Effects of Pocket Gopher Burrowing on Archaeological Deposits: A Simulation Approach

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The construction of burrows and movement of sediment by pocket gophers alter archaeological deposits by causing vertical size-sorting of artifacts, destruction of fragile artifacts, disruption of sedimentary structures, and organic enrichment of the subsurface. To evaluate the long-term effects of exposure to burrowing, a simulation was developed based on quantitative information on pocket gopher burrows and rates of sediment movement. Simulation results indicate the development of a distinct stone zone composed predominantly of particles greater than 6 cm after 4000–5000 years, and a logarithmic pattern to the rate of strata disruption. The patterns produced by the simulation compare well with patterns exhibited by actual archaeological deposits belonging to California's Milling Stone Horizon. These results suggest that current notions concerning the Milling Stone Horizon and other aspects of California prehistory may require revision, and that more emphasis must be placed on formation process research in such settings.

INTRODUCTION

Over the past two decades, studies of the processes that affect the form and position of artifacts have occupied an increasingly prominent role in archaeology (Binford, 1981; Schiffer, 1972, 1987). Recognition and control of post-depositional processes that alter or disturb the archaeological record have received the greatest attention (Nash and Petraglia, 1987; Wood and Johnson, 1978). However, it is frequently difficult to identify and unravel the processes responsible for patterns and variation observed in the archaeological record. As a result, we often lack the ability to recognize reliably the nature and extent of disturbance of archaeological deposits, and, thus, the knowledge necessary to minimize the effects of these impacts on our understanding of prehistory. A study of the effects of pocket gopher burrowing on archaeological deposits in California provides an example of this problem and how it may be resolved.

Recent research indicates that extensive pocket gopher burrowing may have substantially altered numerous archaeological deposits in California. Several studies demonstrate the potential for vertical mixing and size-sorting of artifacts and soil particles by pocket gophers (Bocek, 1986; Erlandson, 1984; Erlandson and Rockwell, 1987; Johnson, 1989; Pierce, 1982; Wood and Johnson, 1978). Some (Johnson, 1989; Pierce, 1988) suggest that archaeological patterns attributed to different cultural processes may have resulted instead from the

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cumulative action of pocket gophers over time. However, none of these studies provides a model of pocket gopher disturbance with sufficient detail to allow prediction of long-term effects. This paper presents a general, partly quantitative model of disturbance by pocket gopher burrowing. The model is based on patterns of sediment movement and burrow structure documented through studies of living pocket gopher (*Thomomys* sp.) communities. Quantitative portions of the model are translated into a computer simulation to evaluate the long-term effects of burrowing on vertical distributions of artifacts and stratigraphic integrity. Simulation results are compared to data from heavily burrowed archaeological deposits to assess the validity of the simulation.

The model and simulation produce patterns of vertical size-sorting, stratigraphic mixing, and destruction of fragile remains comparable to those found in actual archaeological deposits. In fact, many of the characteristics of archaeological deposits assigned to the Milling Stone Horizon (Moratto, 1984; Wallace, 1955, 1978) in southern and central California match those generated by pocket gopher burrowing. The model allows formulation of specific expectations regarding artifact distributions, assemblage content, and stratigraphic integrity in deposits from various contexts and ages. These expectations demonstrate the utility of computer simulation for understanding archaeological formation processes. Furthermore, the results have implications for how we record, interpret, and report the archaeological record. Currently, inconsistencies in describing the archaeological record and failure to treat the record as a product of geological processes severely limit our ability to gain accurate knowledge of formation processes and therefore, past cultural systems.

A MODEL OF POCKET GOPHER DISTURBANCE

In California, burrowing rodents constitute over half of the population of all native mammals (Grinnell, 1923:138). Of these rodents, the most abundant as well as the most prodigious burrower is the pocket gopher (*Thomomys* sp.), four species of which live within California (Hall, 1981:454–480). The model presented here derives primarily from information on the burrowing behavior of *Thomomys umbrinus,* the most common pocket gopher in California and the southwestern United States (Hall, 1981:469–475). Debate exists over the accurate taxonomic status of pocket gophers in the southwestern U.S. and northern Mexico. Some argue for two species, *Thomomys bottae* to the north and *T. umbrinus* in the south, while others lump all pocket gophers of this area into one species, *T. umbrinus,* recognizing only subspecific distinctions due to the presence of genetic mixing. In this article, *Thomomys umbrinus* following Hall (1981) is used. In presenting this model of pocket gopher disturbance, I use the term sediment to refer to the particles, including artifacts, moved by burrowing and borrow collapse.

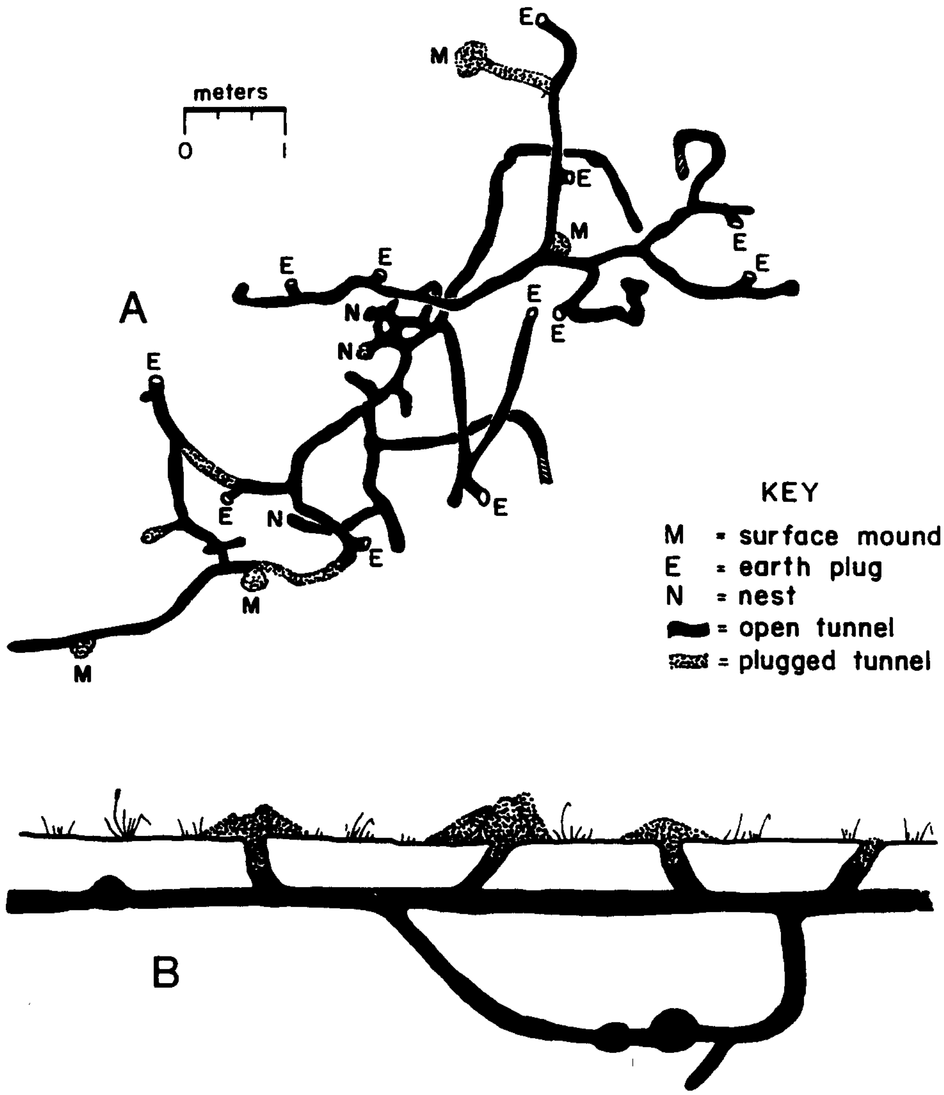

Figure 1. Plan view (A) and vertical section (B) of typical pocket gopher burrow systems (from Miller, 1957 and Hickman, 1977).

Burrows and Burrowing Behavior of *Thomomys umbrinus*

Pocket gophers feed primarily on subsurface plant parts. As a result, pocket gophers spend virtually all of their lives underground. Individual burrows consist of two main parts—tunnels and chambers (Figure 1). Each pocket

Table I. Pocket gopher burrow volume in 10 cm depth intervals.

Depth Interval (cm)	Tunnel Volume[a] (cubic cm)	Chamber Volume[b] (cubic cm)	Total Volume (cubic cm)	Percent Volume
0–10	56,982	0	56,982	5.3
10–20	523,195	156	523,351	48.8
20–30	219,636	966	220,602	20.6
30–40	50,248	6,580	56,828	5.3
40–50	71,486	11,730	83,216	7.8
50–60	68,378	8,690	77,068	7.2
60–70	30,045	7,560	37,605	3.5
70–80	6,732	870	7,602	0.7
80–90	4,146	0	4,146	0.4
90–100	4,146	0	4,146	0.4

[a] Data from Miller, 1957: Figure 4, Table 1.
[b] Data from Miller, 1957: Table 1.

gopher maintains one or more main tunnels excavated within the root zone parallel to the ground surface. These main tunnels can be quite long (up to 90 m), and are segmented by frequent lateral tunnels. The lateral tunnels are used for grazing on roots, and as passages through which loose sediment is taken to the surface. Tunnels average approximately 6.5 cm in diameter, slightly larger than the pocket gopher. Tunnels form the majority of the burrow, occurring primarily between 10 and 30 cm below the surface. Chambers used for nests, food storage and waste disposal and deep, vertical, sump tunnels occur between 40 and 70 cm below the surface in deeper extensions of the main tunnel. These deeper chambers are regularly 15–25 cm in diameter, and located beneath rocks, tree roots, or other objects for protection from predators (Buechner, 1942; Grinnell, 1923; Ingles, 1947; Miller, 1957; Storer, 1933; Storer and Usinger, 1963:339). Although open tunnels occasionally extend as deep as 2 m below the surface (Miller, 1957; Reichman et al., 1982), well over 90% of the average total burrow volume occurs within the upper 70 cm, with most of the volume concentrated in the upper 30 cm (see Table I).

Sediment loosened during burrowing is either periodically expelled from the burrow or transported elsewhere within the burrow to plug old tunnels or chambers. Pocket gophers move most of the loosened sediment to the surface through short, vertical passages opened every few inches along the main tunnel (Grinnell, 1923). The rate of sediment movement to the surface by gophers varies greatly depending primarily on the population density at a given location. Table II presents estimates for the rates of sediment movement by different species of pocket gopher in various contexts and population densities.

Pocket gopher burrows grow by the addition of basic building units consisting of a main burrow segment and its associated lateral branch (Reichman et al., 1982). The individual burrows and burrow communities are highly structured systems that vary in size and spacing according to the size of the individual

Table II. Estimates of the rate of sediment movement to the surface by pocket gophers.

Taxon	Location	Rate (mtons/h/yr)	Population Gophers/h	Source
Thomomys umbrinus	David, CA	95	89	Miller, 1957
	alfalfa field	126	124	Miller, 1957
T. monticola	Huntington L., CA mountain meadow	20	25	Ingles, 1952
T. monticola	Yosemite Natl. Pk.	0.003	?	Grinnell, 1923
T. Talpoides	Logan, UT garden	104	74	Richens, 1966
T. talpoides	Wasatch Plateau, UT	14	10–40	Ellison, 1946
Geomys breviceps	College Station, TX ungrazed grassland	1	?	Buechner, 1942
G. breviceps	College Station, TX overgrazed grassland	19	?	Buechner, 1942

rodents, population size, soil type, and resource productivity (Davis, 1938; Davis et al., 1938; Hansen and Remmenga, 1961; Reichman et al., 1982). In a study of two pocket gopher communities in northern Arizona, Reichman et al. (1982) found that interburrow spacing is quite regular and consistent between the two locations, and that burrow length is inversely related to plant productivity. However, other studies show that burrow size and the density of burrows vary with soil conditions and plant resource productivity (Hansen and Remmenga, 1961; Howard and Childs, 1959). Hansen and Remmenga (1961) also demonstrate that burrow size and spacing vary inversely with burrow density and that burrow density increases with an increase in habitat quality.

Effects of Pocket Gopher Burrowing on Archaeological Deposits

The often rich, friable earth in archaeological middens presents optimal habitats for burrowing rodents. In California, such deposits often support large populations of pocket gophers. Burrowing by pocket gophers may affect archaeological deposits in four ways: (1) displacement or movement of sediment; (2) selective destruction of fragile artifacts such as bone, shell, and charred plant pieces; (3) disruption or obliteration of sedimentary structures; and (4) organic enrichment of the subsurface. The extent to which these processes affect a given archaeological deposit is determined by several interrelated factors including, geomorphic context, rodent population size/burrow density, rate of burrowing by the rodents, and particular cultural and noncultural depositional history.

Movement of Sediment

In the course of excavating their burrows, pocket gophers push loosened sediment into small mounds on the surface or use it to fill other portions of the burrow system. This process results in both vertical and horizontal movement of sediment. Horizontal movement occurs as sediment excavated from one spot is pushed horizontally some distance before it is taken to the surface or left in an old chamber or tunnel. Although horizontal displacement of artifacts may be minimized by the great regularity with which pocket gophers expel sediment onto the surface, it certainly occurs to some unknown degree (Bocek, 1986). Very little information is available concerning the patterns and distances of horizontal transport of sediment by pocket gophers, making this process difficult to systematically model.

In contrast, vertical movement resulting from pocket gopher burrowing is quite well documented, and has been the focus of all archaeological studies of pocket gopher disturbance. Three types of vertical movement are evident. First, gophers transport particles smaller than the diameter of their tunnels during the course of excavating and filling burrow systems (Hansen and Morris, 1968). Most of this excavated material is brought directly to the surface. Second, particles move down through open tunnels or through the collapse of tunnels under the force of gravity and/or moving water. The particles involved in these first two types of vertical movement rarely exceed 6 cm in diameter, and are generally less than 4 cm in diameter (Johnson, 1989). Third, particles larger than the diameter of the tunnels move down in the deposit. As gophers remove sediment from around larger objects, voids are created that eventually collapse under the weight of overlying sediment. The material that moves down during burrow collapse includes particles of all sizes. The larger particles, which the gophers cannot move upward, continue to sink until they reach the bottom of the burrow.

The effects of the vertical movement of sediment by pocket gophers at particular locations depend on several factors. Johnson (1989) identifies the depth of burrowing, rate of burrowing, rate of sediment aggradation, and rate of sediment erosion as important in recognizing the characteristics and amount of time involved in the production of stone zones by pocket gophers. To these can be added the particular history of artifact deposition (continuous vs. discontinuous, short duration vs. long duration), and the size and composition of the artifacts deposited.

Destruction of Fragile Artifacts

Pocket gophers use their powerful jaws and sharp claws to loosen sediment while burrowing. As a result, fragile artifacts such as bone, shell, and charred plant remains may easily be broken. When pocket gophers push the loosened material onto the surface, the fragile remains are subjected to increased weathering by sunlight, extreme temperature and moisture changes, and trampling by large mammals. The combination of these processes can lead to the rapid destruction of such objects, and can also obscure, and perhaps even create wear on the edges of stone artifacts (Behrensmeyer, 1978; Driscoll, 1967, 1970; Gifford, 1980; Gifford-Gonzales et al., 1985; Hare, 1980; Lyman and Fox, 1989; Miller, 1975; Shipman, 1981).

In specific deposits, the tendency for burrowing to destroy artifacts varies with the kinds of artifacts deposited and the rate of deposition. In a deposit containing a variety of floral and faunal remains, weathering associated with burrowing can alter the relative frequencies and vertical distributions of taxa and specific elements due to their differential susceptibility to weathering (Driscoll, 1970; Lyman, 1984). For example, changes in proportions of remains of various shellfish species with depth noted by Bocek (1986) may result from the differential weathering of more fragile mussel versus the more robust horn snail and oyster shells rather than from differential movement as Bocek suggests. In contrast, fragile remains deposited on stable surfaces may be initially protected from intense weathering at the surface by burial with sediment brought to the surface by pocket gophers. Continued burrowing may eventually lead to the destruction of virtually all fragile remains within the zone of burrowing. The amount of time necessary for this destruction is currently unknown since it depends on several factors, such as weathering rates, that are poorly known.

Disruption of Sedimentary Structures

Through excavation of burrows and transportation of sediment, pocket gophers disrupt or obliterate the structure and boundaries of strata and features within archaeological deposits. Strata boundaries and structures contained within at least the upper 70 cm of a deposit are particularly susceptible to the burrowing activities of pocket gophers. The degree to which burrowing disrupts strata in particular deposits depends on several factors including the rate and depth of burrowing, the rate of deposition or erosion at the site, and the extent to which burrowing involves the reuse of existing tunnels rather than the construction of new ones.

Organic Enrichment of Subsurface

Pocket gophers carry organic matter from the surface into their burrows where it is deposited in storage chambers, nests, and abandoned tunnels. In addition, feces are often concentrated in defecation chambers dispersed along the burrow system. Both of these processes lead to the organic enrichment of subsurface deposits. As this material decomposes, the nutrient level of these subsurface zones increases. In addition to the purposeful transport of organic material below the surface, sediments from an organically enriched A horizon or cultural midden can filter downward into lower portions of the burrow through the collapse and filling of tunnels and chambers. Whether this enrichment process produces measurable changes in subsurface zones depends on the original organic content and chemical composition of the zone of accumulation.

SIMULATION OF POCKET GOPHER DISTURBANCE

The qualitative model presented above describes the processes involved when pocket gophers burrow in archaeological deposits. However, from this model alone, it is difficult to appreciate the nature of specific effects over various time intervals. By converting portions of the model into a dynamic, quantitative computer simulation, the effects of burrowing over extended time intervals can be evaluated. Computer simulations have recently been used to assess the time-dependent effects of other post-depositional processes with considerable success (Wandsnider, 1989; Yorston et al., 1990).

Translation of the model into a simulation program involves two steps: (1) the processes to be simulated must be made explicit and quantitative; and (2) specific values for the quantitative portions must be provided. The first step requires that all ambiguities in the model be resolved while the second step furnishes the values to actually run the simulation. At both steps, distortions can be introduced that affect the validity of the simulation or how well the simulation fits the real world (Stanislaw, 1986). These two steps are discussed in detail below so that assumptions and potential distortions can be evaluated.

Step 1: The Simulation Algorithm

There is currently sufficient information to simulate only two aspects of the burrowing effects model—the vertical movement of sediment and the disruption of sedimentary structures. These two processes are controlled by the rate and depth of burrowing and by the rate of deposition and erosion. In addition, the vertical movement of artifacts is controlled by the history of artifact deposition and the sizes of artifacts involved. To translate the model into a simulation program, I make the following assumptions:

1. The rodent population and amount of burrowing is constant through time.
2. The volume of the deposit is constant through time.
3. No artifacts or other sediment are added to the deposit after the initiation of the burrowing simulation (no deposition).
4. No artifacts or other sediment are subtracted from the deposit after the initiation of the burrowing simulation (no erosion).
5. All sediment less than 6 cm in diameter excavated during burrowing are moved to the surface of the deposit.
6. Downward movement of sediment of all sizes occurs through the collapse of burrows resulting in their filling with sediment from directly above the collapsed tunnel.
7. Any movement of sediment through burrowing or the collapse of tunnels results in the disruption of any stratification or structure that may have been present in that portion of the deposit.
8. The amount of sediment moved to the surface from a given depth interval is proportionate to the volume of the burrow system in that depth interval and to the total volume of sediment moved to the surface.

The first assumption may not be correct in all situations, but is simple and therefore its impact on the simulation is easily analyzed. The third and fourth assumptions of no deposition or erosion were chosen arbitrarily to simplify the simulation, but limit the applicability of the simulation results to deposits on geologically stable surfaces and in which artifact deposition occurred over short duration relative to the duration of burrowing. The fifth and sixth assumptions specify how pocket gopher burrowing moves sediment. The 6 cm size cutoff for upward movement is based on studies by Johnson (1989) and information on the average size of pocket gopher burrows through which the sediment is carried. Virtually all of the excavated sediment less than 6 cm is either expelled onto the surface or used to fill the lateral grazing tunnels located within the upper portion of the deposit. However, pocket gophers also use a small proportion of the loosened sediment to fill or plug deeper portions of the burrow system. The affect of this violation of assumption 5 on the validity of the simulation cannot be specified exactly, but is probably minimal. Assumption 6 is also a distortion of the model since some particles fall or are carried down by water and fill deeper portions of the burrow. The degree to which downward movement occurs through collapse versus filling probably varies considerably among different kinds of deposits. I chose to limit downward movement to collapse as the most conservative approach. However, since filling by transport through open burrows includes only material smaller than the diameter of the burrows, we can expect that the downward movement of these small particles will, in some cases, be more rapid and exhibit a different pattern than portrayed in this simulation. The eighth assumption drives the simulation by allowing the calculation of burrowing rates for different depth intervals using the equation:

$$\mathrm{PVM} = (\mathrm{PM}) \times (\mathrm{PBV}) \qquad (1)$$

where

PVM = proportion of volume of sediment moved to surface per year per depth interval

PM = a constant derived by dividing the volume of sediment moved to surface per year by the total volume of deposit containing the burrow system

PBV = proportion of total burrow volume at given depth interval

The simulation program monitors the movement of particles greater and less than 6 cm in diameter in 10 cm thick depth intervals from the surface to 1 m below the surface. The simulation runs in 1-year increments. To begin the simulation, the operator enters the initial vertical distributions of the large (>6 cm) and small (<6 cm) particles, the rates of sediment movement per level per year, and the number of years the simulation is to run.

The first procedure in the simulation involves moving small particles from each of the levels in proportion to the burrow volume in each level, and adding this material to the upper most level. This is done by multiplying the volume of particles less than 6 cm in diameter in each level by the rate of sediment movement by pocket gophers (PVM) calculated with eq. (1) given above. The product of this operation in each level is subtracted from that level, and the sum of the subtracted material from all levels is added to the volume of small particles already present in the uppermost 10 cm level (Level 1).

The next step in the simulation moves both small and large particles down to fill the voids left by the movement of small particles to the surface. Beginning with Level 9 (80–90 cm below the surface), the amount of small and large particles to be moved down to Level 10 (90–100 cm) is calculated by multiplying the relative volumes of each size class in Level 9 by the amount of burrow void or tunnels in Level 10. The product of each size class is subtracted from Level 9 and added to Level 10 so that the void is filled in Level 10 with small and large particles in the proportions with which they occur in Level 9. This procedure for moving material down continues for Levels 8 and 9, then Levels 7 and 8, and so on until all of the voids created by moving material to Level 1 are filled.

The results of the first iteration of the simulation are used as the starting point for the next, and this form of iteration continues until the number of years selected at the outset have been simulated. Although both time and the processes of burrow excavation and collapse are continuous, the 1-year time increment used in this program is small enough to be functionally continuous relative to the time depth and intervals treated by most archaeologists. If a smaller time increment is necessary, data are available to increment the simulation at intervals of at least 1 day. However, daily and seasonal variations in the amount of burrowing by pocket gophers (Bandoli, 1981; Miller, 1948) make the annual increment optimal.

The program monitors the disruption of strata by keeping track of the percentage of the volume of material in each level that has moved either up or down. With each iteration of the program, the material moved for the first time is transferred to a disturbed category. The simulation is designed so that the probability that burrows will be excavated in undisturbed deposit is proportionately equivalent to the volume of undisturbed deposit in a given level.

Step 2: Rates and Starting Values

The only values needed to run the program are the relative volume of burrows in each depth interval, the rate of sediment movement to the surface, and the initial values for the vertical distribution of large and small particles. Values for the rate of deposition and erosion are unnecessary as these are held constant (at zero) in the simulation. I derived the information needed to calculate the depth and rate of burrowing from Miller (1957), who investigated 17 *Thomomys umbrinus* burrows in an irrigated alfalfa field in Davis, California. While excavating nine burrow systems, Miller recorded: (1) the linear footage of tunnels found within 5.1 cm (2 in.) depth intervals extending down to 101.6 cm (40 in.); (2) the diameter of burrow tunnels; (3) the length of open and plugged tunnels; and (4) the depth, size, and contents of food caches and nests. I selected these data in part because they provide sufficient quantitative information to calculate the necessary values. Miller's data also have two additional advantages. First, the lack of barriers to burrowing in the deep alluvium of the site he studied limits the constraints on burrow construction to behavioral patterns of the pocket gophers alone. Although this may not reflect conditions in many archaeological deposits, it is the best starting point for the simulation. Second, the vegetation in the alfalfa field is roughly similar to lush vegetation growing on many archaeological midden deposits. This similarity in habitat may maximize the similarity of values for pocket gopher population size and burrow density.

To calculate the volume of burrows in different 10 cm depth intervals (see Table I), I multiplied the length of tunnel measured for each interval by the average area of the tunnels (34 cm^2), and added the volume of chambers (nests and food caches). Since Miller (1957: Table 1) provided only a single depth measurement for the chambers, a set of calculations were required to determine the amount of volume per 10 cm depth interval. For each chamber, I divided the volume by the height to determine the amount of volume per centimeter of depth and, using the depth given as the center of the chamber, allocated the appropriate volume to each 10 cm depth interval.

To calculate the rate of sediment movement using eq. (1), values are needed for the volume of sediment moved to the surface per unit time and the total volume of the matrix containing the burrow system. Miller (1957: Table 2) presents the volume of sediment in fresh piles at the mouths of five burrows over a period of 27 days following irrigation of the field. An average of 1,543 cubic cm of sediment was transported to the surface per burrow per day or 0.563 cubic m per burrow per year. The average volume of deposit containing each burrow is approximately 67 cubic m (average burrow area multiplied by 1 m of depth). With these values, the constant PM in eq. (1) is calculated at 0.008. Thus, over the course of a year, slightly less than 1% of the total volume containing an average burrow is excavated and carried to the surface by pocket gophers. This constant (PM) is multiplied by the proportion of burrow volume in each depth interval to solve eq. (1) and calculate the rate of sediment movement to the surface per year for each depth interval (Table III).

The final set of values needed to run the simulation is the initial distribution of large and small particles within the deposit. Since this version of the simulation assumes a geologically stable surface, artifacts must have been left on the surface with the exception of those deposited in pits and other excavated features. Thus, for the simulation results reported in this paper, all large and small artifacts begin the simulation within the uppermost level (Level 1, 0–10 cm). In addition, no artifacts are added or lost from the deposit after the beginning of the simulation.

Simulation Results

Figures 2 and 3 show the vertical distributions of small (<6 cm) and large (>6 cm) artifacts produced by the simulation program as it was run over various time intervals. Both small and large artifacts move downward initially as

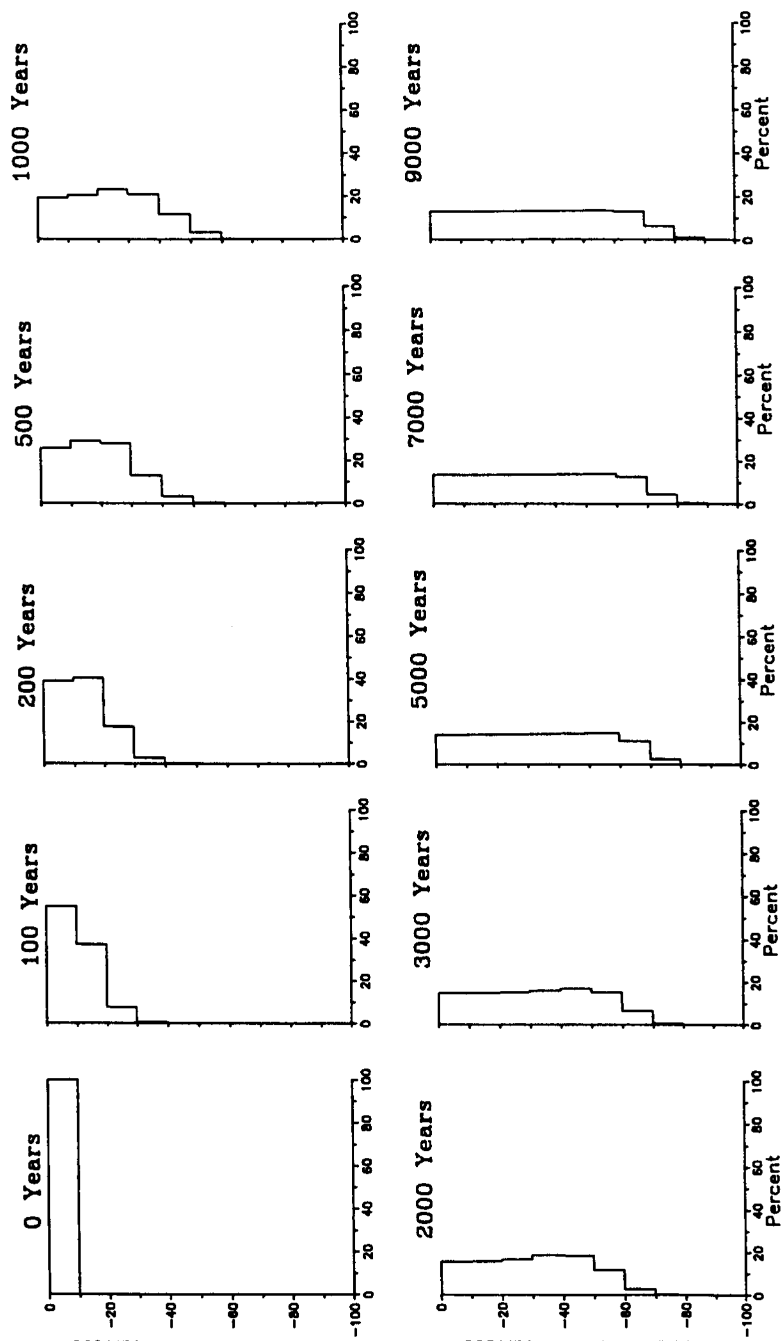

Figure 2. Simulated vertical distribution of small artifacts (<6 cm) over various time intervals.

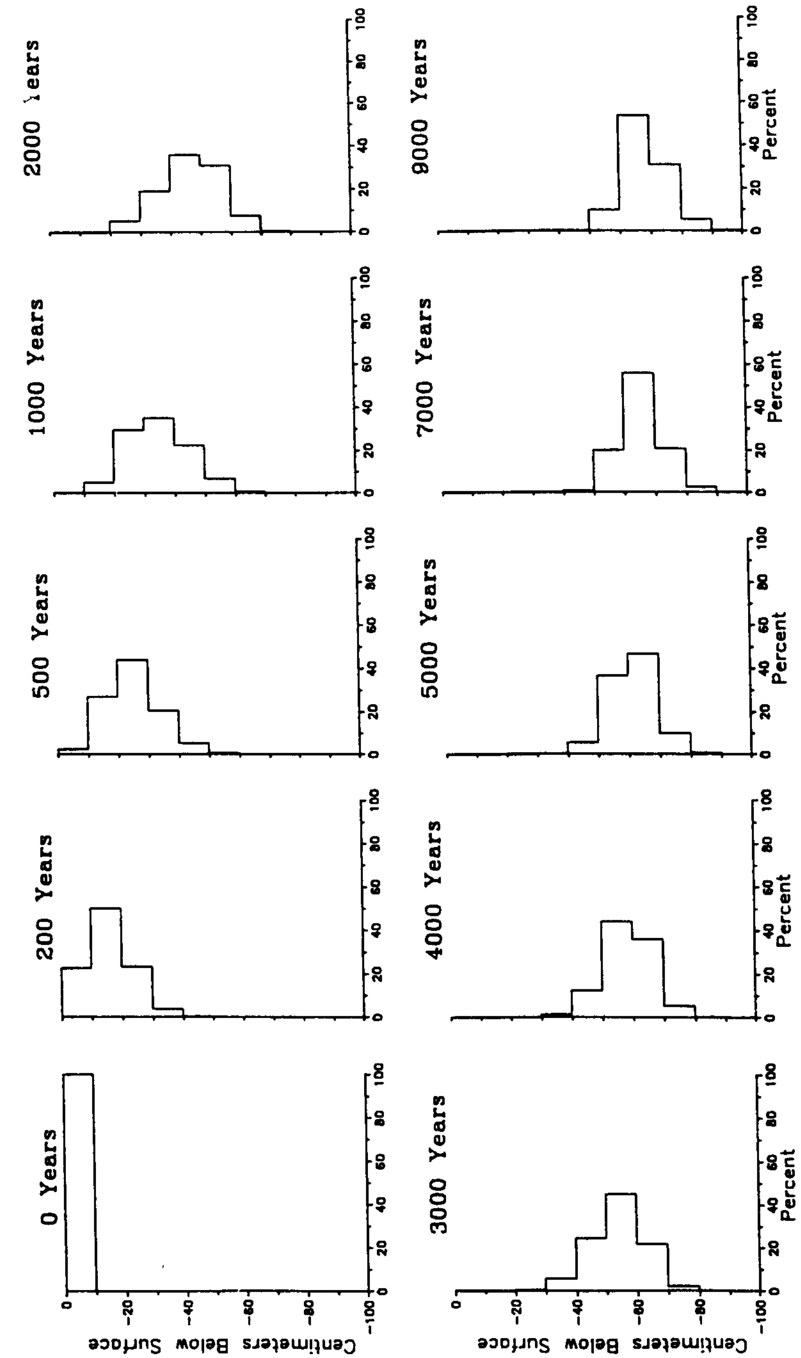

Figure 3. Simulated vertical distribution of large artifacts (>6 cm) over various time intervals.

Table III. Calculation of proportion of sediment moved to the surface per depth interval per year by pocket gophers (*Thomomys umbrinus*)

Depth Interval (cm)	Proportion of Burrow Volume (PBV)	×	Proportion Moved (PM)	=	Proportion Volume Moved (PVM)
0–10	0.0532		0.008		0.00043
10–20	0.4884		0.008		0.00391
20–30	0.2059		0.008		0.00165
30–40	0.0530		0.008		0.00042
40–50	0.0777		0.008		0.00062
50–60	0.0719		0.008		0.00058
60–70	0.0351		0.008		0.00028
70–80	0.0071		0.008		0.00006
80–90	0.0039		0.008		0.00003
90–100	0.0039		0.008		0.00003

sediment and artifacts from the surface fill burrows excavated in deeper portions of the deposit previously devoid of artifacts. The large artifacts continue to sink at an ever slower rate as they accumulate in the lower reaches of the burrow system. After 4000–5000 years, the simulated pocket gopher burrowing has sifted all of the large artifacts from the upper 30 cm of the deposit, concentrating them at lower depths. Since sediment moved to the surface by pocket gophers can contain small artifacts, the artifacts less than 6 cm enter into a cycle of upward and downward movement. Thus, small artifacts tend to become evenly dispersed through the upper 50–60 cm of the deposit rather than concentrating at lower depths as do the large artifacts. After 3000 years, the upward and downward movement of small artifacts equalizes and it becomes difficult to distinguish the vertical distributions of small artifacts over subsequent time intervals.

Figure 4 depicts the rate curve for the simulated disruption or mixing of sediment of all sizes in an average cubic meter over 10,000 years. Burrowing disrupts the deposit rapidly at first, affecting almost 60% of the deposit within the first 1000 years. As the proportion of the deposit affected by burrowing increases, the rate at which new burrows encounter and mix undisturbed material decreases in an almost logarithmic fashion. Although slightly less than 20% of the deposit remains intact after 10,000 years of simulated burrowing, all of this undisturbed material occurs below a depth of 60 cm. Figure 5 shows the differential effect of disturbance with depth over various time intervals. The upper 30 cm of the deposit, the location of most burrowing activity, is almost completely mixed within the first 1000 years of the simulation. Below this zone, the rate of mixing decreases roughly as the burrow volume decreases, leaving the lowest levels relatively intact.

Testing the Simulation Validity

To what extent do these simulation results accurately reflect the actual processes of mixing and artifact movement in archaeological deposits exposed

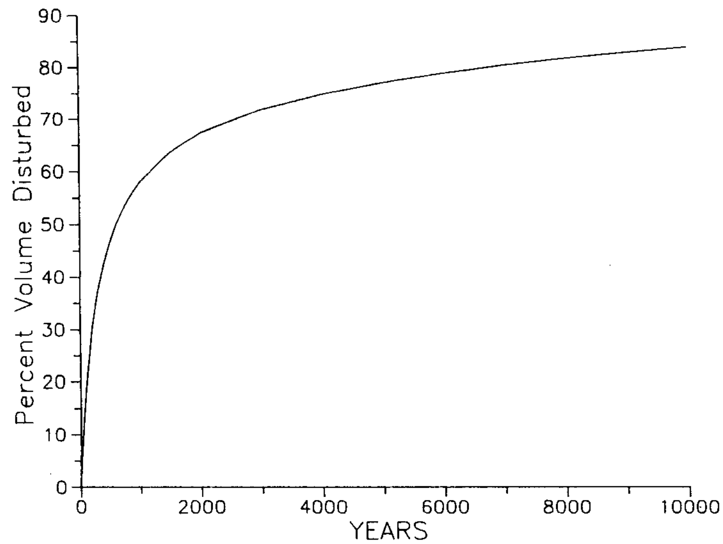

Figure 4. Simulated rate of disturbance per cubic meter.

to pocket gopher burrowing? Answering this question requires testing the validity of the simulation. This commonly entails comparing the output of the simulation to values derived by exposure to the same conditions in the real world (Stanislaw, 1986). To accomplish this, archaeological deposits possessing the following characteristics must be located: (1) large (>6 cm) and small (<6 cm) artifacts deposited on a surface at a known point in time; (2) this surface must have been geologically stable since artifact deposition; and (3) pocket gophers must have been present in the deposit since artifact deposition. Unfortunately, archaeological site reports rarely contain sufficient information on stratification, artifact size, or geomorphic setting to determine if the deposits meet the conditions listed above. However, two reports from southern California provide adequate information to serve as initial tests of the simulation short of reanalyzing collections or conducting new excavations.

Sweetwater Mesa

The Sweetwater Mesa Site (Ca-LAn-267) lies on the top of a grass covered Upper Pleistocene marine terrace 76 m above sea level and 330 m north of the shore at Malibu, California (King, 1967). The terrace is deeply dissected on the east and west of the site, and slopes gently up to the base of the Santa Monica Mountains nearly 1 km to the north. Approximately 16 cubic m of deposit were excavated from 11 pits measuring 1.5 × 1.5 m (5 × 5 ft) in 15.2 cm (6 in.) levels down to 61 cm (24 in.) in three field sessions between 1961 and 1963. The

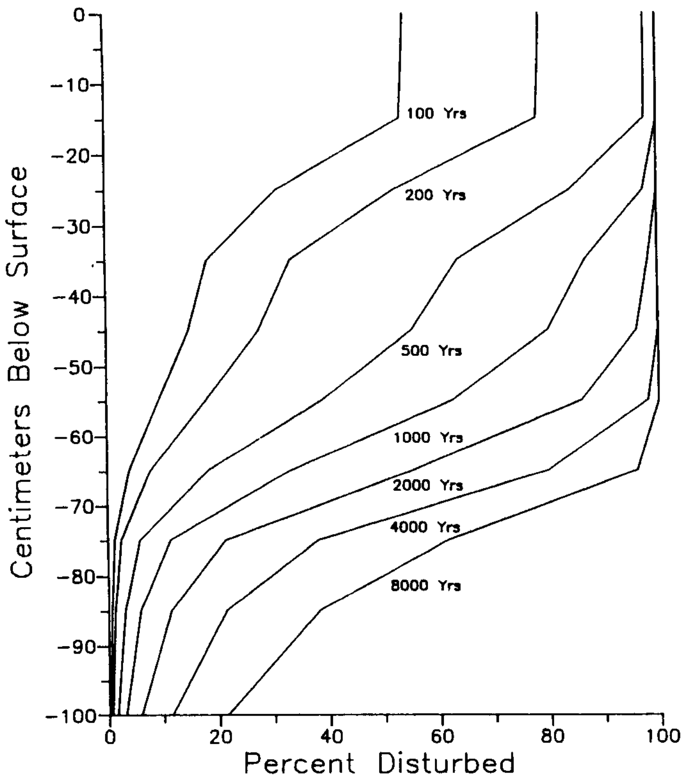

Figure 5. Simulated amount of disturbance with depth over various time intervals.

deposit contains relatively well-developed soil horizons, but lacks evidence of depositional layers or any sign that significant nonartifactual deposition has occurred since the exposure of the marine terrace. Between 30 and 45 cm below the surface, the excavations exposed a stone line or "floor" composed primarily of large artifacts. The most prominent soil feature is a Btk horizon beginning about 33 cm below the surface that shows Stage II to Stage III carbonate accumulation. Two radiocarbon dates, 6310 ± 100 (UCLA-918F) and 6870 ± 100 (UCLA-918G), were obtained on marine shells recovered from the deposit along with other artifacts. After calibration and correction (cf. Taylor, 1987:126–131), these dates suggest an age of roughly 7000 B.P. for the occupation resulting in the deposition of artifacts. Given the Pleistocene age of the surface, it is likely that the artifacts were all initially deposited on the surface. King observed evidence of pocket gophers living in the site both in the form of krotovina and hills of loose sediment at the mouths of burrows.

King (1967:33–52) provides the range of length, width, and thickness mea-

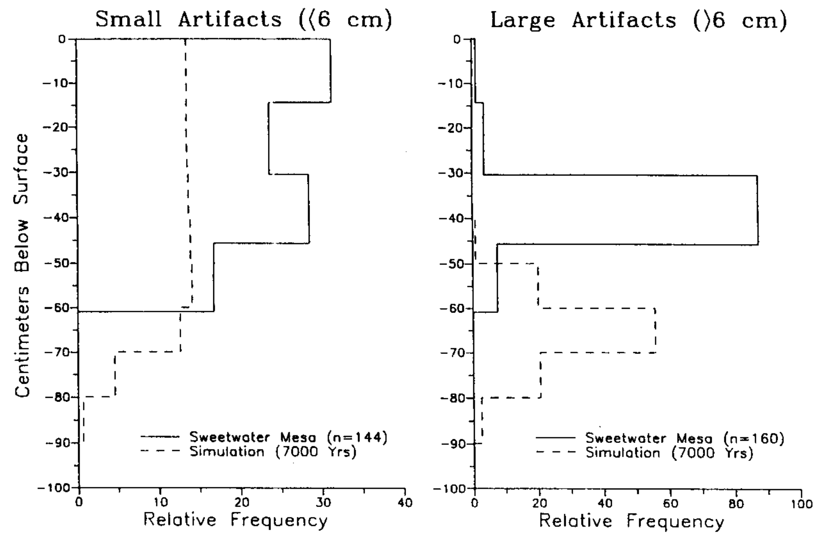

Figure 6. Vertical distributions of large (>6 cm) and small (<6 cm) artifacts at the Sweetwater Mesa site in relation to simulated distributions.

surements on artifacts assigned to each type. Using these data, I divided the artifact types into large, small, and mixed categories. The large category includes all types whose minimum length is greater than 6 cm. The small category includes all types with maximum lengths of 6 cm or less. The mixed category includes all the remaining types. The small artifact category at the Sweetwater Mesa Site includes the following artifact types: Knives (Type I), Gravers and Drills (all Types), Small Cores, Domed Scrapers (all Types), Thin Flake Scrapers, Other Illustrated Scrapers, Concave Endset Scrapers (Types I, III, and IV), Biface Scrapers (Types I, IIa, and IIb), Quartz Crystals, Bone Artifacts, and Shell Ornaments (all Types). The large artifact category includes: all groundstone Types (Manos, Small Handstones, Metates, Pestles, Mortars, Mortar Depressions, Pitted Stones, Grooved Stones, and Cogged Stones; excluding fragments), Periphery Cores, Battered Flakes, Cobble Biface, Cobble Multiface, Large Scrapers (Type Ia), Cortex-based Scrapers (Types I, III, and IV), Bifacially Flaked Large Flakes, Knives (Type II), Nosed Scrapers, Concave Endset Scrapers (Type II), and Biface Scrapers (Type IIc). The frequencies of artifacts for the two size categories in each excavated levels were obtained from King's (1967) Figure II.

Figure 6 shows the vertical distributions of artifacts in the large and small categories. For comparison, the graphs also include vertical distributions of large and small particles generated from 7000 years of simulated burrowing. The small artifacts at Sweetwater Mesa occur in similar frequencies across the upper three levels and then their abundance decreases markedly in the lowest level. The relative frequency of large artifacts peak between 30 and 45 cm, coinciding with the stone line observed by the excavators. The form of these distributions compares well with the simulated distributions, although the positions of peaks and relative frequency values clearly differ for the large artifacts. For both the large and small artifacts, the distributions appear compressed vertically in comparison to the simulated distributions. This could result from excavation of shallower burrows by the pocket gophers at Sweetwater Mesa than the gophers that formed the basis of the simulation. The presence of the moderately cemented Btk horizon may have inhibited deeper burrowing at Sweetwater Mesa. The accumulation of large artifacts at the top of the cemented zone supports this conclusion. Alternative explanations for differences between the actual and simulated distributions, such as inaccurate burrowing rates or incorrect dating of the occupation, do not account for the marked accumulation of large artifacts in a stone line after their initial deposition of the surface.

Sayles Site (Locus A)

The Sayles Site (Ca-SBr-421) is located in Crowder Canyon near Cajon Pass, California, between the San Gabriel and San Bernardino Mountains at an elevation of about 980 m. The site is divided into four Loci (A, B, C, and D) spread out on a dissected alluvial terrace and hill slope on the west side of Crowder Creek (Basgall and True, 1985). Locus A, the site of excavations in 1965 and 1966 (Kowta, 1969), lies on a level terrace surface approximately 20 m above the normally dry bed of Crowder Creek. Four areas were excavated within Locus A. In one of these areas, also designated Locus A, 43 cubic m were excavated from a total of 11 pits (1.8 × 1.8 × 1.2 m). Kowta (1969:9, Figure 1 and Plate 1) describes three soil horizons encountered in the excavation: a friable to loose, light yellowish-brown A horizon with a clear lower boundary at approximately 30 cm; a hard, dark B horizon with an irregular lower boundary produced by krotovina at approximately 76 cm; and a light colored, loamy coarse sand with occasional quartzite cobbles (possible C horizon) extending into the floor of the excavation. Slope wash may contribute some sediment to the site, but the degree of soil formation and lack of visible sedimentary layers suggest that the surface has generally been stable. Artifacts occur throughout the deposit, but are most frequent in the B horizon. Hydration rind measurements on eight obsidian artifacts from Locus A produced seven readings between 4.1 and 4.6 μm and one reading of 8.5 μm (Jackson, 1985). Based on a locale specific hydration rate, Basgall and True (1985:9.3) suggest an age range for the occupation at Locus A from 1800 to 2400 B.P. with a possible earlier occupation around 3000 B.P.

In his report on the Sayles Site, Kowta (1969:11–31) provides the minimum and maximum values for the length, width, and thickness of artifacts included in each artifact type. Using the same criteria as with the Sweetwater Mesa Site, I divided the artifacts recovered from Kowta's Locus A into large (>6 cm),

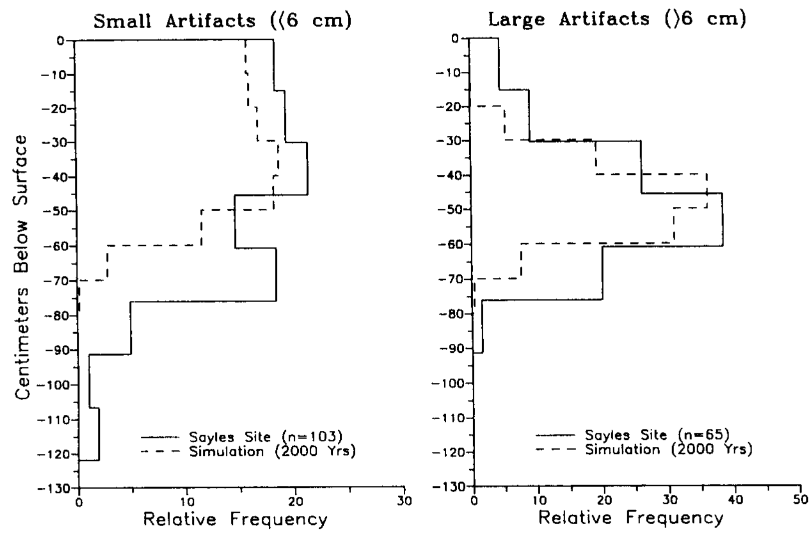

Figure 7. **Vertical distributions of large (>6 cm) and small (<6 cm) artifacts at the Sayles Site (Locus A) in relation to simulated distributions.**

small (<6 cm), and mixed categories. Small artifacts at the Sayles Site include: Pendants, Paint Stones, Projectile Points, Small Steep-edged Scrapers, Prismatic Flakes, Quartz Crystals, and Small Flaked Objects. Large artifacts include: Milling Stones, Straight-edge Scrapers, Cleaver Scrapers, Bifacial Choppers, and Flaked Hammerstones. Manos are not included in this study because of the presence of fragments. Frequencies of large and small artifacts in each excavated level were compiled from Kowta's (1969) Table 4.

Figure 7 shows the vertical distributions of large and small artifacts along with the distributions created by 2000 years of simulated burrowing. Comparing the two sets of distributions indicates that the Sayles Site contains a greater number of large and small artifacts below 60 cm than the simulated distributions. This disparity may be accounted for by artifacts deposited during an earlier occupation (3000 B.P.), or possibly sufficient accumulation of colluvial sediment on the site causing the zone of burrowing to rise through time. In the upper portion of the deposit, the correspondence between the simulated and actual distributions is striking.

DISCUSSION AND CONCLUSIONS

The similarities between the simulated distributions and the vertical distributions at the Sweetwater Mesa and Sayles Sites validate the rates of sediment movement and the notion of size sorting employed in the simulation of pocket gopher burrowing. The disparities between the model and actual distributions appear to relate to situation specific differences in burrow depth, occupation history, and geomorphic setting. The validity of the patterns of disruption of strata and depositional structures produced by the simulation cannot be assessed with the two examples used here since the lack of such layers and structures at the sites may result from other pedogenic processes. However, the rapidity of disturbance by pocket gopher burrowing is attested to by the mixed and discontinuous condition of strata at an aboriginal village site abandoned in the early 19th century and subsequently buried by alluvial deposits (Pierce, 1982).

Given the success of the simulation at tracking the long-term effects of pocket gopher burrowing, we can now assess the impacts these patterns of size sorting, strata disruption and destruction of fragile remains have had on the archaeological record and our understanding of California prehistory. Despite their differences in age, both the Sweetwater Mesa and Sayles Sites have been assigned to the same culture historical unit, the Milling Stone Horizon. The concept of the Milling Stone Horizon was developed by Wallace (1954, 1955) to draw attention to a group of sites located along the southern California coast that produced similar artifact assemblages and were thought to date to the early or middle Holocene. Milling Stone Horizon sites are typically large, deep deposits containing great quantities of milling stones (basin metates and manos) and large core tools (hammerstones and scrapers), fewer projectile points, flake tools, and polished stone discoidals ("cogstones" and "charmstones"), and little or no shell, bone, and charred plant remains. The sites are often found in elevated locations such as hill tops and terraces that receive little or no natural deposition. The larger artifacts such as milling stones and core tools commonly occur in stone lines or zones like those at Sweetwater Mesa and the Sayles Site (Greenwood, 1969; King et al., 1968; Pritchet and McIntyre, 1979; Walker, 1952). These shared characteristics have led to the view that the Milling Stone Horizon sites were occupied by large, sedentary, autonomous populations subsisting primarily on vegetal resources, particularly small hard seeds, with a minor contribution from hunting, fishing, and shellfish collecting.

As with Sweetwater Mesa and the Sayles Site, several of the characteristics that have led archaeologists to group sites into the Milling Stone Horizon may result from pocket gopher burrowing rather than any close historical or genetic relation. If true, this has implications for the veracity of culture historical constructs and interpretations of prehistoric adaptations currently employed in southern California. The 8000 year range of dates on Milling Stone Horizon sites (Basgall and True, 1985:10.20) has already undermined the utility of this construct for culture history. In addition, recent work on early Holocene deposits protected from pocket gopher burrowing by deep burial document subsistence patterns that include significant shellfish collection and hunting (Erlandson, 1988; Glassow, 1988). The pattern of occurrence of Milling Stone Horizon sites on elevated landforms may be due to the presence of stable surfaces on these landforms, providing exposure to burrowing and increased visibility of early material.

The effects of pocket gopher burrowing are not limited to the Milling Stone Horizon. Many archaeological deposits in California lack stratification (commonly referred to as undifferentiated midden deposits), and, consequently, archaeologists excavate and analyze these deposits using arbitrary depth intervals (normally 10 cm). If the lack of stratification is due to extensive burrowing, the assumption of superposition that equates depth with time is incorrect for these deposits. The "stratigraphic reversal" of radiocarbon dates noted by Erlandson and Rockwell (1987) may be only one example of a more general pattern of mixing that weakens chronological interpretations based on vertical position of artifacts within deposits affected by burrowing. In addition to chronological problems, patterns identified in regional studies involving the comparison of subsistence assemblages and vertical distributions of artifacts from upland (stable) and lowland (depositional) environments could derive from differential exposure to burrowing rather than behavioral differences between people that occupied the two areas (Dreyer and Deal, 1982). Studies based on surface assemblages could also be affected by pocket gopher burrowing. Although gophers may facilitate the discovery of buried deposits by bringing artifacts to the surface, they also bury artifacts deposited on the surface and create surface assemblages depleted of large artifacts.

Unfortunately, the extent to which the problems discussed above color our understanding of California prehistory cannot now be thoroughly evaluated. Archaeologists have not adequately described the deposits in which they dig nor have they regularly produced the information needed to conduct reliable taphonomic studies from published reports. However, existing evidence warrants a cautious reappraisal of current views on the Milling Stone Horizon and other topics. At the same time, it would be inappropriate to use the information presented in this paper to regard heavily burrowed deposits as insignificant or useless for archaeological research. Such deposits may be used to address questions of site structure since horizontal movement, although not treated specifically here, appears to be minimal. However, extraction of chronological and subsistence information requires application and possibly development of new methods together with a greater concern for the context and history of deposits. Clearly, the processes that formed the archaeological record as we find it today greatly influence our understanding of the past. If we are to decipher these formation processes, we must treat the archaeological record as a product of geological processes of transport, deposition, and post-depositional alteration.

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REFERENCES

Bandoli, J.H. (1981). Factors influencing seasonal burrowing activity in the pocket gopher, *Thomomys bottae*. *Journal of Mammalogy* **62,** 293–303.

Basgall, M.E., and True, D.L. (1985). *Archaeological Investigations in Crowder Canyon, 1973–1984: Excavations at Sites SBr-421B, SBr-421C, SBr-421D, and SBr-713*. San Bernardino, CA: California State Department of Transportation, District 8.

Behrensmeyer, A.K. (1978). Taphonomic and ecologic information from bone weathering. *Paleobiology* **4,** 150–162.

Binford, L.R. (1981). *Bones, Ancient Men and Modern Myths*. Orlando: Academic Press, 320 pp.

Bocek, B. (1986). Rodent ecology and burrowing behavior: Predicted effects on archaeological site formation. *American Antiquity* **51,** 589–603.

Buechner, H.K. (1942). Interrelationships between the pocket gopher and land use. *Journal of Mammalogy* **23,** 346–348.

Davis, W.B. (1938). Relation of size of pocket gophers to soil and altitude. *Journal of Mammalogy* **19,** 338–342.

Davis, W.B., Ramsey, R.R., and Arendale, J.M., Jr. (1938). Distribution of pocket gophers (*Geomys breviceps*) in relations to soils. *Journal of Mammalogy* **19,** 412–418.

Dreyer, B., and Deal, K. (1982). A reevaluation of groundstone assemblages in the northern Sacramento Valley. Northern California Archaeology Symposium, Chico, California.

Driscoll, E.G. (1967). Experimental field study of shell abrasion. *Journal of Sedimentary Petrology* **37,** 1117–1123.

Driscoll, E.G. (1970).Selective bivalve shell destruction in marine environments, a field study. *Journal of Sedimentary Petrology* **40,** 898–905.

Ellison, L. (1946). The pocket gopher in relation to soil erosion on mountain range. *Ecology* **27,** 101–114.

Erlandson, J.M. (1984). A case study in faunalturbation: Delineating the effects of the burrowing pocket gopher on the distribution of archaeological materials. *American Antiquity* **49,** 785–790.

Erlandson, J.M. (1988). Of millingstones and molluscs: Littoral collectors of the southern California coast between 7500 and 8500 Cal BP. Annual Meeting, Society for California Archaeology, Redding, CA.

Erlandson, J.M., and Rockwell, T.K. (1987). Radiocarbon Reversals and Stratigraphic Discontinuities: The Effects of Natural Formation Processes on Coastal California Archaeological Sites, *In* D. Nash and M. Petralglia, Eds., *Natural Formation Processes and the Archaeological Record,* BAR International Series 352, pp. 51–73. Oxford: British Archaeological Reports.

Gifford, D.P. (1980). Ethnoarchaeological Contributions to the Taphonomy of Human Sites. *In* A.K. Behrensmeyer and A.P. Hill, Eds., *Fossils in the Making,* pp. 93–106. Chicago: University of Chicago Press.

Gifford-Gonzales, D.P., Damrosch, D.B., Damrosch, D.R., Pryor, J., and Thunen, R.L. (1985). The third dimension in site structure: An experiment in trampling and vertical dispersal. *American Antiquity* **50,** 803–818.

Glassow, M. (1988). Early Holocene environment and adaptation on Vandenberge Air Force Base. Annual Meeting, Society for California Archaeology, Redding, CA.

Greenwood, R.S. (1969). The Brown Site, Early Milling Stone Horizon in southern California. *Society for American Archaeology Memoir* **23.**

Grinnell, J. (1923). The burrowing rodents of California as agents in soil formation. *Journal of Mammalogy* **4,** 137–149.

Hall, E.R. (1981). *The Mammals of North America, Volume 1,* 2nd ed. New York: John Wiley and Sons, 890 pp.

Hansen, R.M., and Morris, M.J. (1968). Movement of rocks by northern pocket gophers. *Journal of Mammalogy* **49,** 391–399.

Hansen, R.M., and Remmenga, E.E. (1961). Nearest neighbor concept applied to pocket gopher populations. *Ecology* **42,** 812–814.

Hare, P.E. (1980).Organic Chemistry of Bone and Its Relation to the Survival of Bone in the Natural Environment. *In* A.K. Behrensmeyer and A.P. Hill, Eds., *Fossils in the Making*, pp. 208–219. Chicago: University of Chicago Press.

Hickman, G.C. (1977). Burrow system structure of Pappogeomys castanops (Geomyidae) in Lubbock County, Texas. *The American Midland Naturalist* **97,** 50–58.

Howard, W.E., and Childs, H.E., Jr. (1959). Ecology of pocket gophers with emphasis on Thomomys bottae mewa. *Hilgardia* **29,** 277–358.

Ingles, L.G. (1947). *Mammals of California*. Palo Alto: Stanford University Press.

Ingles, L.G. (1952). The ecology of the mountain pocket gopher, *Thomomys monticola. Ecology* **33,** 87–95.

Jackson, R.J. (1985). Appendix I: Analysis of obsidian hydration on archaeological specimens from Crowder Canyon. *In* M.E. Basgall and D.L. True, *Archaeological Investigations in Crowder Canyon, 1973–1984: Excavations at Sites SBr-421B, SBr-421C, SBr-421D, and SBr-713*. San Bernardino, CA: California State Department of Transportation, District 8.

Johnson, D.L. (1989). Subsurface stone lines, stone zones, artifact-manuport layers,and biomantles produced by bioturbation via pocket gophers (*Thomomys bottae*). *American Antiquity* **54,** 370–389.

King, C.D. (1967). The Sweetwater Mesa Site (LAn—267) and its place in southern California prehistory. *Arachaeological Survey Annual Report* **9,** 27–79. Los Angeles: University of California.

King, C.D., Blackburn, T., and Chandonet, E. (1968). The archaeological investigation of three sites on the Century Ranch, western Los Angeles County, California, *Archaeological Survey Annual Report* **10,** 12–107. Los Angeles: University of California.

Kowta, M. (1969). The Sayles Complex: A late Milling Stone assemblage from Cajon Pass and the ecological implications of its scraper planes. *University of California Publications in Anthropology* **6,** Berkeley, CA.

Lyman, R.L. (1984). Bone density and differential survivorship of fossil classes. *Journal of Anthropological Archaeology* **3,** 259–299.

Lyman, R.L., and Fox, G.L. (1989). A critical evaluation of bone weathering as an indication of bone assemblage formation. *Journal of Archaeological Science* **16,** 293–317.

Miller, G.J. (1975). Weathering Cracks, Fractures, Splinters, and Other Similar Natural Phenomena. *In* E.H. Swanson, Ed., *Lithic Technology: Making and Using Stone Tools*, pp. 211–226. Chicago: Aldine.

Miller, M.A. (1948). Seasonal trends in burrowing of pocket gophers (*Thomomys*). *Journal of Mammalogy* **29,** 38–44.

Miller, M.A. (1957). Burrows of the Sacramento Valley pocket gopher in flood—irrigated alfalfa fields. *Hilgardia* **26,** 431–452.

Moratto, M.J. (1984). *California Archaeology*. Orlando: Academic Press.

Nash, D., and Petraglia, M., Eds., (1987). *Natural Formation Processes and the Archaeological Record,* BAR International Series 352. Oxford: British Archaeological Reports.

Pierce, C.D. (1982). Chapter 5: Stratigraphy, Features and Site Formation. *In* C.D. King et al., Eds., *Archaeological Investigations at Talepop (LAn-229)*, pp. 5.1–5.87. University of California, Santa Barbara: Social Process Research Institute.

Pierce, C.D. (1988). California's Milling Stone Horizon: Of Mice or Men. 53rd Annual Meeting, Society for American Archaeology, Phoenix, AZ.

Pritchet, J., and McIntyre, A. (1978). The Running Springs Ranch Site: Archaeological investigations at Ven-65 and Ven-261. *Institute of Archaeology Monograph XII*. Los Angeles: University of California.

Reichman, O.J., Whitham, T.G., and Ruffner, G.A. (1982). Adaptive geometry of burrow spacing in two pocket gopher populations. *Ecology* **63,** 687–695.

Richens, V.B. (1966). Notes on the digging activity of a northern pocket gopher. *Journal of Mammalogy* **47,** 531–533.

Schiffer, M.B. (1972). Archaeological context and system context. *American Antiquity* **37,** 156–165.
Schiffer, M.B. (1987). *Formation Processes of the Archaeological Record.* Albuquerque: University of New Mexico Press.
Shipman, P. (1981). *The Life History of a Fossil.* Cambridge: Harvard University Press.
Stanislaw, H. (1986). Tests of computer simulation validity. *Simulation and Games* **17,** 173–191.
Storer, T.I. (1933). Control of the injurious rodents in California. *California Agricultural Extension Station Circular* **79.**
Storer, T.I., and Usinger, R.L. (1963). *Sierra Nevada Natural History.* Berkeley: University of California Press.
Taylor, R.E. (1987). *Radiocarbon Dating, An Archaeological Perspective.* Orlando: Academic Press.
Walker, E.F. (1952). Five prehistoric archaeological sites in Los Angeles County, California. *Publications of the Frederick Webb Hodge Anniversary Publication Fund* **VI.** Los Angeles: Southwest Museum.
Wallace, W.J. (1954). The Little Sycamore Site and the early milling stone cultures of southern California. *American Antiquity* **20,** 112–123.
Wallace, W.J. (1955). A suggested chronology for southern California coastal archaeology. *Southwestern Journal of Anthropology* **11,** 214–230.
Wallace, W.J. (1978). Post—Pleistocene Archaeology, 9000 to 2000 B.C. *In* R.F. Heizer, Ed., *Handbook of North American Indians, Volume 8, California,* pp. 25–36. Washington, DC: Smithsonian Institution Press.
Wandsnider, L. (1989). Long-term Land Use, Formation Processes, and the Structure of the Archaeological Landscape: A Case Study from Southwestern Wyoming. Ph.D. Dissertation, University of New Mexico, Albuquerque.
Wood, W.R., and Johnson, D.L. (1978). A Survey of Disturbance Processes in Archaeological Site Formation. *In* M.B. Schiffer, Ed., *Advances in Archaeological Method and Theory,* Vol. 1, pp. 315–381. Orlando: Academic Press.
Yorston, R.M., Gaffney, V.L., and Reynolds, P.J. (1990). Simulation of artefact movement due to cultivation. *Journal of Archaeological Science* **17,** 67–83.

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