960s, fell into disuse when construction of Interstate-5 blocked it in 1965. Mounds have re-formed in the ensuing 47 years (black arrows). Inset shows close-up of duripan developed in glacial outwash, exposed in a diversion ditch. Photo courtesy D.N. Johnson, taken early March 2011.

sides of U.S. Highway 287, near Tie Siding on the Sherman Peneplain, Albany County, Wyoming, and the east side of California State Highway 139, ~7 km north of Canby on the Modoc Plateau, Modoc County, California (cf. Johnson et al., 2011). And of course, innumerable hybrid mounds are documented as having formed historically (references cited in "Hybrid Mima Mounds" section above).

San Luis Obispo County, California, is home of the Carrizo Plain National Monument, and to hundreds of thousands, if not millions, of Mima mounds, produced primarily by burrowing rodents, perhaps augmented by badgers and other rodent predators. The Carrizo Plain comprises a northwest-southeast structural basin created by the San Andreas Fault, which occupies its eastern side. The Monument consists of 101,000 ha (250,000 acres) of mounded terrain, but mounds occupy a far greater area than the Monument per se. The landscape, and the multitude of burrowing animals that occupy it, are a collective window into what much of the entire western side of the San Joaquin Valley and adjacent Coast Range hills and ridges were like before intensive agriculture, grazing, and oil extractions began (Braun, 1985; Williams, 1992). For those who wonder how rapidly Mima mounds can form by burrowing animals, the Carrizo Plain is the place to learn.

Figure 9 consists of photographs of mounds that formed since the 1980s, prior to which the fields were under cultivation. Mounds here are commonly 7–12 m in diameter, range between 20 and 50 cm in height, and, depending on location, have densities between 45 and 60 ha. Variation from these values, however, can vary considerably depending on location (Braun, 1985). The mounds are formed on broad, low slope alluvial fans that emanate from surrounding mountains. But they also have formed on many other geomorphic surfaces and soils of the surrounding hillslopes, including the adjoining Elkhorn Plain, and slopes of the Temblor Range to the east and south. The mounds, called "precincts" by kangaroo rat specialists, are the self-made activity centers of k-rats, other burrowing rodents (Wallace, 1991), their commensals, and their predators.

The principal mound-makers are kangaroo rats (several species) and pocket gophers, and of these the endangered giant kangaroo rat or GKR (*Dipodomys ingens*) plays a major role. Its main presettlement distribution was over much of the western San Joaquin Valley and adjacent Coast Range hills and slopes, where it is now nearly extirpated. It presently occupies only 2% of its historic range (Prugh and Brashares, 2011). Except during breeding season, each mound is normally occupied by one adult, male or female (cf. Williams and Kilburn, 1991; L.R. Prugh, 2011–2012, personal commun.). Because GKR longevity is 2–4 years, like pocket gophers, many generations must be involved in making and maintaining mounds.

Some Key Biomantle Principles of Soil Bioturbation

Figure 10 summarizes in a tabular and organized fashion what happens, other things equal, when different soil animals bioturbationally operate on soils and substrates that have different textures and particle sizes. Biomantle principles explain why most mounds in the Mississippi Valley and Gulf Coast that are formed in fine materials (Aronow, 1963, 1968, 1976, 1978, 1988) will result in profiles like 3 and 6 (bottom), regardless of bioturbator type. The profiles are biogenically unsorted (i.e., *nonbiostratified*) because the mixture of clast sizes required for sorting is absent.

The principles also explain why gravelly mounds in southwest Missouri (Chapter 4), in Minnesota (Chapter 5), parts of California (Chapters 1 and 6), and in much of the Pacific Northwest (Chapters 4 and 6), which formed in gravelly materials bioturbated by animals such as pocket gophers and moles, result in profiles like 2 and 5. Any stones larger than the animals can move through their burrows settle downward to the base of the biomantle, which is the main zone of bioturbation. Such profiles and mounds invariably display basal stone layers, with walnut-sized and smaller pebbles scattered throughout. These profiles are biogenically sorted, and hence biostratified (cf. Johnson et al., 2002, 2008).

If, on the other hand, mounds form in gravelly soils where the dominant bioturbators are very small, like ants, termites, and or worms, the resulting profiles will resemble 1 or 4. These again are profiles and mounds that have basal stone layers, but lack pebbles or coarse fraction in the upper profile (beyond a few bird gastroliths, which eventually migrate to the stone layer). These profiles likewise are biogenically sorted (biostratified).

What Figure 10 does not display, however, are two other closely related and important biomantle principles. The first is that all bioturbated, biomixed, and biosorted particles (bottom row) will be slightly smaller in size due to *particle comminution*, the grain-to-grain grinding and abrasion that occurs during bioturbation, and in the case of earthworms and other soil organisms, during "ingestion comminution." The second principle, articulated by James Thorp many years ago (Soil Survey Staff, 1975, p. 21) is that whenever loose soil is bioturbationally heaped onto the surface and exposed to rainwash and or snowmelt, the finer particles are washed away—elutriated, which imparts a coarser texture to the surface.

Biomantle processes have operated geologically since burrowing life forms first evolved, likely in the pre-Cambrian. Understanding what they do on landscapes today will help us infer what they did in the past, and more accurately interpret the geologic record.

AN UPDATED MIMA MOUND MAP OF NORTH AMERICA

Mima-like mounds, and smaller bioturbational heaps and spoil that resemble them, were once ubiquitous over North America (light-colored areas of Fig. 11), and still are in uncultivated lands. With exceptions in Illinois and Wisconsin, Mima-type mounds (dark brown color) are unknown east of the Mississippi River. Shaded zones of Figure 11 indicate a transition between the two mound types. Note the abrupt boundary along the central-lower Mississippi River, coincident with eastern faunal limits of two major mound-makers, *Atta texana* and *Geomys bursarius*. Inset map of California Channel Islands shows Mima-like mounds

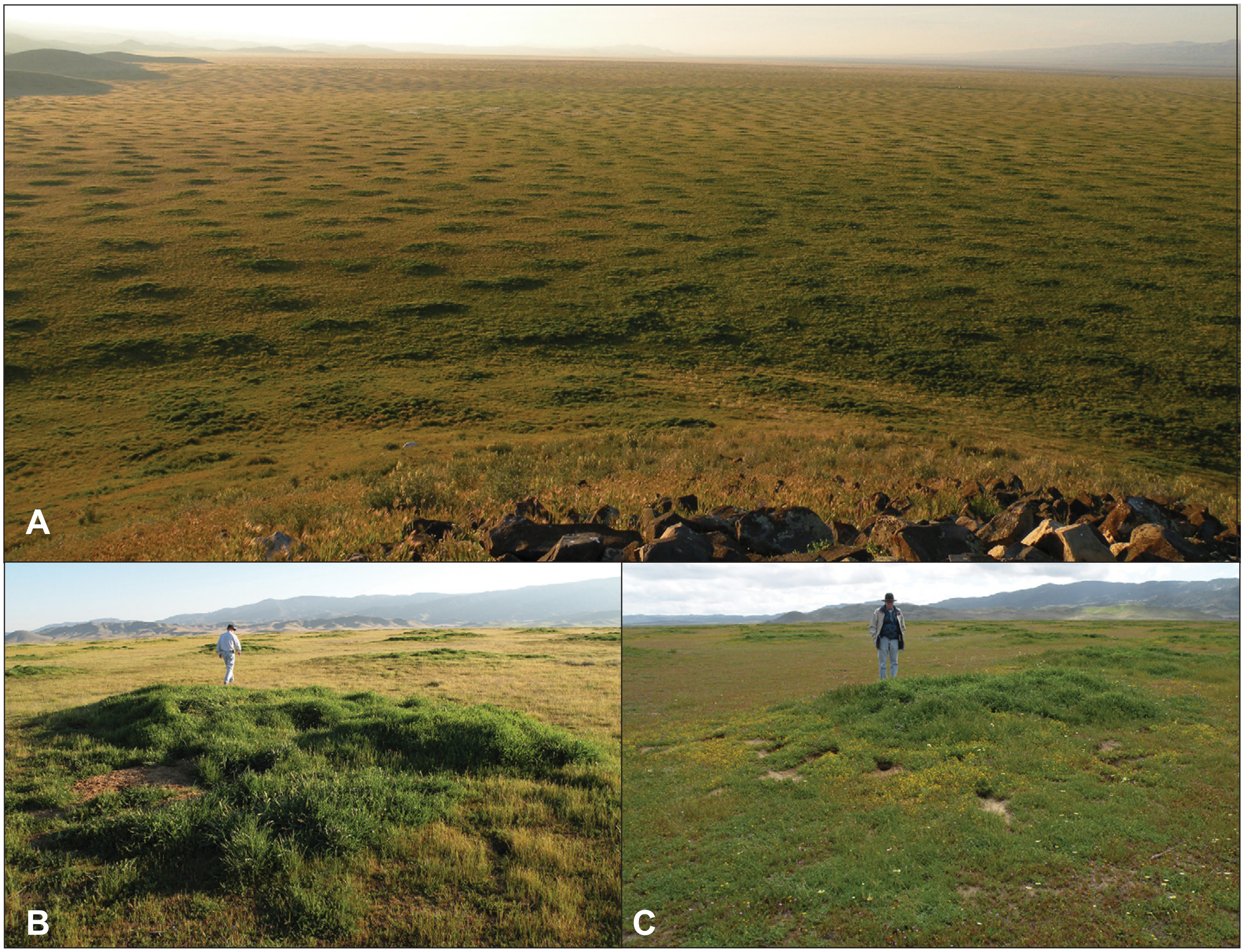

Figure 9. New Mima mounds that have historically "sprouted" on land cultivated into the 1970s and 1980s, Carrizo Plain National Monument, San Luis Obispo County, California. Photo A: taken from the summit of a small basalt-capped conical hill off Soda Lake Road, the main northwest-southeast road in the monument. View is to the northwest. The giant kangaroo rat, GKR (*Dipodomys ingens*), is primarily implicated in producing and maintaining many or most mounds, called "precincts." But, some mounds are co-inhabited, and thus co-produced and co-maintained, by Botta pocket gophers (*T. bottae*). Photos B and C taken along Soda Lake Road several kilometers north of conical hill. Views are southwest, with Caliente Range in the distance. Mounds are roughly circular shaped and have irregular perimeters, and uneven bumpy surfaces that resemble large grass-covered soil heaps. Photo B displays fresh bioturbated pocket gopher heaps; mound in photo C shows multiple "comet-like" GKR entrances, invariably sprinkled with fecal pellets. Photos courtesy D.N. Johnson.

(tan color) on one single island, Santa Catalina—the only one inhabited by a fossorial rodent (*Spermophilus beecheyi nesioticus*; cf. Johnson and Johnson, 2010). Map is based on the historical record (literature) and on the personal multidecadal observations of volume contributors D.L. and D.N. Johnson.

THE DEEP, EXTENSIVE, AND UNEVEN SOIL MOUND LITERATURE

Aronow (1978, 1988) lamented, understandably—as have others, on the vastness and confusing nature of the literature on Mima-prairie mounds. Price (1950, p. 359) in apparent frustration said: "Many writers have evidently written as though the mounds were a mere scientific curiosity and have treated them lightly, rushing to give a 'solution' on the basis of hearsay, examination of photographs, or external examination of mounds in the field." Readers who examine this deep and uneven literature might agree.

Rather than comprehensively review this extensive body, which would be painstaking, tedious, and require much space, assembled selections have been included in Appendices C–F. Together with chapter references, the appendices give readers a large selection of the diverse and deep Mima-pimple-prairie-natural-soil mound literature.

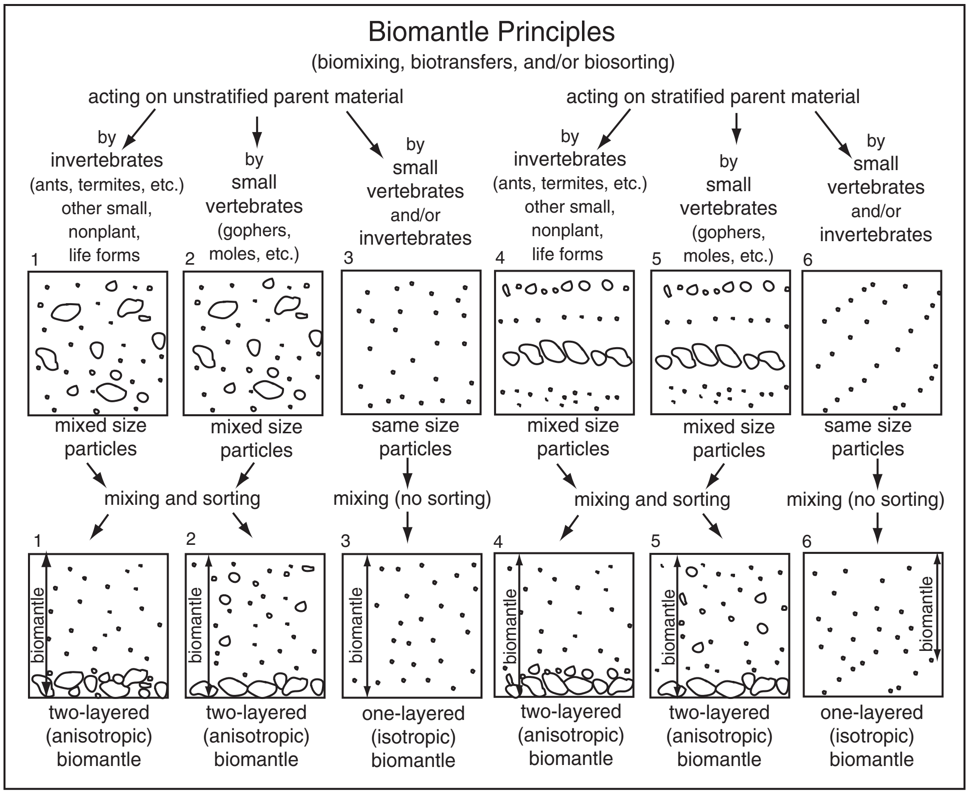

Figure 10. The "key biomantle principles" diagram, which shows the relationships between soil particle sizes and stratified sediments, and types, kinds, and sizes of bioturbators, and predicted textural profiles of soils and soil mounds after bioturbation over some period of time (see text for discussion).

APPENDICES

There are six end-volume appendices. Appendix A consists of a "patterned ground" paper that was mainly about Mima mounds written in the 1960s by geologist Roald H. Fryxell, which, while never published was nevertheless widely circulated and cited by various Pacific Northwest mound researchers (Fryxell, 1964). Appendix B consists of lengthy excerpts of Mima mound papers written nearly a century earlier in the 1870s, by geologists Joseph LeConte and Grove Karl Gilbert (LeConte, 1874, 1875, 1877; Gilbert, 1875). All three distinguished scientists by dint of their persuasive personalities, and their writings, played key and important roles in establishing different strands of genetic thought about the origin of Mima mounds.

Appendix C is an alphabetized selection of the profusion of names and synonyms that have been used to describe Mima mounds. In this regard, every name carries a concept, and thus a message to the reader. It is assumed that the multitude of names and synonyms used to describe mounded landscapes has played a role in creating an aura of confusion and uncertainty that has surrounded Mima mounds. The list provides interested readers access to a wide author-identified sampling of mound literature.

Appendix D is a timeline selection of a wide range of key mound papers, with a synopsis of the author's view or theory on how mounds form, or have formed. The list is expanded and updated from one in Huss (1994). Many of the papers focus on specific areas, but others are more broadly regional or general. If the author(s) is (are) uncertain as to genesis, uncertainty is indicated. The purpose of the list is to recapitulate the key mound literature in a concise, coherent, and tabular way, but still convey to readers the diversity of genetic views on mound origins which have contributed to the controversy surrounding Mima mounds. As in Appendix C, it also provides readers access to the genetic literature.

Appendix E lists references cited in Appendices C and D. It is not a complete list of mound- related papers, but it is substantial.

Appendix F is an alphabetical list of masters' and doctoral theses produced in North America, at least those of which the editors are aware. There are 48 entries, 34 masters' and 14 doctoral theses. Because the subject is a popular theme for graduate study and likely will remain so, each entry identifies author, date, thesis title, thesis granting institution, each students' major advisor, and a précis of major points and or conclusions drawn. The purpose is to alert readers, especially students and their advisors, to most of the mound-linked and mound-focused theses that exist to date on the subject.

LAST WORDS

The contributors to this volume, plus those whose works and views are highlighted in the appendices—like scientists generally—execute research by means of preferred philosophies, world views, methodologies, research strategies, and explanatory frameworks, the contemplated usefulness of each must vary

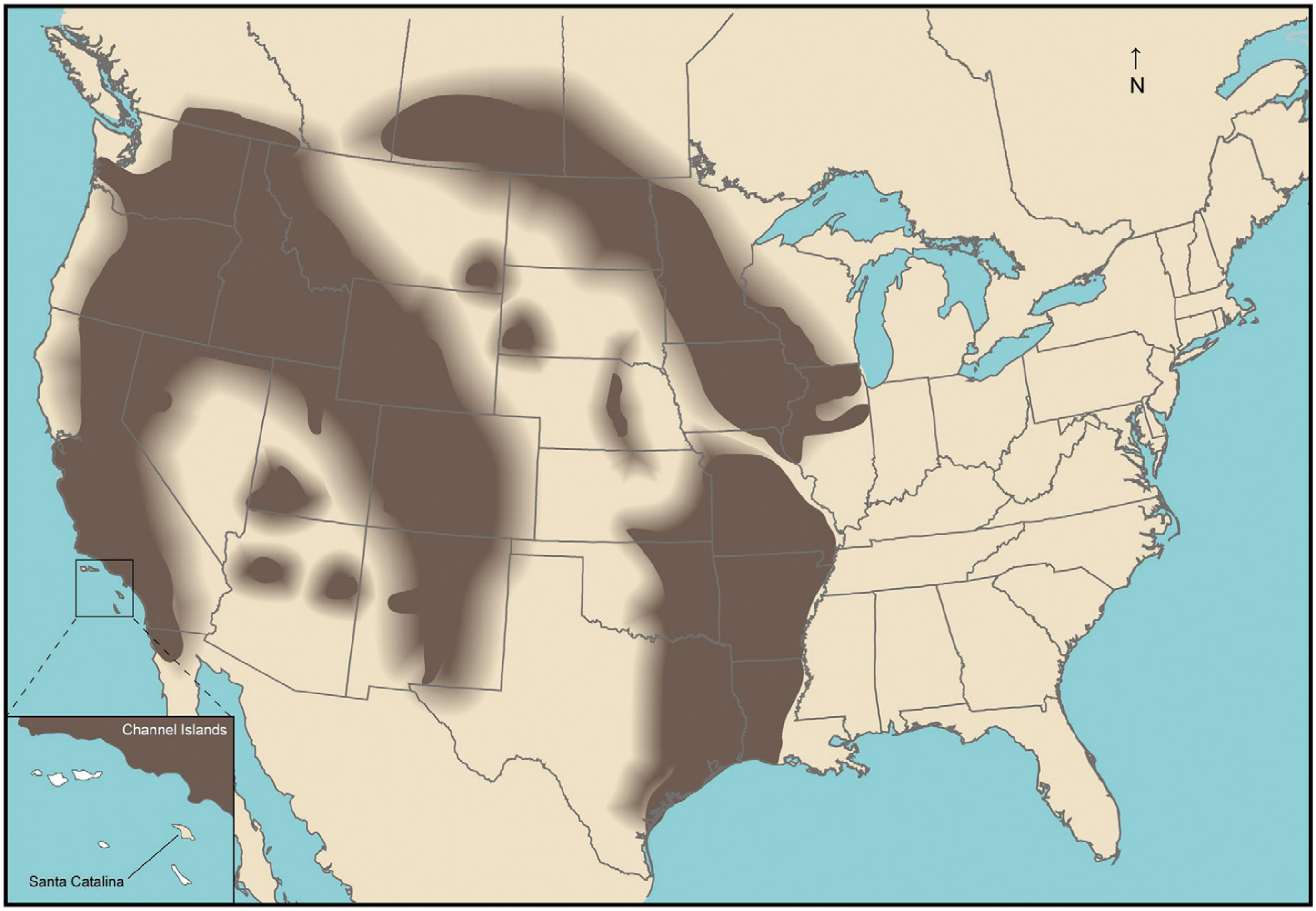

Figure 11. Generalized map of Mima mound distributions in North America. Dark brown denotes areas where *fixed activity centers*, or *Mima-type mounds*, are known to be present and/or commonly found. Light color denotes areas where *unfixed activity centers*, or *Mima-like mounds*, are either present and/or commonly found. Neither mound type is exclusive to its mapped area. (Notably, unlike Santa Catalina, on which mound-makers [ground squirrels] and Mima-like mounds both occur, other California Channel Islands lack mound-makers, and thus—predictively—mounds.) Updated from maps in Washburn (1988), Cox (1984), Price (1949), from personal experience, and from information contained in this volume. (See text for discussion.)

between us all. Such research diversity is partly what moves science forward. Approaches employed and/or formulated by contributors to this volume will, we confidently predict, expand and strengthen our explanatory paradigm in the interconnected fields of archaeology, ecology, geomorphology, soils, and earth surface process studies.

But, will the views, arguments, and evidence assembled in this volume put to rest the long controversy that has swirled around the subject? For some, probably not, but for others it might, and for them, if it does " . . . it will stop a great amount of conjecture and give rest to puzzled brains, for every person who sees such land wonders how it ever got that way" (Whitney, 1921).

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