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CHRONOLOGY AND SPATIAL DISTRIBUTION OF LARGE MAMMAL BONES IN PIT 91, RANCHO LA BREA

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ABSTRACT

The Rancho La Brea tar pits represent a collection of Pleistocene fossils from an unusual sedimentary environment. A taphonomic analysis of a single tar seep, Pit 91, reveals a complex history of deposition and diagenesis for specimens found there. Radiometric dating of 46 bones from Pit 91 documents at least two episodes of deposition, one from 45,000 to 35,000 yr and another, shorter interval from 26,500 to 23,000 yr. Interestingly, the law of superposition was not upheld consistently in this case study, as some younger bones were found at a greater depth than older bones, implying that taphonomic time averaging took place. Bones are distributed as disarticulated elements in two large concentrations that span both depositional episodes. In general, long bones are oriented horizontally, with little or no preference for cardinal orientation. Degree of weathering or abrasion is not correlated with depth. Bone-on-bone contact (pit wear), however, increases with depth, suggesting possible compaction of bones through time. These results, combined with the disarticulation common to nearly all recovered specimens, suggest a postentrapment journey for the bones unique to asphalt deposits.

INTRODUCTION

The purpose of this paper is to investigate the unusual taphonomic history of the Rancho La Brea tar pits. The objectives of this study are twofold. First, a large sample (46 specimens) of bones from one pit (Pit 91) was radiocarbon dated. Dates were obtained using a relatively new and very precise method that isolates single amino acids (Stafford et al., 1991) and reduces potential contamination by carbon residues from the permeating asphalt. These dated bones can be placed in a spatial context using the positional data collected at the time of recovery. Second, the distribution of such characteristics of specimens in the three-dimensional space of the pit as weathering stage, pit wear—a type of surface modification unique to Rancho La Brea—and abrasion was examined. Combined, these results shed light on the stratigraphic and temporal controls on deposition within the tar pits.

The Rancho La Brea tar pits of Los Angeles, California, are undoubtedly one of the world's most spectacular fossil deposits. As true Lagerstätten—uniquely dense collections of well-preserved fossil material—the pits have yielded over 3 million late Pleistocene plant and animal fossils representing over 600 species (Akersten et al., 1983; Marcus and Berger, 1984; Stock and Harris, 1992). Vertebrate skeletal material is little altered from its original state, although permeated with asphalt (Quinn, 1992). The fossils, from 45,000 to 4,000 yr in age (Marcus and Berger, 1984), span a time of significant climatic and faunal change in North America that includes the movement of humans into the continent and concurrent megafaunal extinction (Martin and Klein, 1984). The large quantity of bones recovered from the area has been used for taxonomic

and paleoecological studies (e.g., Van Valkenburgh and Hertel, 1993; Binder et al., 2002; Van Valkenburgh and Sacco, 2002; Coltrain et al., 2004; Ward et al., 2005).

One of the most striking demonstrations of the uniqueness of the paleoecology of these deposits is the trophic distribution of taxa recovered. Mammalian carnivores dominate the deposit, mainly represented by the dire wolf (*Canis dirus*) and the saber-toothed cat (*Smilodon fatalis*). Overall, 90% of the specimens are carnivores, which is the inverse of studied trophic pyramids where herbivores outnumber carnivores 10 to 1 (Eisenberg, 1981; Stock and Harris, 1992). The proposed explanation for this discrepancy is that trapped herbivores attracted carnivores, which in turn, also became trapped in the asphalt (Stock and Harris, 1992).

Relatively few chronologic analyses of biotic change have been done at Rancho La Brea despite the general paleontological interest in these deposits. This is due largely to a lack of basic information on the taphonomy (preservational biases) and chronostratigraphy of the tar pits. Temporal mixing and taphonomic time averaging (Behrensmeyer and Hook, 1992) within each deposit may have occurred owing to the unique nature of the pits and the assumed plastic properties of the matrix. It is very difficult to use the collection for comparative paleoecological and evolutionary studies without a firm understanding of the biases that affected preservation and confidence in fossil ages (Stock, 1929; Akersten et al., 1983).

The work of Spencer et al. (2003) represents a significant step toward understanding taphonomic processes involved with deposition in the tar pits, specifically Pit 91, but it lacks a spatial and temporal context. As discussed here, positional data on all bones were taken during excavation, including XYZ data for one or multiple points on each bone (depending on bone type), as well as strike and dip (vertical and horizontal orientation) in a small subset of cases (Shaw, 1982). Spatial data have the potential to reveal much about the dynamics of deposition and possible postdepositional movement of bones. For example, tubular concentrations of vertically oriented bones would suggest vertical flow of the asphalt, whereas a predominance of horizontally oriented bones suggest little vertical movement or later vertical compaction.

The La Brea Tar Pit Seeps

Fossils from the tar pits were first described in 1875 (Denton, 1875), and peak excavation occurred between 1905 and 1915 (Stock and Harris, 1992). Over 100 sites were excavated over an area covering 9 hectares during this period. Early excavations focused on obtaining the remains of larger animals for museum collections, and few orientation data were collected, although depth within a specified grid was recorded (Shaw and Quinn, 1986; Stock and Harris, 1992). In 1969, the Natural History Museum of Los Angeles County reopened a previously known locality, Pit 91, for excavation. More than 45,000 specimens from Pit 91 have been identified and cataloged in a computer database, each with detailed three-dimensional positional information. These data formed the basis for the taphonomic analyses published by Spencer et al. (2003).

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	3	4	5	6	7	8	9	10	11	12
E	0	87	4	13	20	0	3	0	5	0
F	5	9	29	54	109	84	66	120	707	1
G	37	13	55	227	110	17	64	337	330	0
H	3	3	4	276	1817	710	468	238	231	393
I	0	1	16	3488	1492	767	161	579	634	119
J	0	0	0	1588	627	39	49	19	699	134
K	0	133	255	3	30	70	184	1637	1129	-
L	214	2975	1718	8	3	5	195	1808	2156	-
M	1940	2661	72	81	41	1	118	1001	1221	108
N	493	41	259	199	784	37	70	4	420	10

FIGURE 1—Plan view of Pit 91 grid layout showing the cumulative number of bones found in each grid at all depths. Shaded grids show areas of particularly high concentrations of bones discussed in the text. North is at the bottom of the grid, and east is to the left.

The specimens are preserved in sand and clay impregnated with asphalt. The asphalt migrated from older Paleogene oil deposits, pooling at the surface to form asphalt pools. Animal and plant remains were trapped in this asphalt and then were covered by alluvial sediments derived from the nearby Santa Monica Mountains (Quinn, 1992). In the case of Pit 91, the bones were removed from the pit systematically to retain as much information as possible about bone orientations and juxtapositions. The fossils were excavated in 3' × 3' × 0.5' units, commonly referred to as grids by excavators. Grids are given a letter-number combination according to their north-south, east-west position, respectively (Fig. 1). Depth is recorded as feet and inches below a datum at the top of the pit; the decision to use English system measurements rather than metric measurements permitted more ready comparison with the provenance data for La Brea material collected between 1913 and 1915, and these measures are used throughout this study. To alleviate confusion, the following conversion is provided: 1 foot or 1' = 12 inches or 12" = 30.48 cm. Within each grid, the position and orientation of all bones over .25 inches (0.635 cm) long were recorded prior to their removal from the matrix. In addition, for a small sample of large bones, strike and dip were taken for the determination of orientation, and, on large bones, multiple points of positional references were recorded to allow for future orientation determination (Shaw, 1982; see Fig. 2).

The accepted mode of accumulation of Rancho La Brea vertebrates is entrapment in shallow seeps of sticky asphalt (Shaw and Quinn, 1986; Stock and Harris, 1992). Both fluvial action and trampling, however, also likely played significant roles in taphonomic processes (Shaw and Quinn, 1986). In addition, carnivores were likely attracted to the site by trapped, dying, and dead herbivores. Notably, skeletons are almost always fully disarticulated, complicating interpretation of postmortem events. To understand better the taphonomic history of Pit 91, a detailed examination of the mammal material was undertaken. All cataloged bones of mammal species larger than 5 kg were examined by trained students for such evidence of surface modification as tooth marks due to carnivore modification, scratches produced by trampling, weathering, abrasion, insect damage, and rodent gnaw marks. Skeletal element representation data were collected for each species and examined to document biases in preservation. Recently published results (Spencer et al., 2003) demonstrate that bones underwent little weathering, were buried rapidly, and were not

FIGURE 2—Example of positional data taken for large bones within Pit 91 (from Shaw, 1982). N and W = the north and west sides of the grid, respectively; BD = below-datum measurements.

abraded by fluvial action. Skeletons were not complete, and Spencer et al. (2003) argued that scavenging carnivores carried off missing elements.

MATERIALS AND METHODS

Dating Methods

Temporal data were obtained via radiocarbon dating of 46 bones from Pit 91 (Table 1). Dated bones were chosen to sample both the depth and breadth of the pit to test if bones at similar depth were of similar age and whether age increased with depth. In addition, dates were obtained for four bones from a putative single individual of *Nothrotheriops shastensis*, as well as bones known to be from different individuals of *Canis dirus*. Radiocarbon dates were obtained by Thomas Stafford, at Stafford Research Laboratories, Inc., and John Southon, at the Lawrence Livermore National Laboratories, using the following procedure. After an initial wash with tap water to remove any loose sediment, an approximately 2 cm × 2 cm × 1–0.5 cm section of dense, cortical bone was removed using a Dremel tool or a jeweler's saw. Molecular level ¹⁴C dating was applied to the bone fragments. This technique isolates individual amino acids for dating by accelerator mass spectrometry (Stafford et al., 1991). Although more time intensive than the more customary dating of bulk collagen or gelatin, dating of individual amino acids is demonstrably more accurate when bone preservation is good (Stafford et al., 1991). Well-preserved bones retain much of their collagen and a high nitrogen content, with both ranging from 0.6% to 3.5% of whole bone; the Rancho La Brea bones are very well preserved with 0.87–3.56% nitrogen (Dobrenz and Matter, 1965) and 2.8% of their collagen intact (Wyckoff et al., 1964; Ho, 1967).

Despite the excellent chemical preservation of the Rancho La Brea material, radiocarbon dating is far from routine. Because of the presence of asphalt throughout the bones, extreme care must be taken to remove as much of the asphalt residues as possible to minimize the potential for contamination. The earlier work of Ho et al. (1969) was a major advance in dating petroleum-impregnated fossils. With the advent of accelerator mass spectrometry technology that enables 1 g or less of bone to be dated, even greater chemical pretreatments can be performed and were used with this sample. The methods used in dating the bones examined in this research combined the best of Ho's and Stafford's techniques.

Small 5-mm-diameter plugs of bone were removed and then extracted

TABLE 1—Radiocarbon dated specimens. Age is estimated in years before present; specimens are listed in ascending order of estimated age. Grid column refers to coordinates of the grid location as illustrated in Figure 1. Asterisks indicate the *Canis dirus* left radii from grid I-6 mentioned in the text. SE = standard error of the age estimate in years.

LACMRLP#	Taxon	Element	Grid	Grid depth	Age (yr)	SE
R14493	<i>Canis dirus</i>	radius	L-11	8.5'–9'	14,040	50
R32497	<i>Canis dirus</i>	tibia	H-7	10.5'–11'	23,060	90
R21648	<i>Smilodon fatalis</i>	astragalus	M-11	7.5'–8'	24,930	240
R25591	<i>Smilodon fatalis</i>	tibia	L-10	8.5'–9'	25,710	140
R27932	<i>Smilodon fatalis</i>	caudal vertebrae	L-10	9.5'–10'	25,740	100
R36301	<i>Smilodon fatalis</i>	calcaneum	L-11	9.5'–10'	26,120	280
R35212	<i>Smilodon fatalis</i>	humerus	L-10	10.5'–11'	26,150	280
R29708*	<i>Canis dirus</i>	radius	I-6	10.5'–11'	26,840	120
R22719	<i>Smilodon fatalis</i>	humerus	H-8	8.5'–9'	27,220	140
R16695	<i>Smilodon fatalis</i>	radius	I-6	9.5'–10'	27,350	120
R22420*	<i>Canis dirus</i>	radius	I-6	8.5'–9'	27,460	130
R16837	<i>Canis dirus</i>	radius	M-4	7.5'–8'	27,560	130
R48706	<i>Smilodon fatalis</i>	astragalus	L-11	11.5'–12'	27,620	150
R28227	<i>Canis dirus</i>	humerus	H-7	9.5'–10'	27,660	120
R54035	<i>Canis dirus</i>	radius	I-6	12.5'–13'	27,680	140
R45830	<i>Smilodon fatalis</i>	thoracic vertebrae	L-10	11.5'–12'	27,820	150
R50699*	<i>Canis dirus</i>	radius	I-6	12'–12.5'	27,860	140
R50952	<i>Canis dirus</i>	radius	I-6	11.5'–12'	27,890	130
R36962	<i>Canis dirus</i>	humerus	M-11	10.5'–11'	28,070	130
R23755	<i>Smilodon fatalis</i>	tibia	H-6	8.5'–9'	28,150	360
R34802	<i>Smilodon fatalis</i>	humerus	H-8	10.5'–11'	28,170	160
R22376	<i>Smilodon fatalis</i>	radius	I-6	8.5'–9'	28,240	160
R39006*	<i>Canis dirus</i>	radius	I-6	11.5'–12'	28,270	130
R50546	<i>Canis dirus</i>	tibia	M-11	11.5'–12'	28,310	170
R26134	<i>Smilodon fatalis</i>	tibia	I-7	9.5'–10'	28,320	140
R30312*	<i>Canis dirus</i>	radius	I-6	11'–11.5'	28,330	200
R22385	<i>Nothrotheriops shastensis</i>	calcaneum	I-11	10.5'–11'	28,350	240
R23621	<i>Canis dirus</i>	femur	I-7	8.5'–9'	28,360	160
R27065*	<i>Canis dirus</i>	radius	I-6	9'–9.5'	28,400	130
R41785*	<i>Canis dirus</i>	radius	I-6	9.5'–10'	28,430	140
R39292	<i>Canis dirus</i>	radius	I-7	10.5'–11'	28,510	380
R38722	<i>Nothrotheriops shastensis</i>	astragalus	K-8	11.5'–12'	28,530	240
R29823	<i>Canis dirus</i>	humerus	I-6	10.5'–11'	28,580	380
R36388	<i>Nothrotheriops shastensis</i>	cuboid	I-8	11'–11.5'	28,590	240
R39320	<i>Canis dirus</i>	humerus	I-7	11'–11.5'	28,620	200
R11704	<i>Puma concolor</i>	humerus	H-7	8.5'–9'	28,650	250
R54033	<i>Puma concolor</i>	radius	I-11	10'–10.5'	28,650	240
R34667	<i>Canis dirus</i>	thoracic vertebrae	M-11	9.5'–10'	35,800	400
R37351	<i>Canis dirus</i>	humerus	L-11	10.5'–11'	39,090	580
R18896	<i>Canis dirus</i>	radius	M-4	7.5'–8'	41,010	580
R15408	<i>Canis dirus</i>	tibia	M-4	7'–7.5'	41,800	800
R39004	<i>Canis dirus</i>	humerus	I-6	11.5'–12'	41,940	790
R49462	<i>Canis dirus</i>	innominate	H-7	11.5'–12'	43,000	720
R42645	<i>Smilodon fatalis</i>	metacarpal	H-8	11.5'–12'	44,300	850
R26494	<i>Canis dirus</i>	innominate	H-7	11.5'–12'	44,600	1100
R15199	<i>Canis dirus</i>	ulna	M-4	6.5'–7'	44,650	2830

using a Soxhlet apparatus with methanol, toluene, and benzene to remove gross petroleum contamination. Next, the bones were decalcified in 0.2N HCl and washed in 0.5% KOH; the collagen was extracted into hot acidic water to isolate gelatin. The gelatin was hydrolyzed to yield amino acids and a tarry, insoluble residue, and the hydrolysate was passed over the XAD resin. The gelatin extraction and XAD steps were especially effective in removing contamination sequentially (T. Stafford, personal communication, 2004). The isolation of individual amino acids required different concentrations of HCl to elute each amino acid from an ion-exchange resin. This technique has the potential of eluting petroleum residues remaining on the resin after the solvent washes. Removing the petroleum residues before placing the amino acids on the ion exchange resin eliminated the final source of contamination.

Surface-Modification and Orientation Data

Data on surface modification are from the Spencer et al. (2003) data set. Positional data for these specimens were taken from the original Pit 91 database, as were data for a small subset of bones (147 specimens)

for which strike-and-dip data were taken at the time of excavation (Shaw, 1982). Strike and dip were obtained for 21 specimens of the dated bones through polar-coordinate transformation of the XYZ data in the original data set.

Shipman (1981) describes a method for determining if orientation data are random, which involves calculating the percentage of bones that would be found in each directional bin if the distribution were completely random (i.e., an equal number of bones in each bin). The actual percentages are then found, and counts above what is predicted under random distribution are tallied. If this tally is over 33%, then the bones are considered to have a distribution pattern that is nonrandom.

To investigate if there has been settling in Pit 91, bone density versus depth was analyzed. The hypothesis is that denser bones should settle more readily than lighter ones. A regression was performed on the bone density of 170 adult *Bison* sp. bones versus depth. Density was taken from findings on modern vertebrae of *Connochaetes taurinus* from Lam et al. (1999) and were used as the density for the bison bones. A possible explanation for the pit-wear data is that bones that have been in the deposit longer have had more time to accumulate furrows. Again, a pre-

FIGURE 3—Distribution of dated bones within Pit 91. Points representing individual bone ages are ordered from youngest to oldest (left to right). Error bars show estimated error (95% confidence intervals) of radiocarbon dates, although some error bars are so small as to be obscured by the data-point markers. Note the tendency of the dates to cluster, with three distinct depositional episodes.

liminary test was performed with the small sample of dated bones that have pit-wear data ($n = 36$) to explore the possibility that pit wear correlates with age of the bones.

All statistics and graphical representations were performed with SPSS, v.11, Microsoft Excel, v.X, JMP, v.3, and the R Package, all for Mac OS X. All specimens are housed within the George C. Page Museum, a subdivision of the Natural History Museum of Los Angeles County.

RESULTS

Radiocarbon Dates

The radiocarbon dating method gives very precise dates; the average standard error of dates over all samples is ± 344 yr. The error increases with age, and if the nine oldest dates are removed, this average is halved to 171 yr. The 46 dates suggest three distinct episodes of entrapment, confirmed by K-Means clustering, pseudo-F-statistic < 0.001 : (1) a diffuse episode from 45,000 to 35,000 yr ($n = 9$), (2) a short, concentrated, interval from 26,500 to 23,000 yr ($n = 36$), and (3) 14,000 yr ($n = 1$; see Fig. 3). Notably, the earlier entrapment times appear to have begun suddenly and then tapered off, implying that the seepage of tar to the surface started suddenly, capturing many animals relatively quickly, and then gradually ceased. It should be noted that the single specimen, a *Canis dirus* radius, that yielded the youngest (14,000 yr) date is from a disturbed area of the pit, and so it is possible, and perhaps likely, that this specimen was not actually from Pit 91.

When stratigraphic depth is examined relative to radiocarbon age, it is apparent that the law of superposition, which states that older fossils lie below younger fossils, does not hold for this pit, and that some time averaging has occurred (Fig. 4). In Pit 91, older bones are found above younger bones. This implies that bones have moved vertically after deposition. Older bones may have risen relative to younger ones, or younger bones may have sunk or been pushed beneath older bones. To investigate this further within a more constrained spatial context, 12 bones were dated from one grid, I-6. The spatially restricted bones show the same lack of predicted superposition (Fig. 5). Dates for seven left radii of dire wolves were examined from grid I-6 because there is the possibility that dated bones were from a few individuals whose bones skewed the results, since those from the same individual would have similar radiocarbon dates (Table 1). These dates all come from the middle depositional epi-

FIGURE 4—Side view of Pit 91 showing depths of dated bones. Bone depth is shown by grid position. Age of bone or bones found within a certain grid is represented by patterns that correspond to depositional episodes (see text). If two patterns are included in a grid, two bones of different dates were found within that grid; $\times 2$ and $\times 3$ indicate that two or three bones, respectively, of the same age were found within that grid.

sode (26,500–23,000 yr), and are not clustered at the same depth; they are spread throughout the depth of the pit, from 8'6" to 12'6".

As a further test of any correlation between depth and age, a Mantel's test was performed on the bones for which both types of data were available ($n = 41$). A Mantel's test compares two distance matrices in order to determine whether the matrices are similar by finding the correlation between these distances using a permutation algorithm. In this case, we tested whether bones that are separated widely in depth are also separated widely in age. Both age and depth were standardized to z-scores, and distance matrices were calculated for each variable. The Mantel's test on these matrices showed them to be dissimilar (Mantel's $r = -0.057$, $p = 0.576$), demonstrating that age and depth are not correlated and that time averaging occurred. In addition, the number of furrows on bones does not correlate with time ($r^2 = 0.014$, $p > 0.45$).

Bone Distribution and Orientation

The distribution and orientation of all bones throughout the pit were investigated to explain the possible mixing inferred from the distribution of dated bones. A plot of 23,000 mammalian bones within Pit 91 for which positional data were available (Fig. 6) shows that the bones are

FIGURE 5—Temporal distribution of bones from grid I-6. Points represent ages of individual bones, and error bars indicate 95% confidence intervals. Dotted horizontal lines separate depth categories.

FIGURE 6—Plots of all large mammalian bones from Pit 91. A) View from the north (with East and West as marked). B) Plan view, with cardinal directions as indicated.

unevenly distributed throughout the pit, with three apparent concentrations within the three-dimensional space (see Figs. 1 and 6): one relatively shallow concentration in the northeast corner (9,294 specimens), one just southwest of this that covers the entire depth of the pit (10,489 specimens), and a large and deep concentration on the west side of the pit (10,864 specimens; note that not all specimens are plotted owing to their density). The latter two concentrations may actually be part of a single large concentration that was disturbed by the early (1915) excavations. These were shallow excavations that removed bones without shoring up the sides to prevent collapse (Shaw, 1982). In Figure 6, each fossil is represented by a single point; thus, there is no indication of bone orientation, size, or shape and no way to visualize whether adjacent bones might be clustered in similar orientations. Nevertheless, these plots show that bones are not evenly distributed throughout the pit and reveal denser concentrations of bones both laterally and vertically.

The orientation of bones was investigated as a measure of transport in the pits. If there was substantial flow in the deposit, caused by either movement of water over the tar prior to deposition or movement of the tar itself after deposition, long bones should align with the direction of flow (Voorhies, 1969). A subset of 147 long bones was chosen from those bones for which strike and dip were measured in the field. Although Pit 91 bones show a slight preference for being oriented N-S or NW-SE, this preference is only slightly above Shipman's criterion for nonrandomness (38.7% vs. 33%; see Fig. 7A), implying little lateral flow.

Many vertical bones could indicate vertical flow in the pit and might explain the lack of superposition of dates discussed earlier. Using Shipman's (1981) technique, we found that the distribution of vertical orientations did not differ significantly from zero (Fig. 7B; $\mu = 29$, $p < 0.0001$), implying little vertical flow. A subset of bones for which orientation data could be obtained from the XYZ coordinates of opposite ends of the bone ($n = 21$) was also investigated for orientation preference. These bones show no preferred cardinal direction (24.4% vs. 33% in Shipman's test). Their vertical orientation does deviate more from horizontal than the larger sample ($\mu = 31.5$), but this also does not differ significantly from zero ($p < 0.0001$). These tests assume that vertical flow is possible in the pit and that the motion is purely vertical, but this may not be the case (see the Discussion below).

Surface-Modified Bone

Depth was compared with three surface-modification variables—weathering, abrasion, and pit wear—for those bones for which wear and precise depth data were available ($n = 13,369$). The relationship between carnivore tooth marks and depth was not examined, as tooth marks are very rare (2% of the sample; Spencer et al., 2003). Evidence for weathering—caused by exposure to a subaerial environment prior to deposition—and abrasion—caused by fluvial transport (Shipman, 1981; Lyman, 1994)—is also rare. The majority of weathered specimens (93%) are in weathering stages 0–2, indicating short subaerial exposure, and nearly

FIGURE 7—Orientation for a sample of bones from Pit 91. A) Horizontal orientation represented by a rose diagram. Wedge length indicates the number of bones found oriented in that direction. B) Vertical orientation represented by a histogram. The x-axis is angle of dip, and the y-axis is number of bones found with a particular dip. The bone icons at the top give a graphical indication of dip.

half of the bones (48%) show no or minimal abrasion (Spencer et al., 2003). Average weathering stage shows no correlation with depth (Fig. 8A; $r^2 = -0.143$, $p > 0.1$); bones at the top of the pit are just as weathered as those at the bottom of the pit. Abrasion does correlate positively, but weakly, with depth ($r^2 = 0.034$, $p < 0.0001$). Inspection of the graph of average abrasion versus depth (Fig. 8A) reveals that this correlation is probably caused by a change in average abrasion stage at a depth of 88–98 inches, although this decrease represents a change of $<1^\circ$ of abrasion. Interestingly, this corresponds to a nonsignificant dip in weathering stage and may indicate a period of relatively rapid burial in the pit, when the bones experienced little aerial exposure or fluvial transport.

Pit wear is a surface modification unique to the tar pits and the amazing

FIGURE 8—Bone characters versus depth. A) Graph of average surface modification versus depth. Weathering and abrasion are measured in stages as defined in Spencer et al. (2003). Pit wear is measured as average number of pit-wear furrows per bone. B) Number of bones at each depth class. Depth is in inches in both graphs.

density of specimens, likely caused by bone-to-bone contact (Fig. 9; Shaw and Quinn, 1986). Pit wear does show a relation with depth, with deeper bones showing more pit-wear furrows than those at shallow depths (Fig. 8A; $r^2 = 0.113$, $p < 0.0001$). The deepest bones show the most pit wear, although there are fewer deep bones ($n = 144$ bones at a depth 148–158 inches). None of these correlations can be accounted for by poor sampling at different depths (Fig. 8B). A regression of bone density versus depth did not show that denser bones were found deeper in the pit ($r^2 = 0.006$, $p > 0.25$). This is also true when the test is limited to bones from just the second depositional episode, 26,500–23,000 yr ($n = 28$, $r^2 = 0.034$, $p > 0.30$). The small sample size, especially in relation to the large number of bones within the pit, may be limiting the power of these analyses.

DISCUSSION

Results from our analyses show a varied history of bone deposition, distribution, and transport through the pit. The most easily interpretable result is the episodic nature of entrapment as demonstrated by the radiocarbon dates. Marcus and Berger (1984) already established that the entire La Brea collection spans a long time (45,000–4,000 yr), and that deposition likely was not continuous. Our new dates support this view. The

FIGURE 9—Picture of a pit-worn bone (LACMHC 22121). Arrows indicate large pit-wear furrows.

pattern of two, possibly three episodes is also interesting and open to some interpretation. Entrapment seems to have started suddenly and tapered off at the end of an episode. The beginning of an entrapment period may have been a consequence of tectonic activity in the area. Southern California is one of the most tectonically active areas in the world, owing to its proximity to the San Andreas fault system (Quinn, 1992; Petersen and Wesnousky, 1994). Movement along a fault could have opened a new fissure, allowing asphalt to seep to the surface in a new area, while at the same time disrupting the source for a different asphalt pool. Seeps have been observed to migrate—stop flowing in one area and begin flowing in another—following major earthquakes in historical times (C. Shaw, personal communication, 2005).

The episodic nature of deposition is also supported by the shallow concentration in the northeast corner of the pit, corresponding to grids L4, L5, M3, and M4 (see Fig. 1). This concentration seems to be separated from the rest of the pit, and the dates obtained for bones from this pit are some of the oldest in the sample. Three of the four bones from this concentration are older than 35,000 yr (Fig. 4), although at least one of the bones is from the middle depositional period (26,500–23,000 yr). The mixing of dates within the deposit as a whole may be accounted for partly by these different areas of densely packed specimens. Bones deposited within one area may have been incorporated later into nearby concentrations, resulting in time averaging. In this case, older material from the northeast concentration could have eroded into the main concentration, accounting for the older ($>35,000$ yr) bones within the larger concentration, most of which are from the middle depositional period (26,500–23,000 yr). Studies of smaller-scale, micropaleontological sites have shown that time averaging more often happens from reworking, not mixing (Cutler and Flessa, 1990). The lack of evidence of abrasion does not seem to support reworking transport; however, if it occurred over a relatively short distance or through low-energy mechanisms, then there may have been no surface modification of the bones (Behrensmeier et al., 2000).

These new dates also allow for a better estimate of entrapment rates. In particular, the middle entrapment episode, 26,500–23,000 yr, covers a relatively constrained time span. If this is further limited by removing the seven youngest bones from the terminal tapering-off period, 29 bones remain (or 63% of the 46 dated specimens), spanning 28,600–27,200 yr—a period of only 1,400 yr. Spencer et al. (2003) estimated that there are at least 31 individuals of the most common large herbivores present in Pit 91—*Bison antiquus*, *Equus occidentalis*, and *Paramylodon harlani*. If it is assumed that the dated bones represent a random sample across the entire depositional history of the pit and that the herbivores were also trapped randomly during that same time, it is estimated that 63% of the herbivores, or approximately 19 of them, were trapped during the constrained 1,400 yr period. This gives an entrapment rate of one herbivore trapped about every 70 yr, which agrees well with the Marcus and Berger (1984) estimate of around one entrapment event every 50 yr.

The data from the orientation study suggest a lack of horizontal fluvial transport, in agreement with previous abrasion and weathering analyses (Spencer et al., 2003). If there was water-driven flow over the asphalt pool prior to deposition, then it would be expected that bones would align with the direction of flow or show a bimodal pattern with two clusters of orientations at right angles to each other (Voorhies, 1969). Orientation data show no preference for a particular direction or a perpendicular bimodal pattern. The vertical orientation data show that the orientations of the long axes of most long bones within the deposit do not differ greatly from horizontal. Some vertical motion may have been possible over the long periods that the tar seeps were active, but perhaps not with enough directional force to cause alignment. The sample size of the orientation data set is small, however, and a greater representation of the orientation of bones throughout the pit may reveal more subtle clusters of obliquely oriented bones.

The weathering and abrasion data imply that few bones were transported. This is similar to the finding of Spencer et al. (2003), although it is still unclear from these new data whether there is any three-dimensional clustering of the few worn bones. Data indicate that neither abrasion nor weathering varies significantly with depth but not whether they might be clustered by both depth and horizontal position simultaneously. The pit-wear data demonstrate a correlation with depth; bones with more pit-wear are found deeper in the pit. This may be the result of compaction, especially if, as hypothesized, pit-wear results from bone-to-bone contact and subsequent motion of the bones relative to each other. If the bones are denser than the surrounding matrix, and if any sort of postdepositional motion is possible within the pit, then they may have moved lower in the pit lower relative to the matrix. As more bones settled at greater depth, the concentration rose, allowing for pit-wear through bone-to-bone contact. The plot of bones versus depth (Fig. 8B) does point to an increase in bone number with depth, except in the very deepest grids.

The lack of correlation of bone density versus depth does not support a settling by density, although it cannot rule out some kind of settling. The crowding of bones within the pit may have prevented complete sorting according to density. This may also explain the lack of preferred orientation, if crowding of bones impeded the movement of bones relative to flow direction. Another possible explanation for the lack of sorting by density comes from recent findings that demonstrate that, once bones are permeated with asphalt at Rancho La Brea, they are similar in density to the matrix (L. Conyers, personal communication, 2005). The possibility of settling needs to be investigated further and may be elucidated by other spatial patterns found in the pit.

Although the orientation data suggest a weak or absent role of flow in bone transport, skeletons are always disarticulated in Pit 91; in some cases excavators have discovered widely separated elements from single individuals (S. Cox, personal communication, 2005). To obtain some idea of how far bones from a given individual may have been dispersed, the positions of four ankle bones of a putative individual ground sloth, *Nothotheriops shastensis*, were examined (Table 1). These bones are thought to be from a single individual because they were found relatively close

TABLE 2—*Nothotheriops* bone positions, given as the distance of each bone from the others. Horizontal distances are shown in the upper half of this distance matrix, vertical distances are shown in the lower half. Distances are in inches.

LACMRLP#	R36388	R38722	R22385
R36388 (left cuboid)		55.64	118.56
R38722 (right astragalus)	4		122.20
R22385 (left calcaneum)	12.25	16.25	

in the pit, articulate well (i.e., are of similar size), have similar weathering and abrasion stages, and have similar dates (Table 1). The elements were found at distances from each other of 4.5–12 feet horizontally and 4–16 inches vertically (Table 2). From this it can be inferred that bones from a given individual were transported laterally across a depositional plane but were not mixed much vertically. This transport could be the result of fluvial action, carnivore ravaging, or dispersal during trampling by other mammals. Orientation data do not support fluvial transport, and there is almost no evidence of trampling-induced scratch marks on Pit 91 bones. Spencer et al. (2003) demonstrated that carnivore ravaging probably played a role in the representation of bones from individuals found in the deposit. Although the ankle bones were chosen because they often do not disarticulate, even as a result of carnivore ravaging (Marean and Spencer, 1991), transport by carnivores is still a possible explanation.

The possible settling of the bones described earlier may also account in part for the finding of time averaging. This is true even when bones from the relatively small area of one grid are examined (e.g., I-6, Fig. 5). Trampling, as has been suggested by Shaw and Quinn (1986), may account for some of the mixing observed and certainly for some of the disarticulation and mixture of bones. The low frequency of scratch marks, a presumed indicator of trampling, runs counter to this (Spencer et al., 2003), but there have been no studies of bone trampling in such a plastic matrix. Other studies of transport by trampling showed maximum displacements of <16 cm (Graham, 1993), not enough to account for the displacements inferred by our dated specimens. Trampling a bone mired in asphalt may not leave the scratch marks normally associated with this modification. An actualistic experiment of trampling on bones in asphalt might reveal the markings, if any, that would be made in this situation.

The prospect of detailed microevolutionary analyses on taxa in Pit 91 is not promising, given the evidence of temporal mixing. Younger bones are not always found above older ones, even within the middle depositional episode, 26,500–23,000 yr, as evidenced by the data from grid I-6. Comparisons made with a statistically significant sample between the northeast concentration—with its predominantly older bones—and the larger concentration—mainly from the middle episode—could reveal change through time.

Preliminary analyses suggest that the depositional history of the tar pits is complex, as expected from their unusual sedimentologic characteristics. After an animal was entrapped in the asphalt, the journey taken by its carcass was not over. The lack of evidence of fluvial action, the disarticulation of the skeletons, and apparent time averaging all point to unusual postentrapment transport. Trampling is a possibility, but the near absence of scratch marks is inconsistent with this hypothesis. Data on bone orientation are minimal ($n = 147$ bones), and thus, the role of flow cannot be fully assessed. For example, excavators have noted other concentrations during their work, including a presumed overbank deposit and a concentration of water-worn bones (C. Shaw and S. Cox, personal communication, 2005) whose significance cannot be assessed with current data.

CONCLUSIONS

The La Brea tar pits provide a unique example of a fossil deposit as indicated by their depositional context, preservational quality, and quantity of data recorded for specimens. Recent studies have begun to use

these data to investigate the taphonomic history of this locality, with the hope that stratigraphic and temporal controls will allow for their use in studies investigating evolutionary trends across the Pleistocene-Holocene transition. This study builds on this work and attempts to put the taphonomic data in a spatial context. These results demonstrate a complex picture of depositional history within Pit 91:

1. Animals sampled represent two to three distinct intervals of entrapment: 45,000–35,000 yr, 26,500–23,000 yr, and possibly at 14,000 yr.
2. The law of superposition does not apply in these deposits; some time averaging has occurred, as younger bones are found commonly deeper in the deposit than older bones.
3. Bones are distributed throughout the pit, but two main clusters are present: one to the northeast, and a large central concentration. The cause of these clusters remains unclear.
4. There is no apparent clustering of bones with weathering or abrasive surface modification, but the most pit-worn bones occur deepest in the pit.
5. A preliminary set of orientation data indicate that most bones are near horizontal and have no preferred cardinal direction

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