

SECTION 1. GEOLOGICAL AND DEPOSITIONAL SETTING

The Cerutti Mastodon (CM) bonebed (Bed E) and strata preserving other invertebrate and vertebrate fossil remains were contained within a 12 m-thick series of flat-lying, late Pleistocene fluvial sediments that unconformably overlie the upper Oligocene Otay Formation and upper Pliocene San Diego Formation above an irregular erosion surface¹. Although not exposed at the surface, the Otay Formation and San Diego Formation in this area are in fault contact along a north-south fault splay of La Nacion Fault Zone². There is no evidence that the Pleistocene deposits are offset by this faulting. Overall, the Pleistocene sediments consist of cyclic sequences of fining-upward sedimentation units, grading from conglomeratic sands to silts. The most common lithologies are reddish-brown, fine-grained, micaceous, compact, silty sands and brown, poorly sorted, somewhat compact silts. Some of the silt beds contain large amounts of soil carbonate (caliche), as well as ped structures, suggesting development as paleosols in an overbank depositional setting. In addition, the conglomeratic sands are often cross-stratified, suggesting deposition in active stream channels. Together, these sedimentological conditions suggest deposition in a meandering river near base level.

Pleistocene sediments are widespread in the coastal region of San Diego County, although in most cases these sediments are associated with elevated marine abrasion platforms (terraces) that formed during periods of marine high stillstands on a rising coastline. Earlier studies have summarized the age and distribution of these abrasion platforms and their associated sedimentary covers and provided a terrace chronology for the coastal region^{3,4}. By far the most extensive Pleistocene marine terrace is the Nestor Terrace, which has been radiometrically dated at 120 ka and correlated with MIS 5e^{3,5}. The shoreline angle for the Nestor abrasion platform averages 22-23 m above mean sea level (amsl) and serves as a proxy for the relative position of

sea level in this area during MIS 5e. Largely because of faulting associated with La Nacion Fault Zone and the Rose Canyon Fault Zone to the west², there are no exposures of the marine Nestor Terrace in the immediate vicinity of the CM site. Consequently, it is not possible to directly correlate the Pleistocene CM and Nestor Terrace stratigraphic sequences by reconstructing paleo stream gradients. It is noteworthy, however, that the Nestor Terrace shoreline angle is below the elevation of the CM bonebed (~45 m amsl), which lies approximately 6 km inland from the eastern shore of present day San Diego Bay. The resulting minimum elevation difference between the CM site and the Nestor Terrace shoreline angle is 23 m, which suggests a gradient of ~3.8 m per km compared to ~2.1 m per km for the modern Sweetwater River in its lower reaches. This difference in gradient suggests that the Pleistocene surface at the CM site is older than the Nestor Terrace (i.e., older than 120 ka).

The microstratigraphy at the CM site consists of four primary horizons, including in ascending order: Bed C (a 105 cm-thick, rusty brown, massive, micaceous silt), Bed D (a 21 cm-thick, yellowish, fine- to coarse-grained, massive to cross-bedded, friable, arkosic sand with heavy mineral laminations), Bed E (a 20-30 cm-thick, medium brown, massive, sandy silt with abundant carbonate nodules, calcified root casts and pyrolusite staining) and Bed F (a 20 cm-thick, rusty brown, massive, clayey silt with common small carbonate nodules).

With the exception of some shells of pulmonate gastropods and rodent teeth from Beds D and F, the vast majority of fossils recovered from the CM site were recovered from Bed E and consist of mineralized bones, bone fragments and teeth of a single individual of *Mammut americanum*. Other fossils collected from Bed E include remains of rodents, birds, reptiles and terrestrial invertebrates. There was no articulation of mastodon skeletal elements and no anatomical trend to their position in the bonebed. Many bones are fragmentary and display

distinct types of breakage. In one case, refitting pieces of a single mastodon molar were found spread over three different grid units (Fig. 1c). The anterior half of the tooth (CM-286) was found in grid unit E3, while the posterior half (CM-103) came from grid unit C1. An enamel cusp fragment (CM-148) of this same tooth was found in grid unit D2. The greatest concentration of bones came from grid units D3 and E3, which contained portions of molars, long bones, and ribs (Concentration 1; Fig. 1). Of special note was the discovery of both femur heads side-by-side, one (CM-252) with its articular surface up and one (CM-258) with its articular surface down (Extended Data Fig. 3b). Adjacent to the femur heads lay fragments of ribs, one of which (CM-253) was found lying directly on a pegmatite cobble fragment (CM-254). Also found in this concentration was a large piece of femoral diaphysis displaying distinct spiral fracturing and evidence of percussion (CM-288; Fig. 1c; Extended Data Fig. 4a-e; Supplementary Video 3). In grid units J4 and K4 a large, spirally-fractured piece of long bone (CM-340) was found with a distinct impact notch (Fig. 2d; Supplementary Video 4). This fractured bone occurs adjacent to two complete thoracic vertebrae and two complete ribs (Fig. 1a). In grid unit B2 the distal 70 cm of a tusk (CM-56) was found distal end down in an upright orientation (62°-64° dip), concave curvature to the south. The proximal end of the tusk had been removed by the backhoe at the level of Bed E (shown as a circular feature in grid unit B2; Fig. 1a; Extended Data Fig. 3c). The tusk extended from Bed E through Bed D, reaching 65 cm into Bed C (Extended Data Fig. 7c). Coarse-grained sand matrix from Bed D was found as an infilling alongside the tusk some 40 cm into Bed C.

In contrast to the disarticulated condition of the mastodon remains was the discovery of a partially articulated skeleton of *Fulica americana* (American Coot) collected in grid unit B5. The entire pectoral region, including the right and left wings and coracoids, was found still articulated

with the sternum. Articulated portions of the legs were also recovered. In addition, several rodent skulls recovered from Bed E were found with articulated lower jaws.

The large cobbles and smaller cobble fragments recovered from Bed E (Fig. 1a; Extended Data Fig. 3e, f) consist of fine-grained metavolcanic cobbles (andesite) and coarse-grained plutonic cobbles (pegmatite). These lithic clasts range from approximately 1 to 30 cm in diameter. The more intact, larger cobbles display smoothly rounded surfaces, while many of the smaller cobble fragments have sharp, angular edges that lack signs of abrasion. Of the larger cobbles (>20 cm), four are andesites (CM-7, 114, 281 and 383) and one is a pegmatite (CM-423) (Fig. 4a, e, f; Extended Data Fig. 5g, h). There are several instances in which cobble fragments and/or large cobbles found separated in the bonebed could be refitted after laboratory preparation (removal of caliche). In the case of the large cobble (CM-423) found in grid unit G5, six cobble fragments in grid units D3, E2 and E3 were refitted to it (Supplementary Video 7). The grid unit E2 cobble fragment (CM-109) was separated by over 3 m of bonebed from the parent cobble (CM-423) in grid unit G5. Several other small fractured pegmatite cobble fragments were also found in Concentration 1 that could not be refitted to the large cobble. However, it is plausible that all these pegmatite cobble fragments are part of the same original cobble.

Approximately 7,300 kg of Bed E matrix was stockpiled and screenwashed. The washed concentrate produced isolated dental remains of small mammals including rodents (e.g., *Microtus*, *Neotoma*, *Peromyscus* and *Thomomys*) and rabbit (*Sylvilagus*). Calcareous nodules/internal shells of a slug (*Deoroceras*), were also recovered from the washed concentrate.

SECTION 2. SEDIMENT ANALYSIS

Soil stratigraphic, pipette grain-size, thin section and x-ray diffraction analyses (Extended Data Fig. 1b, c) of the CM bonebed (Bed E) and the beds immediately above and below (Beds F

and D, respectively) suggest low-energy fluvial deposition followed by pedogenesis. Soil and sediment descriptions reveal a well-developed Bt-Bk-C profile (Beds F, E and D respectively) with moderate to strong, very coarse, angular to subangular blocky structures in the Bt and Bk horizons (Extended Data Fig.1b, c; Supplementary Table 1). Clay films on ped faces and pedogenic carbonates are present. Further evidence for pedogenesis is provided by root etching on mastodon bones and rhizohalos in the Bk horizon⁶. Total sand from sediment size-analysis reveals a clear upward-fining sequence through the Bt-Bk-C profile (Extended Data Fig. 1c). These data, coupled with the presence of cross-bedding in the C horizon in Bed D (Extended Data Fig. 1b) indicate fluvial deposition. Total clays increase near the top of the Bt and Bk horizons and decrease with depth through each horizon (Extended Data Fig. 1c), another typical pedogenic signature. X-ray diffraction of the clay minerals in Bed E suggests that they are dominated by smectite, an indicator of soil development. Thin section analysis of sediments in Bed E reveals subangular granitic mineral grains; these also are dominant in the fluvial cross-bedded sands of Bed D. This suggests that beds D and E have the same lithologic source and is strong evidence that both beds were stream-deposited.

Supplementary Table 1. Soil and sediment descriptions. Color: refers to comparison with Munsell soil color chart value. Structure: 1-weak, 2-moderate, 3-strong, f-fine, m-medium, vc-very coarse, abk-angular blocky, sbk-sub angular blocky. Consistence: Wet; so-nonsticky, s-sticky, vs-very sticky, po-nonplastic, vp-very plastic. Dry; so-soft, h-hard. Pores: 1-few, 2-common, vf-very fine, f-fine, m-medium. Texture: LS-loamy sand, SiC-silty clay. Clay films: 1-few, f-faint, d-distinct, pf-ped faces. Stage: refers to the amount of soil-carbonate accumulation based on four-stages from low (I) to high (IV).

Layer	Horizon	Color	Structure	Gravel %	Consistence		Pores	Texture	Clay films	Stage	Notes
					Wet	Dry					
Bed-F	Bt	10 YR 6/4 (dry) 10 YR 4/3 (wet)	2/3, vc, abk/sbk	0	s/vs, vp	h	1m, 2f/vf	SiC	1, f, pf	I+	none
Bed-E	Bk	10 YR 6/2 (dry) 10 YR 5/3 (wet)	2/3, vc, abk/sbk	0	s/vs, vp	h	1m/f, 2vf	SiC	1, f/d, pf	II+	mastodon layer, root etching on bones
Bed-D	C		1, f/m, sbk	0	so, po	so	1m, 1vf	LS	none		trough cross-bedding

In summary, the depositional environment for Beds D, E and F represents a slowly aggrading fluvial system. A flood plain depositional setting is strongly supported by sediment particle-size data. Post-mortem, the mastodon bones and associated cobbles eventually were buried by continued low-energy fluvial deposition. The pedogenic A horizon, which likely formed on a paleo-landscape above the mastodon bonebed, has been removed by erosion. As the Bt and Bk horizons developed, pedogenic clays and calcium carbonate accumulated, and some of the bones and cobbles became encased in calcium carbonate. This pedogenic evidence indicates that although erosion removed the A horizon developed at the top of Bed E, the preserved portion of Bed E consisting of the developed Bt and Bk horizons is undisturbed by later fluvial or other geologic processes.

Alternative explanations for the formation of the bonebed, for example high-energy flood deposits and plunge pools formed during high-flow conditions, can be rejected for several reasons. High-flow conditions would have size-sorted the bone and cobble fragments with less dense fragments being deposited far downstream. Two sets of mammoth remains have been recently excavated from plunge pool deposits in the central United States. At the first site⁷, the mammoth died on a point bar and desiccated to the point that the skull fragmented, the molars became isolated and the tusk disintegrated into fragments. A subsequent flood event redeposited generally oblong elements over the end of the point bar into a small plunge pool. Here molars, a phalanx and several tusk fragments were found in a jumbled accumulation. Subsequently, complete limb elements were found on the point bar deposit upstream. The second site was in an alluvial fan setting (report in progress). Less dense elements like rib fragments, vertebrae and the brain case were distributed down a narrow paleo-gully and deposited in a pile in a plunge pool with elements lying at high angles of repose. At both these sites, size and density similarities

determined which elements were differentially moved in relatively high-energy fluvial events. These conditions are quite dissimilar to the CM site where elements of all sizes and density, including large cobbles and tiny bone fragments, were found distributed in a 20-30 cm-thick deposit of silts and fine sands with no evidence of disturbance by high-energy fluvial events.

The lack of evidence of high-energy fluvial conditions at the CM site also calls into question possible alternative explanations for the occurrence of tusk CM-56, which was found vertically oriented and extending from Bed E down into the underlying strata through Bed D into Bed C. What strictly fluvial conditions could be responsible for orienting one tusk (CM-57) horizontally and the other (CM-56) vertically? And besides human activity, what purely biological conditions could be responsible for this taphonomic pattern? It appears to be impossible that a mastodon could somehow force its own tusk into the underlying deposits, because the mastodon would have to have been positioned completely vertical to drive its tusk into the deposits at the required angle (Extended Data Fig. 7c). With geological and biological processes eliminated, the most reasonable hypothesis for the vertical orientation of the tusk is that the tusk came out of the skull naturally, or possibly was removed from the skull by humans, and that the tusk was then purposely socketed by humans deep into the underlying deposits for some unknown reason.

SECTION 3. USEWEAR AND IMPACT MARKS ON CM HAMMERSTONES AND ANVILS

CM-7, Andesite Cobble.

This cobble measures 27.4 cm-long, 15.6 cm-wide and 15.7 cm-thick and weighs 8.85 kg (Extended Data Fig. 5j). The cobble was found on the eastern margin of Concentration 2 (Fig. 1a). One corner of the cobble was hit by the backhoe when the site was first discovered and has a small amount of damage along one edge over a distance of 95 mm. This modern damage is easily

recognized by the fresh coloration of the fracture. An unknown, but significant, part of the cobble is missing as indicated by a fracture plane forming a flat edge that occurred prior to the time of burial when the CM site formed and before excavation. A flake (CM-141) that refits to the broken surface (Extended Data Fig. 5m) was found *in situ* two meters from CM-7. Numerous sharp andesite fragments were also found in the general area and although they do not refit to the cobble, they may have come from the missing part of the cobble. Cobble CM-7 is hypothesized to have been used as a hammerstone based on the presence of usewear and impact damage, its position away from the main concentrations of fractured bone and molars, the breakage pattern and the refitting flake that was found one meter from andesite cobble anvil CM-114 (Fig. 3). Usewear on the upper surface of CM-7 includes relatively fresh fractures (step scars, undetached flakes) and impact features (Hertzian initiations) along two battered margins suggesting that CM-7 may also have functioned as an anvil. Several phases of wear formation are indicated by variation in the intensity of edge rounding (Extended Data Fig. 5l). The intensity of edge rounding is higher on the external platform edge of flake CM-141 than on the internal platform edge, which is relatively fresh. The edge rounding is also higher on the external platform edge of flake CM-141 than on the battered margins of CM-7.

CM-114, Andesite Cobble.

This cobble measures 19.9 cm-long, 16.2 cm-wide and 11.3 cm-thick and weighs 4.15 kg. The cobble was found at the center of Concentration 2, which contained impact-fractured bone and molar fragments and broken andesite fragments (Fig. 1b). The upper surface exhibits breakage, including fresh fracture surfaces with thin pieces of the cobble cortex missing. The breakage appears to occur along a pre-existing natural fracture plane and is hypothesized to be damage from impact. The underside of the cobble is relatively flat, which would have provided a

solid base for its use as an anvil. There is a flake scar present on this under surface, although the flake was removed before the cobble was introduced to the site, as indicated by the rounded edges of the flake scar. However, along the proximal edge of the old flake scar (which forms a relatively low edge angle with the upper cobble surface), there are fresher fractures and impact scars, including undetached flakes. The latter are similar to fresh scars on the upper surface ridge and indicate stone-on-stone impact. The weathered upper cortical surface also has small zones with striations and abrasive polish consistent with impact on bone and stone. CM-114 is interpreted as an anvil based on its location at the center of this concentration, its relatively small size (probably too small to be an effective hammerstone) and usewear on the top of the cobble.

CM-383, Andesite Cobble.

This round flat cobble measures 23.7 cm-long, 22.5 cm-wide and 10.7 cm-thick and weighs 7.6 kg (Fig.4e, f; Extended Data Fig. 3e). The cobble was found approximately 2 m southwest of Concentration 1 in grid unit H4 (Fig. 1a). The cobble exhibits macro- and microscopic wear on the surface that was found lying upward, with the under surface exhibiting a rougher surface texture. There is an impact flake removed from one edge on the under surface (Fig. 4h). The flake scar appears fresh and occurs on an older broken surface that exhibits extensive rounding. The flake removed the weathered light tan surface of the cobble. The flake scar exhibits an impact point, radiating lines of force and a feathered termination. The flake scar is 24.2 mm-wide at the point of initiation, expands to a maximum width of 28.2 mm and is 25 mm-long. A small ovoid flake scar that terminates in a hinge fracture occurs within the larger flake scar. This secondary flake scar is 8.9 mm-long, 13.5 mm-wide at the point of initiation and 8.9 mm-long. There is an area of impact damage to one side of the flake scar. This area exhibits an incipient flake crack. The cobble experienced at least two blows in this area. CM-383 is

hypothesized to have been used as a hammerstone, although it could also have served as an anvil based on the use wear present on the upper face of the cobble.

CM-281, Andesite Cobble.

This long, thick, domed cobble measures 29 cm-long, 18.6-cm wide and 14.7 cm-thick and weighs 8.3 kg (Fig. 4a). This cobble was found at the center of Concentration 1 with impact-fractured limb bones including three impact flakes, one impacted femur segment, one impact-broken molar fragment, broken pegmatite fragments from a hammerstone, and other broken fragments of bone, molars and andesite (Fig. 1b). The cobble exhibits macroscopic and microscopic wear along a 103 mm-long ridge on the upper surface. Oriented in line with striations and, along this upper edge, are small flake scars with step terminations indicating stone-on-stone impact (Fig. 4b-d). Based on its location at the center of Concentration 1 and usewear, CM-281 is interpreted as an anvil.

CM-423, Pegmatite Cobble.

This is the largest cobble discovered at the site, measuring 29.8 cm-long, 26.4 cm-wide and 13.8 cm-thick and weighing 14.45 kg (Extended Data Figs 3f and 5g). The cobble is even larger when six refit pieces (CM-109, 254, 262, 283, 284 and 304) are included (Fig. 3; Supplementary Video 7). With the refitting pieces the cobble weighs 18.25 kg. The cobble was found approximately 2 m southwest of Concentration 1 in grid unit G5 (Fig. 1a). Five of the six refitting pieces were found within 0.5 m of andesite anvil CM-281 in the center of Concentration 1 (Fig. 3). Two other small fragments of fractured pegmatite that were probably part of this hammerstone were also found, but have not been refitted to CM-423. This pegmatite cobble exhibits very coarse crystalline structure including large feldspar phenocrysts which cause natural fracture (cleavage) planes in the cobble (see description of CM-254). Percussion impact

is indicated by deep cracks and macroscopic pitting at one end, where the cortical surface has been removed (Extended Data Fig. 5h). CM-423 is interpreted to be a hammerstone based on its size, breakage patterns, refits with other fragments found associated with the anvil and surrounding impact-fractured mastodon limb bone and evidence of impact.

CM-254, Pegmatite Cobble.

This is the largest pegmatite fragment that refits onto cobble CM-423, measuring 17.6 cm-long, 12.4 cm-wide and 8 cm-thick and weighs 2.15 kg. The cobble was found in Concentration 1 with fractured bone, broken andesite and pegmatite fragments and broken molar fragments adjacent to andesite cobble anvil CM-281 (Fig. 3). CM-254 was found with the outer surface down and the broken surface upward and in direct contact with an overlying broken rib (CM-253). A broken bone (CM-263) was found lying beneath CM-254, and can be refitted with CM-255. There are large feldspar phenocrysts at both broken ends of this cobble that broke along cleavage planes, probably when the tip of the hammerstone separated from the main body of CM-423 during a percussion event. CM-254 has rare patches of abrasive smoothing with fine striations but no clear examples of impact (e.g., pitting caused by hammer blows) that are typically, but not always found on stone pounding implements used to break bones. CM-254 is interpreted to be the tip of a hammerstone based on usewear, breakage patterns, refits with other fragments found associated with the anvil and with the large cobble CM-423, and its association with impact-fractured mastodon limb bone around the anvil.

Andesite Cobble Fragments, CM-1, 49, 53, 87, 93c, 228 and 431.

These seven andesite fragments were found in Concentration 2 (Fig. 3), and although they all can be refitted together, they do not refit with any recovered larger cobbles and may indicate the presence of a sixth cobble based on their very smooth outer surfaces which do not

match surfaces on the other andesite cobbles. There is also a possibility that these reassembled andesite fragments are part of the missing portion of hammerstone CM-7 and just have smoother outer surfaces than those preserved on CM-7.

SECTION 4. PROBOSCIDEAN TAPHONOMY – NATURAL VERSUS CULTURAL MODIFICATION OF LIMB BONES

Taphonomy of the CM bonebed is best explained within the broader context of the mechanics of bone breakage. Once the mechanics of bone breakage are defined, it is then possible to determine whether natural or anthropogenic processes modified CM proboscidean limb bones. Natural processes that can modify proboscidean limb bones include environmental, geologic and non-cultural biologic factors, including carnivore activity, trampling by other animals and rodent gnawing. Human use of proboscidean limb bone typically is characterized by a percussion technology used to break limb bones for marrow extraction and tool production⁸.

Mechanics of Proboscidean Limb Bone Breakage

Comprehensive reviews of the mechanical principles of bone taphonomy have been published^{8,9} and provide a rigorous context for exploring the modifications present, or significantly absent, on bone from the CM site.

Three categories of bone fracturing processes have been described, including passive fracturing, static fracturing and dynamic fracturing⁸. Passive fracturing occurs when weathering, which causes desiccation (drying) and chemical decomposition of bone, induces microscopic cracks between the collagen bundles in the bone structure⁸. Because the time required for total bone destruction by weathering can vary depending on the skeletal element involved (e.g., femur vs. rib) and on multiple environmental factors (e.g., temperature, humidity or seasonality), it has been possible to establish a graded series of bone weathering stages¹⁰. Weathered bone does not

retain the viscoelastic and ductile properties of fresh (green) bone. Characteristic modifications of weathered long bones include a series of perpendicular, diagonal or right angle offset fractures caused by tension failure, especially when the bone is later subjected to external forces such as dynamic or static fracturing processes.

Static fracturing is caused by applying constant compressive forces that are evenly distributed⁸ such as those produced by carnivoran bite forces or sediment loading. Dynamic fracturing is caused by high velocity impacts that produce compression, twisting and shearing forces⁸. The characteristics of fractures produced by static and dynamic fracturing processes depend on whether the bone is desiccated or fresh. Desiccated bone exhibits dry-bone fracture patterns that include longitudinal or perpendicular fracture planes with rough surfaces. Bones with spiral fractures⁸ and fracture planes with smooth surfaces¹¹ indicate the bone was broken while fresh (green), but do not conclusively identify the agent that caused the fracture^{8,9}. Dynamic fracturing of fresh bone is, however, a characteristic of hominin action because percussion technology is used to modify bones for nutritional or manufacturing purposes.

Certain bone surface features are also indicative of dynamic fracturing of fresh bone because they indicate a viscoelastic response to tensile and compressive forces. Characteristic features include hackle marks, which are stress relief fractures concave to the origin of impact, step terminations that indicate interruptions in the propagation of force and cone flakes and negative impact scars that are a response to compressive force⁸.

Weathering

Evidence indicating weathering of bone at the CM site is variable. The majority of limb bones do not exhibit extensive weathering cracks (i.e., weathering stage 0 or 1¹⁰), while ribs and vertebrae exhibit some cracks that represent wetting and drying processes and/or diagenetic

processes related to formation of pedogenic carbonate (caliche). All weathering-like features appear to post-date the disarticulation and burial of CM bones. In addition, some limb element fragments e.g., CM-288) with unweathered surfaces are spirally-fractured, with smooth curvilinear fracture planes indicating that the bone was broken while it was still fresh (Extended Data Fig. 4a-e; Supplementary Video 3). Some CM elements (e.g., CM-340) preserved within carbonate concretions exhibit dry-bone breakage that is attributed to post-depositional diagenesis during or after pedogenic carbonate deposition (Supplementary Video 4).

Geologic Processes of Proboscidean Limb Bone Modification

Two geologic processes that might modify proboscidean limb bones at the CM site were considered; fluvial transport and sediment loading. Soil analysis (Supplementary Information section 2), as well as the presence of very small bone fragments and a fragile semi-articulated skeleton of an American coot (SDNHM 51967, 20 associated elements) within the CM bonebed attest to a low-energy overbank deposition of silt and fine sand. This low-energy depositional regime indicates transport by water was not a factor in moving the bones and cobbles or causing the observed breakage patterns.

The weight of overlying sediments (sediment loading) can sometimes break light bones after they have dessicated⁹. However, dry bone breakage patterns are easy to recognize and the resulting dry-fractured fragments typically lie close together. There is no evidence of sediment loading on the CM mastodon bones. However, there is dry-bone fracturing evident on some elements that were encased in pedogenic carbonate concretions, apparently the result of wetting and drying cycles and/or diagenesis during formation of the concretions. Post-depositional dry-bone fracturing, as evidenced by longitudinal and perpendicular fracture planes with rough surfaces is distinguished from the spiral fracture patterns produced by dynamic fracturing of

fresh bone noted on the majority of CM limb bone fragments. There is no evidence at the CM site that geological processes caused breakage of fresh mastodon limb bones.

Biologic Processes of Proboscidean Limb Bone Modification

Two biologic processes, carnivoran gnawing and trampling by large mammals, are known to fracture bone⁹. However, fresh cortical proboscidean limb bone is rarely broken by either agent¹².

Carnivoran gnawing is a common phenomenon in the paleontological record⁹. Bone modification by large carnivorans is limited by jaw size and muscle strength, nutritional content of the bone and access to alternative foods. Carnivorans extract nutrients from bone by gnawing first at the articular ends of the limb bone where the cortex is thin and then proceeding into the diaphysis of the bone. Carnivorans cannot break adult or near-adult proboscidean limb bones at mid-shaft^{8, 13}.

This view is supported by observations at numerous excavated proboscidean sites^{14, 15, 16, 17, 18}, and examination of proboscidean remains in museums in Canada, Mexico, and the USA. No evidence for breakage of adult or near-adult proboscidean limb bones at mid-shaft by carnivorans has been identified. Occasionally carnivoran gnawing has been observed on the articular ends of proboscidean limb bones in the form of gouges and tooth drag marks¹⁹, like those described below.

A taphonomic study of heavily gnawed elephant bones (*Paleoloxodon antiquus*) from late Pleistocene deposits in Germany concluded that the bones were modified by hyenas (*Crocuta crocuta spelaea*) and cave lions (*Panthera leo spelaea*), the largest late Pleistocene bone-processing specialists in the European carnivoran guild¹⁹. Hyenas were the predominant scavenger accounting for 95% of the damage on bone, which primarily consisted of tooth gouge

marks, gnawed epiphyseal ends of adult long bones and preferential preservation of cylindrical long bone diaphyses too thick for the carnivorans to break. That study provides convincing evidence that even the most specialized bone-modifying Pleistocene carnivorans could not break adult or near-adult proboscidean limb bones at mid-shaft. The fact that no tooth gouge marks, no gnawed epiphyseal ends and no cylindrical remnants of long bones were found at the CM site suggests that carnivoran bone modification was not responsible for the observed breakage patterns^{16, 20}.

Trampling of proboscidean bones by large mammals is most common around watering holes where drought or disease has caused mass die offs²¹. However, mass death sites around watering holes where trampling by other elephants has occurred are not an appropriate analogy for single death sites. One study²² has documented in detail bone scatters at seven sites involving single modern elephant deaths and recorded only two fractured limb bones at the seven sites and interpreted those fractures to be the result of the elephants thrashing around as they died. That study concluded that “The paucity of such fractured limb bones in scatters suggests that not much trampling or natural fracturing of weathered bone has occurred on the sites”²².

Another study discussed single-elephant death sites both around watering holes and away from watering holes²³. Evidence of trampling was found less frequently at single elephant death sites than at mass death sites around watering holes. The study concluded that bone scatters away from water sources are rarely affected by trampling and kicking, that even single death sites at water sources may not exhibit heavy trampling and that, “kicking and trampling are hit and miss processes, unless elephants return in large number to the site seasonally, in which case bones may be widely scattered and broken”²³.

Fracturing of proboscidean limb bones while still fresh is rare in modern single-elephant death sites, and no sites have been documented like the CM site, where fresh elephant limb bone is broken into numerous small spirally fractured fragments with evidence of multiple impacts. The femoral diaphyses found at the CM site are broken into small spirally-fractured pieces, whereas more fragile bones like ribs and vertebrae are complete, or more complete than the heavier and denser limb bones. This pattern of differential breakage is exactly the opposite of what is found where proboscidean bones have been extensively trampled. Under trampling, the lightest bones (e.g., ribs and vertebrae) are broken first and into much smaller pieces than the limb bones that have thicker cortical walls resistant to breakage²³.

A recent study of trampled bones from several animals of different body sizes, including elephants, found that trampling did not result in the production of impact notches like the one found on the CM limb bones²⁴. More experimental research is needed with larger samples to further understand the possible features of trampling damage to fresh proboscidean limb bones at single death sites. However, the typical surface features of bone modified by trampling²⁵ (i.e., randomly distributed surface abrasions/striations that intersect and overlap) are not found at the CM site. In particular, the specimens that show evidence of spiral fracture or impact show no evidence of trampling. We conclude that trampling was not responsible for the breakage of the CM limb bones.

Cultural Processes of Proboscidean Limb Bone Modification

Human use of proboscidean limb bone can best be understood within the framework of the technological process used to break bones for marrow extraction and/or tool production. Cultural processes that modify proboscidean limb bones and other bones have been studied for more than 60 years in Europe²⁶, 45 years in Africa²⁷ and 35 years in North America¹². Breakage

of proboscidean limb bone fits within a broader pattern of percussion technology used to break limb bones of large ungulates for marrow extraction that dates to 2.5 Ma at the Bouri Site in Ethiopia, Africa²⁸. Proboscidean limb bone modification using percussion technology by early members of the genus *Homo* began in Africa during the early Pleistocene^{27, 29, 30}. Fractured and flaked proboscidean limb bone, including one biface, has been reported from Olduvai in Tanzania in deposits dating to 1.2 to 1.7 Ma^{27, 29, 30}. One bone biface from the Konzo Site in Ethiopia dates to 1.4 Ma³¹.

A recent overview of Acheulian handaxe production from proboscidean bone lists two sites in Italy, one site in Germany, one site in Hungary and one site in Israel, all dating in the range of 0.5 to 0.3 Ma³². In another recent study, a proto-handaxe produced from proboscidean limb bone and a bifacially-flaked pick made from a proboscidean mandible were described from a site in southwest China that dates to 0.17 Ma³³. Upper Paleolithic humans in Europe had an extensive ivory and bone technology. This technology has also been identified in Japan, where proboscidean bone was bifacially flaked³⁴.

Impact-fractured proboscidean limb bone at Olduvai Upper Bed II dating to 1.34 Ma has recently been described³⁵ and includes two impact (cone) flakes like those found at the CM site (Fig. 2a-c; Supplementary Videos 1, 2 and 5). At Olduvai Upper Bed II, green bone fractures are common on limb bones of all species, especially giraffe and a large bovid, and impact flakes and notches are also recorded on all sizes of limb bones. Researchers concluded that “The presence of impact flakes [*cone flakes*] on carcasses of all sizes supports the contention that dynamic, hammerstone loading is largely responsible for the fragmentation of the appendicular elements”³⁵.

At the 1.3 Ma early Paleolithic site of Fuente Nueva-3 in Orce, Spain, bones of medium-sized animals (227-340 kg) and large ungulates (340-907 kg) preserve cutmarks and 42 percussion fractures, that led researchers to conclude that “Fracturing patterns in the skeletal elements indicate the bones were broken mainly by percussion when they were still in a fresh state. As a result, they show spiral fractures, impact points and flaking”³⁶. These breakage patterns are like those observed at the CM site. Modification of skeletal elements by percussion on animals smaller than proboscideans is recognized in the archaeological record by the presence of impact notches and impact (cone) flakes on thick cortical bone.

Three localities at the early Pleistocene Koobi Fora site in northern Kenya, Africa provide taphonomic evidence consisting of cutmarks and percussion marks on bones of several sizes of animals including proboscideans, indicating that hominins processed bones at 1.5 Ma³⁷.

In North America, the late Pleistocene Clovis people (identified by associated fluted projectile points), were impacting and flaking proboscidean limb bone at the Lange/Ferguson site, South Dakota, USA³⁸. Here an adult female and a juvenile Columbian mammoth (*Mammuthus columbi*) were trapped in a bog, and then killed and butchered by humans. Other proboscidean sites in the USA dating to the terminal Pleistocene and exhibiting impacted and flaked bone, include Lamb Spring, Colorado³⁹, Owl Cave, Idaho⁴⁰, Duewall-Newberry, Texas⁴¹, and Pleasant Lake, Michigan^{42, 43}.

The male mastodon excavated from the Pleasant Lake site peat bog deposits offers multiple compelling lines of evidence for patterned butchery of the left side of the animal by humans⁴². These include cutmarks and disarticulation marks made by either stone or bone tools on the articular ends of limb bones and the axis and atlas, impact notches on the humerus and a rib, multiple flakes removed from one element and wear patterns on expedient bone tools⁴⁴. The

only stone tool present was a large limestone cobble associated with some of the small spirally fractured bone fragments.

The acquisition of thick cortical limb bone segments for the production of either expedient or patterned bone tools requires the breakage of limb bones into smaller usable segments. The most efficient way to produce these tools is to break the limb bone at mid-shaft with a hammerstone. One study concluded that: “Actualistic and experimental studies have failed thus far to identify an agency other than hammerstone use by people that can induce fractures by point loading on fresh proboscidean limb bones”¹². Fresh proboscidean femora, where the straightest and thickest cortical bone is present, provide excellent material for tool manufacture. This suggests an explanation for the numerous missing pieces of cortical limb bone from the bone processing area at the CM site.

SECTION 5. EXPERIMENTAL BREAKAGE OF ELEPHANT (AND OTHER ANIMAL) LIMB BONE

Elephant limb bones, the best modern analogue for Pleistocene mastodon and mammoth bones, have been used by several researchers to replicate Pleistocene percussion technology^{16, 45, 46, 47}. Despite variations in age and gender of the elephant, cause and time of death, hammerstone percussion created similar helical fractures, impact notches and cone flakes in these experiments. Flaking of the cortical limb bone was conducted in some of the experiments. Both longitudinal and lateral flakes and attendant flake scars with distinctive bulbs of percussion were produced.

Two elephant bone breakage experiments were carried out with the overall goal of breaking proboscidean bones using Paleolithic bone percussion technology in order to determine if hypothesized methods produced end products that were comparable to those found at Pleistocene proboscidean sites. In both experiments it was necessary to have at least two people

present, one person to hold the elephant femur on an anvil and the second person to break the bone with a hammerstone.

The first experiment in Tanzania used one elephant femur and was designed to replicate the fracture patterns and anvil use hypothesized for the 18 ka La Sena Mammoth site^{14, 16} in the Great Plains of North America (see Methods). It was hypothesized that a curated hafted hammerstone with a tip about 5 cm in diameter was used to break the La Sena mammoth femur because no cobbles occur naturally in the vicinity of the site large enough to break mammoth limb bones and no cobble was found at the site. Native Americans of the North American central Great Plains used a curated hafted cobble hammerstone in the late prehistoric period to break bison bones because cobbles large enough to accomplish this task are absent over much of the western central Great Plains. A wooden anvil measuring 4 cm-wide was used to replicate the broken mammoth vertebra anvil found socketed vertically in the ground at the La Sena Mammoth Site¹⁶. The top edge of the La Sena bone anvil exhibited wear and it was surrounded by a concentration of small spiral-fractured limb bone fragments¹⁶ like the pattern of bone scatter around anvils at the CM site. In this case, the use of an expedient anvil is best explained by the lack of suitable large cobbles in the immediate area.

In the second experiment (see Methods section) an unhafted 14.7 kg granite cobble was selected (Extended Data Fig. 8b) because it is similar in size to the pegmatite hammerstone found at the CM site and in the same size range as hammerstones used by other researchers to break elephant limb bone^{16, 46, 47}.

Both experiments produced distinctive impact notches on limb bone cortex at the point of hammerstone impact (Extended Data Fig. 8c). Cone flakes (Extended Data Fig. 8d) were also

produced in both experiments. Impact-related damage and anvil wear (Extended Data Fig. 9a, b) from contact with the cobble anvil were also evident on the femora from the second experiment.

The bone assemblages produced by both percussion experiments show breakage patterns that are qualitatively similar to breakage patterns seen in the CM bone assemblage. In all cases, bones exhibit spiral fractures and smooth fracture planes as the result of green-bone breakage. Arcuate-shaped bone impact notches with negative medullary flake scars that extend through the entire cortical bone thickness into the medullary cavity⁴⁸ are present in both the experimental and CM bone assemblages. The morphology and features of impact notches produced experimentally and observed at the CM site indicate they were produced by percussion (dynamic loading)^{49, 50}. Both experiments were filmed (Supplementary Video 8), and still photographs were taken (Extended Data Fig. 8 a-c).

In a 2010 bone breakage experiment cow (*Bos taurus*) bone was used and one to three hammer blows were required to break each of 15 femora. Impact notches, cone flakes and anvil wear (Extended Data Fig. 9c, d) were produced that closely resemble those found at the CM site. In addition, a 1.7 kg argillite hammerstone (Extended Data Fig. 6h) was used to break cow bones on cobble anvils on two occasions for public educational purposes, although the number of blows was not counted. However, one blow struck the anvil and drove a flake off the hammerstone (Extended Data Fig. 6i).

Experiments using cobbles to break elephant and cow bones often result in significant damage to hammerstones when they accidentally impact anvils. Of the five hammerstones used in the experiments described above, three sustained significant damage when they struck an anvil, including one granite hammerstone that was rendered useless on the first blow when the whole tip broke. However, damage usually occurred in the form of flakes removed from the tip of the

hammerstone. Damage on granitic rocks, especially specimens with larger phenocrysts, was more pronounced than on finer-grained granite or andesite. For example, in another experiment, a small granite hammerstone (Extended Data Fig. 6k) used to pound bone (tibia of an adult kangaroo, *Macropus* sp.) on an anvil for only 10 minutes resulted in macroscopically visible pitting but in a very restricted zone (Extended Data Fig. 6l).

The main forms of usewear observed on the experimental pounding hammerstones and anvils (Extended Data Fig. 6) included macroscopic/low magnification traces: pitting (Extended Data Fig. 6a, c, e, g, h-l), crushing (Extended Data Fig. 6i, j), tool breakage (described above) and negative flakes scars with Hertzian and split-cone fracture initiations and step terminations (Extended Data Fig. 6h-j); as well as microscopic/high magnification traces: abrasive smoothing/polish with striations (Extended Data Fig. 6m) and crushing and small step fractures. Previous studies have shown that macroscopic and low magnification usewear on bone pounding tools is not common and is sometimes absent or at least difficult to distinguish from natural wear, particularly on waterworn quartzite cobbles (Extended Data Fig. 6; compare images 6f and 6g)^{51, 52, 53}. The most common macroscopic wear on hammerstones and anvils used to break bones, is probably from missed blows⁵¹. Conversely, a flaked flint chopping tool used to break bone on an anvil sustained massive damage along its used edge and caused extensive wear on the anvil (as observed on an experimental hammerstone and anvil of Dr. Veerle Rots, September 2016). The extent of impact damage on hammerstones and anvils is affected by petrologic properties such as internal flaws, resistance to fracture, technological form (whether flaked or natural) and shape (angularity or sphericity) especially when a hammerstone strikes an anvil. Pitting was present on all experimental hammerstones used to break bone and was especially pronounced with stone-on-stone contact (i.e. powerful missed hammerstone blows or when the

hammerstone slips off the bone and directly strikes the anvil, with less force). Macroscopic negative flake scars were visible on at least one experimental granite hammerstone; and microscopic fracture features (cones of percussion, crushed percussion ridges and undetached flakes) were visible on all experimental hammerstones. In addition, the force and location of blows and the microtopography of implements are likely to be major variables that determine where and if fractures occur and flakes are detached. Cobbles with smooth surfaces used to pound bone during experiments displayed minimal modification, as observed in previous studies with quartzite and basalt^{51, 52, 53}. However, with a low-angle point source of light, microscopic examination of pitted zones on granite and andesite hammerstones revealed striations oriented towards zones of crushing and relatively fresh conchoidal fractures. Oriented in line with striations and crushing on the experimental andesite hammerstone, small flakes were detached with step terminations at locations where relatively steep edges were encountered at the impact zone (Extended Data Fig. 6h-j). At high magnification, abrasive smoothing, striations and polish can be detected on impact zones where there has been stone-on-stone or bone-on-bone contact (Extended Data Fig. 6m). Consequently, the fresh impact features on CM hammerstones and anvils, visible at low and high magnification, are interpreted to be diagnostic of stone-on-stone contact and are consistent with the experimental wear patterns found on bone-breaking tools.

SECTION 6. TAPHONOMY OF SKELETAL REMAINS

Taphonomic analysis of the large mammalian remains from the project area is based on a comparison of the disarticulated partial skeleton of the Cerutti Mastodon (*Mammuth americanum*) with those of other partial skeletons of dire wolf (*Canis dirus*), horse (*Equus* sp.) and deer (*Odocoileus* sp.) recovered from adjacent strata. All of these specimens exhibited scattering and/or loss of some skeletal elements prior to burial but little abrasion or rounding. This pattern

is indicative of low-energy deposition in overbank settings of meandering and/or braided streams. Of these skeletal elements, only the CM remains exhibited extensive green-bone breakage of limb bones prior to burial. This is not seen in the other partial skeletons. Subsequent burial of the four partial skeletons occurred in low-energy, fluvial, fine-grained overbank deposits.

SDNHM Locality 3677 *Equus* sp. (SDNHM 47731)

Steve's Horse Quarry (SDNHM Locality 3677, Extended Data Fig. 7a) lies at an elevation of 44.8 m amsl. The skeletal remains were recovered from a yellowish-brown, massive silt that immediately underlies the sandy silts at SDNHM Locality 3767 Bed E¹ (see *Mammut* below).

The skeleton of *Equus* sp. (SDNHM 47731, size of *Equus* sp. cf. *E. scotti*¹) is approximately 41% complete (much of the left side of the specimen was damaged by excavation equipment and not recovered) (Supplementary Table 2). The bones exhibit no transport abrasion, no weathering and no scavenger tooth marks. No green-bone breakage was observed. Many of the bones show extensive post-depositional crushing, possibly due to sediment loading.

Voorhies Group Numbers (VGN)⁵⁴ apply to fully disarticulated skeletal remains and the transport susceptibility of individual elements. Although disarticulated, the *Equus* specimen was relatively complete, which suggests that removal of skeletal elements by fluvial transport was minimal. The podials and phalanges are 56% complete (Supplementary Table 2). These elements fall in VGN I and II and typically are the first to be removed from a skeleton by fluvial processes following decomposition of the carcass. This suggests that the remains have undergone little fluvial transport. Lack of weathering indicates that decomposition of the carcass and transport were followed by relatively rapid burial.

The overall distribution/shape of the skeletal scatter is long and narrow, approximately 6.5 m-long by 1 m-wide (Extended Data Fig. 7a). The approximate azimuth of this distribution is N86°W. This suggests an east to west current transport direction, which is consistent with the modern drainage pattern in the study area.

The compass directions of three of the eighteen measurable major appendicular elements fall within 7° of N-S, with an average direction of N4°E. These orientations are perpendicular to the axis of the skeletal scatter (N88°E). A group of 5 elements, ranging from N51°E to N73°E, yield an average direction of N59.8°E. Oriented approximately 90° to this group are seven elements, ranging from N35°W to N87°W, and averaging N66.6°W (Supplementary Table 6). These groups of orientations reflect the tendency of long bones to orient either parallel or perpendicular to the prevailing current direction.

SDNHM 3698 *Canis dirus* (SDNHM 49012) and *Odocoileus* sp. (SDNHM 49666)

Wolf Quarry (SDNHM Locality 3698, Extended Data Fig.7b) lies at an elevation of 43.4 to 44.9 m amsl, slightly lower in elevation than SDNHM Locality 3677 (see *Equus* above) and SDNHM Locality 3767 (see *Mammut* below). The skeletal remains were recovered from a reddish-brown, clayey, blocky silt¹.

Two partial skeletons were recovered from this quarry, that of *Canis dirus* (SDNHM 49012) and *Odocoileus* sp. (SDNHM 49666). The *C. dirus* skeleton is approximately 30% complete (Supplementary Table 3). The specimen exhibits heavy weathering. Cortical bone surfaces exhibit extensive cracking but were not splintered (weathering stage 2)¹. This level of weathering suggests about 2-3 years of exposure at the ground surface prior to burial. No transport abrasion or scavenger tooth marks were observed.

Although relatively complete, the *Canis dirus* skeleton lacks most of the distal limb elements. Podials, metapodials and phalanges total only 17% complete (Supplementary Table 3). These elements fall in VGN I and II and typically are the first to be removed from a skeleton by fluvial processes following carcass decomposition. Some fluvial transport prior to burial is suggested. However, the ribs (VGN I) appear to have been broken (perpendicular to the long axis) as well as transported. This breakage also suggests that the carcass was exposed at the surface for an extended period of time prior to burial.

The overall distribution/shape of the *Canis dirus* skeletal scatter is narrow and elongate, measuring approximately 1.4 m at the widest point by 5.8 m-long (Extended Data Fig. 7b). The approximate compass direction of this distribution is N15°W, suggesting a northwest to southeast current transport direction.

Azimuths of eight of the 25 measured elements fall within 12° of the direction of the skeletal scatter (N12°W) and exhibit an average azimuth of 5.3° from N-S (Supplementary Table 7). A single tibia lies approximately perpendicular to this trend at N84°W. The compass directions of eight of the remaining specimens cluster NW-SE, ranging from N28°W to N65°W and averaging N44.8°W. These are within 26° NW of the azimuth of the skeletal scatter. Six elements, ribs, an ulna and a metapodial, lie roughly perpendicular to this group.

Essentially all of the juvenile *Odocoileus* remains (DP4 in wear and M3 unerupted) occur within a 0.9 m by 0.8 m area. This scatter has an azimuth of N28°W and falls along the trend of the *Canis dirus* remains¹ (Extended Data Fig. 7b). The deer skeleton apparently was deposited and buried during the same fluvial event as scattered and buried the *C. dirus* skeletal elements.

The *Odocoileus* skeleton is 0.5% complete (Supplementary Table 4) and primarily consists of the thoracic and lumbar portion of the skeleton. Although these remains fall within

VGN I, it is likely that this portion of the carcass was transported as a single skeletal unit prior to full decomposition, with minimal fluvial scattering of individual elements. Only the right innominate provided a compass orientation of N20°W, which is in line with the overall *Canis dirus* skeletal scatter. No transport abrasion or weathering of bones was observed. Several bone fragments that appear to represent a single juvenile limb element exhibit spiral fracturing and possible tooth marks consistent with carnivoran modification of small, fresh bones.

SDNHM Locality 3767 *Mammot americanum* (SDNHM 49926)

The Cerutti Mastodon (SDNHM Locality 3767; Fig. 1a) lies at an elevation of 45.9 m amsl in Bed E. An unknown portion of the disarticulated skeletal scatter was destroyed during highway and home construction, along the north and northeast sides of the excavation. The overall distribution/shape of the diffuse skeletal scatter is 6.7 m-long by 3.6 m-wide, with the exception of a cluster of two ribs and two vertebrae that lie several meters to the southwest of the main skeletal scatter (Fig. 1a). The approximate azimuth of the skeletal scatter is N54°E $\pm$ about 2° (depending on inclusion of the cluster of ribs and vertebrae). A secondary concentration of fractured limb bones and ribs (Concentration 1) occurs in the south-central part of the skeletal scatter. It is approximately 0.8 m-wide by 2.0 m-long, lying nearly perpendicular to the distribution of the main skeletal scatter (Fig. 1a). Concentration 1 contains two large cobbles, several rib fragments and the proximal femoral epiphyses. Numerous small fragments (< 5-10 cm) of the larger appendicular elements are distributed throughout the main skeletal scatter in Concentrations 1 and 2 (Fig. 1b, c).

The lack of intact large appendicular elements in the *Mammot* disarticulated skeletal scatter precludes their use in determining current directions. Although of questionable utility, the orientation of preserved larger ribs and fragments (N = 10), and one of the two tusks were

measured (Supplementary Table 9). Two ribs are approximately parallel to the main skeletal scatter, and two ribs and the tusk are approximately perpendicular to the scatter. This may reflect a NE to SW current direction, which, if reliable, is distinctly different from that of the *Canis* and *Equus* skeletal remains. The remaining ribs and rib fragments exhibit no preferred orientation and range from N90°E to N70°W.

Two sesamoids, two phalanges and one caudal vertebra, are the only complete small bones that were found in the skeletal scatter (Supplementary Table 5). These elements fall in VGN I, and other podial elements and some vertebrae might be included in VGN II. However, given the fragmented condition of many bones, the significance and utility of Voorhies' classification system is questionable for this type of scatter. No elements exhibit a clear indication of current-induced sorting or orientation.

Discussion

Skeletal remains from three locations, SDNHM Localities 3677, 3698 and 3767, were all recovered from the fine-grained upper portions of an upward fining sequence of fluvial channel and fluvial overbank deposits. Stratigraphic correlation is not precise in such deposits, which often exhibit considerable lateral interfingering and channeling. However, the similar lithology and the close proximity (SDNHM Localities 3677 and 3767 are only 27 m apart and lie 207 m NW of SDNHM Locality 3698) and similar elevations (43.4 to 45.9 m amsl) of these localities reflect their essentially identical overbank depositional setting. The different directions of the skeletal scatters, *Equus* N86°W, *Canis* N15°W, *Odocoileus* N28°W are probably a result of deposition at slightly different places on the floodplain during different depositional events within the meandering stream/overbank system. However, the *Mammut*, with a skeletal trend of N54°E, is oriented close to 90° from the other skeletal scatters.

Although it is not known exactly how much of the skeletons were removed during highway construction, field conditions indicate that the loss was likely minimal, except for the CM site where construction destroyed an unknown but probably significant part of the bonebed¹. Nevertheless, major appendicular element orientations within the *Equus* and *Canis* skeletal scatters (Supplementary Tables 6, 7) are either approximately parallel or perpendicular to the direction of the skeletal scatter. This reflects the tendency of long bones to orient either parallel or perpendicular to the prevailing current direction after the skeleton is disarticulated. Orientations of one tusk and several of the ribs in the *Mammut* skeletal scatter are either parallel or perpendicular to the broad trend of the main bone scatter (Fig. 1a), but because this scatter is so non-linear, its significance is difficult to assess. Because of their curvature, ribs do not consistently orient relative to current directions, and most of the *Mammut* ribs appear to be randomly scattered.

The distribution patterns of bone orientation measurements in the *Canis* and *Equus* disarticulated skeletons are very similar. Bone orientations in both skeletons exhibit a relatively tight cluster, directed N-S. These similar patterns indicate that both the *Canis* and *Equus* remains experienced a very similar sequence of depositional conditions and taphonomic events. The fact that VGN I and II elements are not well represented in either skeletal scatters suggests that these disarticulated skeletal elements have been subjected to similar current regimes.

The *Mammut* skeletal scatter is distinctly different from older (Pliocene and middle Pleistocene) disarticulated proboscidean remains from California and Nebraska^{55, 56, 57} that have not been modified by humans. Such remains do not exhibit the extensive breakage of major appendicular elements, nor do they present abundant smaller, spirally-fractured fragments. The

directions of larger limb elements and ribs in some of these skeletal scatters often reflect current-induced orientations. This is not exhibited by the CM remains.

Extensive scavenging by large carnivorans, dragging parts of the carcass away from the main scatter of the *Mammut americanum*, is not evident. Also, large carnivoran scavenging is not seen in the *Canis* and *Equus* disarticulated skeletons.

Because an unknown portion of the *Mammut* skeleton was lost during highway and earlier residential mass grading activities¹, it is impossible to assess confidently the taphonomic significance of the absence of some skeletal elements (e.g. removal of VGN I and II by currents) or the relative numbers of the missing skeletal elements (Supplementary Table 5). However, it seems highly unlikely (if not impossible) that the missing podial and phalangeal elements would be transported by currents that would leave in place the multitude of much smaller bone fragments seen throughout the skeletal scatter (Fig. 1a).

The presence of abundant small bone fragments, the absence of VGN I and II elements, and the fact that nearly all the major appendicular skeletal elements of the *Mammut* are represented by green-bone fractured pieces, cannot be explained by the sequence of taphonomic events seen in the associated skeletal remains of *Canis*, *Equus* or *Odocoileus*. Also, the selective removal of some VGN I and II skeletal elements and not the smaller bone fragments in the *Mammut* scatter cannot occur in an overbank depositional setting by known geological processes. Indeed, if the podial and phalangeal elements were transported by currents, the smaller bone fragments should also have been transported.

To summarize, the *Canis* and *Equus* remains exhibit the following taphonomic characteristics: decomposition and disarticulation following death, with some weathering and possible scattering and modification of some skeletal elements by scavengers; moderate velocity

current removal of VGN I and II elements, current-induced orientation of major appendicular elements and some ribs (Extended Data Fig. 7a, b) and burial by fine-grained sediments transported under low-velocity overbank currents. In contrast, the *Mammut* remains exhibit the following characters: lack of extensive weathering¹⁰, lack of evidence of scavenging, no demonstrable evidence of removal of elements by fluvial action, extensive green-bone fracturing of the major appendicular elements present and scattering of small bone fragments and unusual or anomalous orientation of the vertically-oriented tusk. These conditions of the *Mammut* remains are not the result of large carnivoran scavenging, did not occur in a high-energy depositional environment and cannot be explained by any known fluvial depositional or burial process. The *Mammut* remains are unique within the Pleistocene fluvial depositional sequence, as are the large cobbles, and indicate that hominins were the primary taphonomic agent at the CM site.

Supplementary Tables 2-5. Skeletal Element Summary and Count. Under the heading “Element” are listed the main classes of bone types within the mammalian skeleton; under “Count” are the number of those elements present in the preserved skeleton. Teeth are listed separately if isolated from the maxilla or dentary. Under the heading “Expected Number” are the numbers of each class or type of element in a complete specimen of the given taxon. The total number of teeth (deciduous or permanent), thoracic, lumbar and caudal vertebrae and ribs may vary in some taxa⁵⁴. An * indicates the count for identified and numbered ribs in SDNHM 49012. This is in excess of the natural state and is not unexpected given the broken nature of the ribs. The total possible number (26) for this element was used. Numbers in parentheses are approximate averages of the variable range, and are used in calculations of totals.

Supplementary Table 2. SDNHM 47731 *Equus* sp. (SDNHM Locality 3677)

Element	Count	Expected Number
skull	0	1
dentaries	0	2
teeth	6	36
cervical vertebrae	3	7
thoracic vertebrae	12	18
lumbar vertebrae	3	6
sacral vertebrae	1	5
caudal vertebrae	0	14-21 (18)
ribs	32	36
innominate	2	2
scapula	0	2
humerus	1	2
radius/ulna	1	2
femur	1	2
patella	0	2
tibia	2	2
podials	7	26
metapodials	3	4
splints	3	8
phalanges	6	12
sesamoids	2	12
total	85	205

Relative completeness of cervical vertebral section 43%

Relative completeness of thoracic and lumbar vertebral section 63%

Relative completeness of large limb elements (including podials) 35%

Relative completeness of feet (metapodials and phalanges) 56%

Skeleton percent complete 41%

Supplementary Table 3. SDNHM 49012 *Canis dirus* (SDNHM Locality 3698)

Element	Count	Expected Number
skull	1	1
dentaries	2	2
teeth		rooted in bone
cervical vertebrae	7	7
thoracic vertebrae	1	13
lumbar vertebrae	4	7
sacral vertebrae	0	3
caudal vertebrae	1	20
ribs	32*	26

innominate	0	2
scapula	1	2
humerus	2	2
radius	2	2
ulna	1	2
femur	1	2
patella	0	2
tibia	2	2
podials	4	26
metapodials	4	36
phalanges	12	56
sesamoids	5	32
total	76	247

Relative completeness of cervical vertebral section 100%

Relative completeness of thoracic and lumbar vertebral section 25%

Relative completeness of large limb elements 64%

Relative completeness of feet (podials, metapodials, and phalanges) 17%

Skeleton percent complete 30%

Supplementary Table 4. SDNHM 49666 *Odocoileus* sp. (SDNHM locality 3698)

Element	Count	Expected Number
skull	0	1
dentaries	2	2
teeth		rooted in bone
cervical vertebrae	0	7
thoracic vertebrae	0	13
lumbar vertebrae	6	6
sacral vertebrae	0	5
caudal vertebrae	0	18-20 (19)
ribs	0	13
innominate	1	2
scapula	0	2
humerus	0	2
radius/ulna	0	2
femur	0	2
patella	0	2
tibia	0	2
fibula	0	2
podials	0	44
metapodials	0	4
phalanges	0	24
sesamoids	0	24

total	9	178
--------------	----------	------------

Relative completeness of cervical vertebral section 0%
 Relative completeness of thoracic and lumbar vertebral section 32%
 Relative completeness of large limb elements (including metapodials) 2%
 Relative completeness of feet 0%
 Skeleton percent complete 0.5%

Supplementary Table 5. SDNHM 49926 *Mammot americanum*⁵⁸ (SDNHM Locality 3767). The skull is represented by a jugal and cranial fragments. Rib and rib fragments are counted as complete elements. Most identifiable major limb elements consist of incomplete parts. Numerous unidentifiable fragments are present (see Extended Data Fig. 2).

Element	Count	Expected Number
skull	1	1
dentaries	0	2
teeth	3	8-10
cervical vertebrae	0	7
thoracic vertebrae	4	18-20 (19)
lumbar vertebrae	0	3
sacral vertebrae	0	4-6 (5)
caudal vertebrae	1	22-27 (25)
ribs	17	36-40 (38)
innominate	0	2
scapula	0	2
humerus	0	2
radius	0	2
ulna	0	2
femur	2	2
patella	0	2
tibia	0	2
fibula	0	2
podials	0	32
metapodials	0	52
phalanges	2	56
sesamoids	2	20
total	32	287

Relative completeness of cervical vertebral section 0%
 Relative completeness of thoracic and lumbar vertebral section 18%
 Relative completeness of large limb elements 20%
 Relative completeness of feet (podials, metapodials, and phalanges) 1%
 Skeleton percent complete 11%

Supplementary Tables 6-9. Element Orientations. The azimuths of the long axes of individual large limb bones from each specimen were measured from the quarry maps¹ and/or from digital scans of original copies of the excavation data on file at the SDNHM¹. In curved tusks, ribs and rib fragments of SDNHM 49926, measurements were taken parallel to a chord from one end of the element to the other. Directions are recorded as north azimuths.

Supplementary Table 6. SDNHM 47731 *Equus* sp. (SDNHM Locality 3677)

Element	Direction
humerus	N07W
scapula	N35E
radius/ulna	N01E
innominate	N03W
innominate	N60W
femur	N73W
tibia	N63W
metapodial	N88W
metapodial	N51W
rib	N52W
rib	N52E
rib	N78W
rib	N71W
rib	N61W
rib	N80W
rib	N54W
rib	N87W
rib	N24E

Supplementary Table 7. SDNHM 49012 *Canis dirus* (SDNHM Locality 3698)

Element	Direction
dentary	N56W
dentary	N42W
humerus	N03W
humerus	N-S
radius	N-S
ulna	N58E
ulna	N31W

scapula	N-S
femur	N63W
tibia	N88W
tibia	N03W
metapodial	N43W
metapodial	N30E
metapodial	N05W
rib	N18E
rib	N28E
rib	N65E
rib	N41W
rib	N20W
rib	N40E
rib	N39W
rib	N41W
rib	N09E
rib	N38W
rib	N42W

Supplementary Table 8. SDNHM 49666 *Odocoileus* sp. (SDNHM Locality 3698)

Element	Direction
scatter	N28W
innominate	N20W

Supplementary Table 9. SDNHM 49926 *Mammut americanum* (SDNHM Locality 3767)

Element	Direction
tusk	N44W
rib	N31E
rib	N44W
rib	N66E
rib	N32E
rib	N32E
rib	N70E
rib	N17W
rib	N29W
rib	N83W
rib	N82E
rib	N20E

SECTION 7. CERUTTI MASTODON SITE RADIOCARBON AND OPTICALLY STIMULATED

LUMINESCENCE DATING

Two attempts were made to radiocarbon date the CM site. The first attempt in the mid-1990s involved submitting a tusk sample to Beta Analytic in Florida¹. This dating attempt failed when it was reported that the tusk fragment did not contain collagen. In 2009, a sample selected from the interior dentine of a molar was submitted to Stafford Laboratories of Colorado. Again, the sample did not contain collagen, so could not be dated.

An initial attempt to date the site by optically-stimulated luminescence (OSL) methods at University of Illinois at Chicago (Steven L. Forman, written communication, 2016) was made in 2008 using samples collected for that purpose during the excavation in 1992-1993. Doses were determined using the multiple-aliquot additive dose technique^{59, 60, 61}. For polymineral fine-grained separates, grains were first exposed to infrared light and then to blue light. Luminescence output obtained under the initial infrared stimulation dominantly reflects feldspar components whereas subsequent blue light stimulation reflects quartz components. Thus, samples UIC2287 and UIC2288 have two separate age estimates, designated by appending either “IR” (infrared light) or “BL” (blue light) after the sample name in Supplementary Table 10. In contrast, data for samples UIC2286 and a second aliquot of UIC2287 were determined from purified quartz fractions obtained after soaking sediment for a week in hydrofluorosilicic acid. Grain-sizes ranged from 63–100 μm for UIC2286 and from 4–11 μm for UIC2287. Equivalent doses for the 1992-1993 samples range from 241 to 270 Gy. Resulting OSL ages determined in 2008 range from 69 ± 9 ka to 99 ± 12 ka (2σ uncertainties) with no statistically significant differences between ages determined by infrared or blue light stimulation, or between polymineralic or pure quartz aliquots (Supplementary Table 10). Significant age differences between Beds E and F were not

observed (weighted-mean age and 95% confidence limit of 73.3 ± 4.1 ka for $N=5$ with a MSWD [mean square weighted deviation] of 0.54), but the OSL age of 99 ± 12 ka for the underlying unit, Bed C, is discernably older.

A second attempt to date the fluvial sediment involved collection of OSL samples from a nearby trench excavated in 2009 into the south side of the sound berm, about three meters from the southeastern corner of the original CM site. The same sequence of stratified silt and sand layers encountered in the 1992-1993 excavation was identified and OSL samples were collected from Beds C, D, E and F by Steven Forman. Those samples were subjected to the same multiple-aliquot additive dose methods used previously. Sediment from the trench excavated in 2009 was coarser than sediment collected from the original CM site and contained abundant grains greater than 250 microns in diameter. This difference is interpreted to represent lateral variation in fluvial facies over the several meters separating the two sample sites. In addition, there appears to be greater compositional heterogeneity in sediments from the 2009 excavation with total dose rates derived from the U, Th and K concentrations varying by 50% (1.94 to 3.25 mGy/year). The equivalent doses from the 2009 samples are about half those of the 2008 samples (>115 to >203 Gy versus 241 to 270 Gy), yet regenerative growth curves for those samples indicate that the 2009 samples are at or very close to saturation. Resulting ages for the 2009 samples are thus reported as minimum ages ranging from >38 to >70 ka.

As a test of the multiple-aliquot additive dose method, a separate split of sample UIC2585 was analyzed using a single-aliquot regeneration protocol⁵⁹ on 30 aliquots of the 150- to 250-micron quartz fraction. Resulting equivalent-dose measurements were within analytical uncertainties generated for each method, and the resulting OSL age estimates for UIC2585 based on both dose measurements were consistent (>62 ka and >70 ka).

To help resolve the differences between the 2008 and 2009 OSL dating results along with the hope of obtaining an age from an independent laboratory, a set of sediment samples from the original 1992-1993 collection was sent to Ronald J. Goble at the University of Nebraska in 2011. Twelve individual aliquots from four separate samples representing Beds C, E, and F were processed using pulsed irradiation⁶⁰ and a 280°C shinedown⁵⁹ as part of a single-aliquot regeneration sequence. Equivalent doses ranged from 180 ± 26 to 223 ± 52 Gy (2σ uncertainties). Most aliquots from all samples had equivalent doses (D_e) that exceeded the upper limits of the saturation plateaus ($D_e > 2 \times D_0$) and could not be dated (Ronald J. Goble, written communication, 2011). Those conclusions were determined on splits of the same material initially provided to the University of Chicago laboratory.

Given results of the three attempts to date the sediments containing the mastodon bones by OSL, we conclude that electron traps in the quartz and feldspar silt grains are close to or beyond their saturation limits. Consequently, even though some individual samples may indicate finite OSL ages, it is more likely that the material is too old to provide a reliable estimate of the age of sediment deposition. We consider the best interpretation of the OSL data to be that sediments representing the CM stratigraphy are greater than 60 to 70 ka. Although other luminescence analytical approaches could be investigated, the apparent antiquity of the site along with other factors inherent in dating of fluvial sediment, such as heterogeneity caused by facies changes, variable sources of quartz within the deposits, and the potential for incomplete solar resetting, will complicate any further efforts for luminescence dating.

Supplementary Table 10. Optically Stimulated Luminescence ages for fluvial sediments from the Cerutti Mastodon Site determined in 2008.

Stratum	Sample number ^a	Anomalous fade ratio ^b	Equivalent dose (Gy)	U conc. (μg/g) ^c	Th conc. (μg/g) ^c	K ₂ O conc. (wt. %) ^c	a value ^d	Assumed H ₂ O content (%)	Cosmic ray contribution (mGy/yr) ^e	Total dose rate (mGy/yr)	OSL age (ka)
Bed F	UIC2288IR	0.99±0.06	241±8	2.2±0.2	6.7±0.2	1.97±0.04	0.062±0.012	10 ± 6	0.19±0.04	3.47±0.34	69±9
Bed F	UIC2288BL	1.00±0.02	270±18	2.2±0.2	6.7±0.2	1.97±0.04	0.073±0.014	10 ± 6	0.19±0.04	3.56±0.34	76±10
Bed E	UIC2287IR	1.03±0.02	251±3	2.5±0.2	6.6±0.2	1.51±0.02	0.075±0.016	10 ± 6	0.18±0.04	3.24±0.32	78±10
Bed E	UIC2287BL	1.09±0.02	252±3	2.5±0.2	6.6±0.2	1.51±0.02	0.098±0.018	10 ± 6	0.18±0.04	3.42±0.32	73±9
Bed E	UIC2287Q ^f	ND	249±5	2.5±0.2	6.6±0.2	1.51±0.02	0.098±0.020	10 ± 6	0.18±0.04	3.43±0.34	72±9
Bed C	UIC2286BL ^g	ND	250±6	2.0±0.2	4.4±0.2	1.65±0.02	ND	5 ± 4	0.18±0.04	2.53±0.24	99±12

^aThe BL designation indicates excitation by blue light (470 ± 20 nm) after exposure to infrared (IR) wavelengths (834 ± 80 nm) with the equivalent dose determined by the multiple-aliquot regenerative dose technique⁶¹.

^bTest for anomalous fading of laboratory induced luminescence signal of approximately 99 Gy after 30 day storage at room temperature. Values of 0.90 to 1.10 indicate little to no fading within analytical resolution.

^cU, Th and K₂O concentrations (conc.) determined by ICP-MS at Activation Laboratories, Ontario, Canada.

^dMeasured alpha-efficiency factor (a value) as defined by Aitken and Bowman⁶².

^eAges included a cosmic ray dose rate from calculations of Prescott and Hutton⁶³.

^fData for sample UIC2287Q were determined on the 4- to 11-micron quartz fraction, isolated by reaction with hydrofluorosilic acid.

^gData for sample UIC2286BL were determined on the 63- to 100-micron quartz fraction with blue light excitation (470 ± 20 nm); other analyses were made on the 4- to 11-micron polymineral fraction.

All errors given at two-times standard deviation. ND = not determined. Data obtained by Steven L. Forman at the University of Illinois at Chicago Luminescence Dating Research Laboratory.

Supplementary Table 11. Optically Stimulated Luminescence ages for fluvial sediments from the Cerutti Mastodon Site determined in 2009.

Stratum	Sample number ^a	Equivalent dose (Gy)	U conc. (μg/g) ^b	Th conc. (μg/g) ^b	K ₂ O conc. (wt. %) ^b	Assumed H ₂ O content (%)	Cosmic ray contribution ^c (mGy/yr)	Total dose rate (mGy/yr)	OSL age (ka)
Bed F	UIC2588BL	>203 ± 7	4.8 ± 0.2	10.6 ± 0.1	1.58 ± 0.04	10 ± 6	0.19 ± 0.04	3.25 ± 0.3	>62
Bed E	UIC2586BL	>115 ± 5	3.9 ± 0.2	9.2 ± 0.1	1.66 ± 0.04	10 ± 6	0.19 ± 0.04	3.03 ± 0.3	>38
Bed E2	UIC2585BLs	>119 ± 21	1.4 ± 0.2	3.2 ± 0.1	1.50 ± 0.04	10 ± 6	0.18 ± 0.04	1.94 ± 0.2	>62
Bed E2	UIC2585BL	>135 ± 6	1.4 ± 0.2	3.2 ± 0.1	1.50 ± 0.04	10 ± 6	0.18 ± 0.04	1.94 ± 0.2	>70
Bed D	UIC2589BL	>117 ± 3	2.3 ± 0.2	6.1 ± 0.1	1.59 ± 0.04	10 ± 6	0.18 ± 0.04	2.41 ± 0.2	>48
Bed C	UIC2587BL	>129 ± 7	3.0 ± 0.2	6.2 ± 0.1	1.62 ± 0.04	10 ± 6	0.18 ± 0.04	2.59 ± 0.3	>54

^aThe BL designation indicates excitation by blue light (470 ± 20 nm) with the equivalent dose determined by the multiple-aliquot regenerative dose technique on the 150 to 250 micron quartz fraction (Jain et al. 2003). BLs designation indicates excitation by blue light (470 ± 20 nm) with equivalent dose determined by single-aliquot regeneration protocols⁵⁹ on 30 aliquots of the 150-250 micron quartz fraction.

^bU, Th and K₂O determined by ICP-MS at Activation Laboratories, Ontario, Canada.

^cAges included a cosmic ray dose rate from calculations of Prescott and Hutton⁶³.

All errors given at two-times standard deviation. Data determined at the University of Illinois at Chicago Luminescence Dating Research Laboratory.

SECTION 8. URANIUM-SERIES AGES

Because of the difficulties in dating sediment at the CM site using OSL methods, an attempt was made to use uranium-series methods to date the bones themselves. Scoping efforts were conducted at the U.S. Geological Survey radiogenic isotope lab in late 2011 to determine whether material was amenable to the method. More detailed efforts followed in 2012 through 2015 to establish a robust minimum age of death and diagenetic U-uptake as described below (see Methods section for analytical details).

Conventionally Calculated $^{230}\text{Th}/\text{U}$ Ages

Conventionally calculated $^{230}\text{Th}/\text{U}$ ages rely on measured $^{230}\text{Th}/^{238}\text{U}$ activity ratios (AR) and $^{234}\text{U}/^{238}\text{U}$ AR data corrected for the presence of any non-authigenic component that would contribute initial ^{230}Th not derived from in-situ decay of U. Corrections are made based on measured $^{232}\text{Th}/^{238}\text{U}$ AR and the assumptions that this material is uniform, has a known U/Th composition (for instance, one similar to average crustal material), and is in radioactive secular equilibrium⁶⁴ (that is, an assumed composition of $^{230}\text{Th}/^{238}\text{U}$ AR = 1.276 ± 0.64 ; $^{230}\text{Th}/^{238}\text{U}$ AR = 1.0 ± 0.25 ; $^{234}\text{U}/^{238}\text{U}$ AR = 1.0 ± 0.1). Uncertainties are propagated through the age calculation so that errors for corrected ratios are only slightly larger than analytical uncertainties if the measured $^{232}\text{Th}/^{238}\text{U}$ AR is negligible (say $\ll 0.1$), but may be large if substantial ^{232}Th is present (i.e., $^{232}\text{Th}/^{238}\text{U}$ AR > 0.2). Initial Th-corrections were negligible for analyses of CM bone relative to analytical uncertainties.

Conventionally calculated $^{230}\text{Th}/\text{U}$ ages for individual analyses of cortical bone from Bed E at the CM site (Spl.1, CM-20, CM-225, and CM-292) ranged from 100.5 ± 0.7 to 126.9 ± 1.1 ka with calculated initial $^{234}\text{U}/^{238}\text{U}$ AR of 1.38–1.49 (Supplementary Table 12; Extended Data Figs. 9e–g, 10a, and 10b). Analyses of bone collected from the initial backhoe

excavation (sample SDNHM-09) have systematically older conventional $^{230}\text{Th}/\text{U}$ ages (up to 152.9 ± 1.5 ka) compared to specimens collected from *in situ* contexts, but yielded initial $^{234}\text{U}/^{238}\text{U}$ AR values in the same range (Extended Data Fig. 10b). Because of the lack of specific stratigraphic context, older ages for SDNHM-09 specimens may indicate that they are from a deeper stratigraphic horizon, or may be an artifact of U-loss, which was not fully evaluated in those bones.

Models of Uranium Uptake

Uranium-series dating methods have been successfully applied to samples of bone, but not without a reasonable understanding of how uranium was incorporated into the samples^{65, 66, 67, 68, 69, 70}. Seventy analyses of fossilized bone from the CM site have an average U concentration of 162 ± 67 ($\pm 2 \times$ standard deviation [SD]) $\mu\text{g/g}$ compared to U concentrations of approximately 0.05 $\mu\text{g/g}$ or less in bone tissue of living animals^{71, 72, 73}. It is clear that large amounts of U have been incorporated into the samples of CM porous carbonated hydroxyapatite after burial and diagenesis. Therefore, conventional $^{230}\text{Th}/\text{U}$ ages that assume closed-system conditions (no addition or subtraction of mass since mineral formation) will underestimate the true age of burial. Understanding the history of diagenetic addition of U is a major challenge in accurately estimating the age of the site.

Bones that experience relatively simple U uptake can provide robust, defensible ages; however, bones that experience more complex uptake histories involving multi-stage episodes of adsorption and leaching are not good candidates for U-series dating^{66, 67}. Evidence of reliable dates include (1) U concentrations and conventional closed-system $^{230}\text{Th}/\text{U}$ ages across a single bone that yield predictable rather than irregular profiles, and (2) analyses of multiple bones from the same stratigraphic horizon that give a narrow range of ages and initial $^{234}\text{U}/^{238}\text{U}$ AR values.

Additional confidence is gained if initial $^{234}\text{U}/^{238}\text{U}$ AR values from U-series results are consistent with known U-isotopic compositions in local water sources, and if other materials less susceptible to diagenetic modification yield similar age results. Analyses of other materials were attempted, including *Mammut* tooth enamel and tusk, bones from small animals (*Sylvilagus* and Reptilia), pedogenic rinds developed on cobble clasts and bones, and calcite-cemented casts of roots or insect burrows. However, those other materials had lower U concentrations, were more susceptible to secondary U mobility, or required large corrections for initial ^{230}Th . Consequently, results from those materials had greater uncertainties and were less reliable and consistent than results obtained from thick cortical limb and rib bones.

U is readily soluble in shallow, oxidizing groundwater, and interaction between those waters and the buried bone resulted in loss of much of the organic matter (collagen) and incorporation of U within the carbonated hydroxyapatite. Patterns of U uptake can take numerous forms depending on the degree of hydrologic saturation and water-migration history of the site, the diffusive characteristics of the bone, and the uranium concentrations in the diagenetic environment⁶⁶. Two simple conceptualizations of U behavior include (1) early uptake, where all U is acquired over a short time span (relative to the age of burial) and then held tightly in place, and (2) linear uptake, where U uptake occurs slowly and continuously until the present. Actual uptake histories are likely more complex. Examination of profiles of U concentration and U-series ages across sections of compact (cortical) bone can offer insights into U uptake processes.

The diffusion-adsorption model (DA model) was developed to explain observed profiles of U concentrations and U-series ages in bone samples^{65, 66, 67}. The model assumes that uranyl complexes (UO_2^{+2}) in aqueous solutions are able to diffuse into porous compact bone and adsorb

into the mineral fraction of bone, facilitated by its large internal surface areas. Laboratory experiments indicate that hydroxyapatite has a strong affinity for uranyl ions⁶⁶ (partition coefficients between 10^4 and 10^5). Therefore, U-uptake depends mostly on how rapidly U can diffuse into a given bone and how effectively it is absorbed by the mineral substrate. Parameters controlling the DA process include the diffusion coefficient in bone (D) and the volume equilibrium constant (R) representing the amount of U absorbed per unit amount of solution⁶⁶. Values purported for D/R depend on variations in the diffusion coefficient, porosity, and the mineral/water partition coefficients, as well as chemical and physical factors present in the burial environment, but are typically on the order of 10^{-12} cm²/s (resulting in rapid uptake rates) and 10^{-14} cm²/s (resulting in slow uptake rates). In the DA model, once a bone reaches equilibrium with U in groundwater, no further uptake occurs, provided diagenetic conditions remain constant⁶⁶. Because Th is not mobile in aqueous solutions nor incorporated into biologic tissue, the presence of ²³⁰Th in fossil bone is mostly a consequence of radioactive decay of ²³⁴U.

More recently, the DA model has been modified to accommodate both diffusion of ²³⁸U and ²³⁴U into the bone along with simultaneous decay of excess ²³⁴U derived from the ambient water contributing U during the process⁷⁴. This so-called diffusion-adsorption-decay (DAD) model acknowledges that diffusion of U is a continuous process and describes the evolution of ²³⁸U, ²³⁴U, and ²³⁰Th activities when diffusion and decay process are coupled⁷⁴. Practical differences between the DA and DAD models are described by Grün et al.⁷⁰. Unlike the DA model, the DAD model does not require U-concentration profiles for age calculations, although those data remain an important diagnostic tool for evaluating the U-uptake history and the suitability of samples for U-series dating⁷⁴. In general, U from migrating water is introduced into the bone starting from the outer and inner surfaces and progressing toward its center. U uptake is

non-linear and proceeds more rapidly during earlier stages and less rapidly during later stages. Addition of U in this manner results in U-shaped concentration profiles that gradually flatten with time until the bone reaches a composition in equilibrium with U in the source water. The distribution of conventionally calculated $^{230}\text{Th}/\text{U}$ ages will result in similar U-shaped patterns, with apparent ages decreasing towards the center of the bone^{66, 74}. Regardless of which approach is adopted (conventionally calculated, DA-, or DAD-model ages), U-series dates of bone represent minimum burial ages provided that U leaching has not occurred^{66, 70}.

Cerutti Mastodon Ages

Profiles of U concentrations and conventionally calculated $^{230}\text{Th}/\text{U}$ ages for sampled specimens (CM-20, CM-225, CM-292) all approximate the U-shaped profiles expected for continuous uptake of U from water enriched in ^{234}U relative to ^{238}U (Extended Data Fig. 10a). Modern soil water or percolating vadose water was not available for analyses; however, modern groundwater analyzed from the shallow saturated zone in a nearby Sweetwater Authority municipal supply well had $^{234}\text{U}/^{238}\text{U}$ AR values of 1.446 and 1.538 (Supplementary Table 12). The similarity of those values to initial $^{234}\text{U}/^{238}\text{U}$ AR values calculated for outer layers of bone assuming closed-system behavior is viewed as evidence that $^{230}\text{Th}/^{238}\text{U}$ data in bone profiles have not been affected substantially by post-depositional U leaching, and that conventional ages are not erroneously old due to U loss.

DAD-model ages for three specimens were calculated using $^{234}\text{U}/^{238}\text{U}$ AR and $^{230}\text{Th}/^{238}\text{U}$ AR data as a function of position for each subsample volume and the iDAD program⁷⁴ (available at <http://www.earth.org.au/codes/iDaD/>). Algorithms implemented in iDAD constitute a forward model that predicts U-series activity profiles across a bone given an age and diffusion coefficient. To do this, the program uses an inversion process based on measured isotope and

position data to estimate age and diffusion properties along with estimates of uncertainty⁷⁴. The model assumes a constant supply of $^{234}\text{U}/^{238}\text{U}$ AR at the inner and outer surfaces of the bone throughout the burial history, and consequently DAD ages are typically older than conventional $^{230}\text{Th}/\text{U}$ ages calculated for the same data (<http://www.earth.org.au/codes/iDaD/>).

Results of the iDAD inversion model allow fitting of maximum likelihood solutions to the measured data. Fits for CM-20 and CM-225 profiles are poor, resulting in probability density functions (PDFs) with wide 95% credible intervals and large age uncertainties (Extended Data Fig. 10c). The PDFs for these two profiles are asymmetric, resulting in maximum likelihood ages that are offset from the PDF peak. This feature is a result of the fact that the maximum likelihood solution solves for the best fit considering multiple parameters including diffusivity coefficient, age, and the $^{234}\text{U}/^{238}\text{U}$ AR of the external source⁷⁴. Resulting maximum-likelihood ages are 137.0 ± 5.6 ka for CM-20 and 126.4 ± 5.5 ka for CM-225, which barely overlap at the 95% confidence limit (Extended Data Fig. 10d). We assume that the poor fits observed in these two samples are caused by inhomogeneous diffusivity across the cortical layer rather than by U loss because U concentration profiles show no evidence of lower values near layer margins (Extended Data Fig. 10a).

In contrast, predicted values of $^{234}\text{U}/^{238}\text{U}$ AR and $^{230}\text{Th}/^{238}\text{U}$ AR more closely match measured values for specimen CM-292. Consequently, the PDF curve is symmetric and yields a narrower 95% credible interval half width. The resulting maximum-likelihood age of 130.2 ± 2.7 ka corresponds to the peak of the PDF curve and is within error overlap of ages from the other two specimens (Extended Data Fig. 10c).

Equilibrium $^{234}\text{U}/^{238}\text{U}$ ratios and apparent correlations with age

Equilibrium $^{234}\text{U}/^{238}\text{U}$ AR values calculated using the iDAD model range from 1.322 to 1.331 for all three specimens. Those values are lower than initial $^{234}\text{U}/^{238}\text{U}$ AR calculated using conventional methods (1.38–1.49, see above). The lower equilibrium $^{234}\text{U}/^{238}\text{U}$ values calculated from the DAD model are closer to present-day measured values than conventionally calculated initial $^{234}\text{U}/^{238}\text{U}$ AR due to the assumption that U was introduced into the sample throughout its burial history, and that the composition of the introduced U remained constant over the entire period. As ^{234}U is continually introduced, ^{234}U decays within the bone and results in accumulation of ^{230}Th daughter; however, newly absorbed U replaces the decayed ^{234}U so that ^{230}Th increases without the same amount of apparent ^{234}U loss required under closed conditions.

However, diffusion rates are low enough that U introduced from the environment loses some of its original ^{234}U through decay prior to reaching the center of the bone. Consequently, U in the interior of the cortical bone has a lower $^{234}\text{U}/^{238}\text{U}$ AR than the margin. The result of this phenomenon is apparent in Extended Data Fig. 10b, which shows positive correlations between $^{234}\text{U}/^{238}\text{U}$ AR and $^{230}\text{Th}/^{238}\text{U}$ AR in bone profiles. At face value, subsamples at bone margins with the oldest conventionally calculated ages also have the highest initial $^{234}\text{U}/^{238}\text{U}$ AR values, and subsamples from the interior have younger ages and lower initial $^{234}\text{U}/^{238}\text{U}$ AR. Consequently, $^{234}\text{U}/^{238}\text{U}$ AR at the margins of the bone more closely reflects the composition of U in the diagenetic environment. If the DAD model and its assumptions are correct, U in soil water at the CM horizon has an isotopic composition that is lower than values measured in shallow groundwater from the supply well just down-gradient from the site. In other thick vadose zones, surface-flow, soil water, and shallow infiltration commonly have $^{234}\text{U}/^{238}\text{U}$ AR values

lower than those observed in underlying groundwater⁷⁵ due to preferential incorporation of recoil-generated ^{234}U as infiltration percolates to greater depths.

Geochronological Conclusions

We interpret the U-series isotope data from systematic profiles across specimen CM-292 and its maximum likelihood model age of 130.2 ± 2.7 ka calculated using the diffusion-adsorption-decay (DAD) model⁷⁴ to best represent the age of the CM horizon. Similarly, calculated ages for profiles of the other two specimens are less well defined and have greater uncertainties (137.0 ± 5.6 ka and 126.4 ± 5.5 ka). However, all three age estimates are within error overlap at the 95% confidence level, and support an approximate 130 ka burial age (weighted mean value of 130.7 ± 9.4 ka using errors for the three individual determinations; Extended Data Fig. 10d). Isotope data are consistent with conceptual models of gradual diffusion and absorption of U into interior portions of cortical bone, and show no obvious evidence for post-burial U leaching that would result in modified $^{230}\text{Th}/^{238}\text{U}$ AR values and erroneously old ages. Maximum likelihood model ages are only marginally older than conventionally calculated $^{230}\text{Th}/\text{U}$ ages for individual analyses of subsamples from inner and outer layers of the cortical bones. Conventionally calculated initial $^{234}\text{U}/^{238}\text{U}$ AR values are consistent with U present in shallow groundwater from nearby wells, although the DAD model indicates that U in shallow infiltration that contributed U to mineral components of the bone may have had a somewhat lower value. The internal consistency of the age and initial $^{234}\text{U}/^{238}\text{U}$ AR data are interpreted as strong evidence that bones have not been subject to post-depositional U leaching.

We conclude that the $^{230}\text{Th}/\text{U}$ dates obtained for CM bone are minimum estimates of the burial age rather than erroneously old artifacts caused by complex post-depositional U mobility. The combined data indicate that mortality and burial very likely occurred at least 130,000 years.

This age estimate is consistent with geologic interpretations based on dated paleo shoreline terraces (inboard of the 120-ka-aged Nestor Terrace) and the fact that the sedimentary environment was one of aggradation rather than incision, likely facilitated by a high sea-stand during MIS 5e. It is also compatible with radiocarbon results which indicate that bone is old enough for all of its original collagen to have been removed (not a strict geochronological limit), and with optically stimulated luminescence results, which are interpreted as evidence that sediments enclosing the bone are older than 60 to 70 ka.

Supplementary Table 12. U-Th concentrations, isotopic compositions, and conventionally calculated $^{230}\text{Th}/\text{U}$ ages and initial $^{234}\text{U}/^{238}\text{U}$ activity ratios for samples of bone and pedogenic carbonate from the Cerutti Mastodon site, and U concentrations and $^{234}\text{U}/^{238}\text{U}$ activity ratios for shallow groundwater from Sweetwater Authority well SW, San Diego County, California.

Sample Name	Sample weight (g)	Depth from outer surface (mm)	U conc. (µg/g)	Th conc. (µg/g)	Measured activity ratios				Detritus-corrected activity ratios		²³⁰ Th/U Age ^c ±2σ (ka)	Initial ²³⁴ U/ ²³⁸ U activity ratio ^c ±2σ
					²³² Th/ ²³⁸ U activity ratio ^{a,b} ±2σ	²³⁰ Th/ ²³⁸ U activity ratio ^{a,b} ±2σ	²³⁴ U/ ²³⁸ U activity ratio ^{a,b} ±2σ	²³⁰ Th/ ²³² Th activity ratio ^a	²³⁰ Th/ ²³⁸ U activity ratio ^{a,b} ±2σ	²³⁴ U/ ²³⁸ U activity ratio ^{a,b} ±2σ		
Mastodon rib bone; Locale #3767 bed E; Specimen #49926; Rib fragment; collected from backhoe excavation, northeast corner of site												
Spl.1A	0.0168	0.5-1.5	130.5	0.038	9.1E-5±9.0E-6	0.9017±0.0036	1.3118±0.0029	9,910	0.9017±0.0036	1.3118±0.0029	118.7±0.9	1.436±0.004
Spl.1B	0.0543	2.2-4.1	132.9	0.013	2.8E-5±2.8E-6	0.8868±0.0035	1.3063±0.0028	31,226	0.8868±0.0035	1.3063±0.0028	116.3±0.9	1.425±0.004
Spl.1C	0.0465	0.2-3.5	132.7	0.024	5.5E-5±3.2E-6	0.8942±0.0038	1.314±0.0029	16,348	0.8942±0.0038	1.314±0.0029	116.6±1.0	1.436±0.004
Spl.1D	0.0977	4.5-6.5	113.7	0.032	8.7E-5±1.8E-6	0.8611±0.0036	1.2958±0.0028	9,897	0.8611±0.0036	1.2959±0.0028	112.4±0.9	1.406±0.003
Various bones; Locale #3767; Specimens collected from backhoe excavation in northeast corner of site												
SDNHM-09A-1	0.0441	1.5-2.7	94.6	0.021	6.9E-5±3.6E-6	0.9737±0.0041	1.2925±0.0028	14,091	0.9737±0.0041	1.2926±0.0028	140.5±1.3	1.435±0.004
SDNHM-09A-2	0.0208	2.7-4.7	83.6	0.033	1.2E-4±8.7E-6	0.9520±0.0038	1.2821±0.0028	7,689	0.9519±0.0038	1.2821±0.0028	137.0±1.2	1.415±0.004
SDNHM-09A-3	0.0548	4.7-6.0	85.8	0.028	1.0E-4±3.2E-6	0.9362±0.0038	1.2786±0.0027	9,243	0.9362±0.0038	1.2786±0.0027	133.5±1.2	1.406±0.003
SDNHM-09A-4	0.0139	6.0-7.5	91.8	0.079	2.8E-4±1.2E-5	0.9265±0.0055	1.2859±0.0089	3,323	0.9265±0.0055	1.2859±0.0089	129.5±2.3	1.412±0.011
SDNHM-09A-5	0.0137	7.5-9.0	89.6	0.043	1.5E-4±1.2E-5	0.9123±0.0038	1.2773±0.0034	5,992	0.9123±0.0038	1.2773±0.0034	127.6±1.2	1.398±0.004
SDNHM-09B-1	0.0460	1.2-3.2	163.5	0.026	4.7E-5±2.0E-6	0.8558±0.0034	1.318±0.0028	18,035	0.8558±0.0034	1.318±0.0028	107.9±0.8	1.431±0.003
SDNHM-09C-1	0.0413	3.0-5.2	145.1	0.010	1.7E-5±2.5E-6	1.0351±0.0048	1.3287±0.0031	60,095	1.0351±0.0048	1.3287±0.0031	148.9±1.6	1.500±0.004
SDNHM-09C-2	0.0245	5.2-7.2	140.4	0.013	2.6E-5±4.4E-6	1.0163±0.0042	1.3245±0.0032	39,772	1.0163±0.0042	1.3245±0.0032	144.7±1.4	1.488±0.004
SDNHM-09E-1	0.0277	5-9	165.1	0.013	2.1E-5±3.3E-6	0.9871±0.0039	1.2599±0.0028	46,006	0.9871±0.0039	1.2599±0.0028	152.9±1.5	1.400±0.004
CM-20: Mastodon rib bone with intact head on one end and sharp fracture on opposite end; Locale #3767 bed E; Specimen #49926; Field #20												
CM-20-01	0.0205	0.5	163.1	0.050	9.6E-5±4.5E-6	0.9567±0.0037	1.342±0.0031	10,011	0.9567±0.0037	1.342±0.0031	125.9±1	1.488±0.004
CM-20-02	0.0332	1.5	152.7	0.009	1.4E-5±3.0E-6	0.9569±0.0039	1.337±0.0028	67,384	0.9569±0.0039	1.337±0.0028	126.9±1.1	1.482±0.004
CM-20-03	0.0242	2.5	145.6	0.009	1.5E-5±4.3E-6	0.9447±0.0036	1.3312±0.0028	64,109	0.9447±0.0036	1.3312±0.0028	125.1±1	1.471±0.004
CM-20-04	0.0213	3.5	133.5	0.023	5.3E-5±5.3E-6	0.9497±0.0039	1.3293±0.003	17,980	0.9497±0.0039	1.3293±0.0030	126.6±1.1	1.471±0.004
CM-20-05	0.0209	4.5	132.9	0.010	2.1E-5±5.5E-6	0.9232±0.0035	1.3285±0.0028	44,268	0.9232±0.0035	1.3285±0.0028	120.7±0.9	1.462±0.003

CM-20-06	0.0269	5.5	131.0	0.015	3.3E-5±4.3E-6	0.8886±0.0034	1.3245±0.0028	27,039	0.8886±0.0034	1.3245±0.0028	113.7±0.9	1.447±0.003
CM-20-07	0.0348	6.5	129.3	0.009	1.8E-5±3.4E-6	0.9185±0.0036	1.3226±0.0028	50,815	0.9185±0.0036	1.3226±0.0028	120.6±1	1.453±0.003
CM-20-08	0.0273	7.5	118.4	0.016	3.9E-5±4.7E-6	0.8615±0.0034	1.3223±0.0028	22,222	0.8615±0.0034	1.3223±0.0028	108.4±0.8	1.438±0.003
CM-20-09	0.0246	8.5	116.6	0.015	3.8E-5±5.3E-6	0.9156±0.0038	1.3178±0.0028	24,327	0.9156±0.0038	1.3178±0.0028	120.8±1	1.447±0.004
CM-20-10	0.0284	9.5	116.4	0.020	5.2E-5±4.6E-6	0.9068±0.0035	1.3097±0.0029	17,280	0.9068±0.0035	1.3097±0.0029	120.2±1	1.435±0.004
CM-20-11	0.0228	10.5	125.2	0.015	3.5E-5±5.3E-6	0.9161±0.0040	1.3107±0.0029	25,954	0.9161±0.0040	1.3107±0.0029	122.2±1.1	1.439±0.004
CM-20-12	0.0299	11.5	131.8	0.014	3.1E-5±3.8E-6	0.8841±0.0034	1.3096±0.0028	28,083	0.8841±0.0034	1.3096±0.0028	115.2±0.9	1.428±0.003
CM-20-13	0.0261	12.5	133.1	0.013	2.7E-5±4.4E-6	0.9367±0.0038	1.3260±0.0028	34,241	0.9367±0.0038	1.326±0.0028	124.2±1	1.463±0.003

CM-225: Mastodon limb bone with spiral fracture; Locale #3767 bed E; Specimen #49926; Field #225

CM-225-01	0.0187	0.5	203.8	0.118	1.9E-4±4.0E-6	0.8947±0.0037	1.3447±0.0031	4,809	0.8947±0.0037	1.3448±0.0031	111.9±0.9	1.473±0.004
CM-225-02	0.0103	1.5	193.0	0.023	3.5E-5±7.7E-6	0.8698±0.0034	1.3364±0.0028	24,940	0.8698±0.0034	1.3364±0.0028	108.0±0.8	1.456±0.003
CM-225-03	0.0087	2.5	195.7	0.022	3.2E-5±8.9E-6	0.8647±0.0034	1.3225±0.0029	26,864	0.8647±0.0034	1.3225±0.0029	109.0±0.8	1.439±0.004
CM-225-04	0.0123	3.5	193.9	0.016	2.3E-5±6.4E-6	0.8594±0.0033	1.3194±0.0028	37,459	0.8594±0.0033	1.3194±0.0028	108.4±0.8	1.434±0.003
CM-225-05	0.0188	4.5	190.9	0.008	9.0E6±4.2e-6	0.8634±0.0033	1.3221±0.0028	101,547	0.8634±0.0033	1.3221±0.0028	108.8±0.8	1.438±0.003
CM-225-06	0.0185	5.5	185.1	0.009	1.1E-5±4.4E-6	0.831±0.0034	1.3195±0.003	72,687	0.8310±0.0034	1.3195±0.0030	102.7±0.8	1.427±0.004
CM-225-07	0.0224	6.5	183.2	0.008	1.1E-5±3.7E-6	0.85±0.0034	1.32±0.0029	80,679	0.8500±0.0034	1.3200±0.0029	106.4±0.8	1.432±0.004
CM-225-08	0.0244	7.5	179.5	0.008	1.1E-5±3.5E-6	0.8129±0.0032	1.3089±0.0027	73,227	0.8129±0.0032	1.3089±0.0027	100.5±0.7	1.410±0.003
CM-225-09	0.0201	8.5	183.4	0.006	7.0E-6±4.1E-6	0.8458±0.0034	1.3006±0.0028	121,794	0.8458±0.0034	1.3006±0.0028	108.4±0.8	1.408±0.003
CM-225-10	0.0209	9.5	184.8	0.009	1.2E-5±3.9E-6	0.8381±0.0032	1.2848±0.0027	71,338	0.8381±0.0032	1.2848±0.0027	109.2±0.8	1.388±0.003
CM-225-12	0.0224	11.5	192.1	0.007	8.0E-6±3.5E-6	0.849±0.0035	1.2727±0.0027	102,933	0.8490±0.0035	1.2727±0.0027	113.5±0.9	1.376±0.003
CM-225-15	0.0209	14.5	197.6	0.008	8.0E-6±3.7E-6	0.8618±0.0033	1.2935±0.0028	107,659	0.8618±0.0033	1.2935±0.0028	112.9±0.9	1.404±0.003
CM-225-18	0.0211	17.5	195.7	0.013	1.6E-5±3.7E-6	0.875±0.0036	1.3166±0.0028	53,415	0.8750±0.0036	1.3166±0.0028	112.1±0.9	1.434±0.003
CM-225-20	0.0268	19.5	196.3	0.021	3.1E-5±2.9E-6	0.9022±0.0036	1.3297±0.0028	29,277	0.9022±0.0036	1.3297±0.0028	115.8±0.9	1.457±0.003

CM-292: Mastodon limb bone; Locale #3767 bed E; Specimen #49926; Field #292

CM-292-01	0.0109	0.25	198.8	0.365	6.0E-4±7.3E-6	0.9065±0.0044	1.3294±0.0028	1,511	0.9064±0.0044	1.3296±0.0028	116.7±1.1	1.458±0.004
CM-292-02	0.0097	0.5	195.1	0.059	9.5E-5±8.0E-6	0.9074±0.0042	1.3338±0.0028	9,558	0.9074±0.0042	1.3338±0.0028	116.3±1	1.463±0.004
CM-292-03	0.0151	1	187.5	0.039	6.4E-5±5.4E-6	0.8919±0.0037	1.3208±0.0027	14,040	0.8919±0.0037	1.3208±0.0027	115.0±0.9	1.444±0.003
CM-292-04	0.0153	1.3	183.6	0.041	6.8E-5±5.4E-6	0.8915±0.0042	1.3212±0.0028	13,059	0.8915±0.0042	1.3212±0.0028	114.9±1	1.444±0.003
CM-292-05	0.0141	2	181.7	0.033	5.5E-5±5.9E-6	0.8891±0.0035	1.3233±0.0029	16,068	0.8891±0.0035	1.3233±0.0029	114.0±0.9	1.446±0.004
CM-292-06	0.0156	2.3	180.0	0.028	4.6E-5±5.4E-6	0.8833±0.0042	1.3162±0.0039	19,162	0.8833±0.0042	1.3162±0.0039	113.9±1.1	1.436±0.005
CM-292-07	0.0133	3	274.3	0.046	5.0E-5±4.1E-6	0.8725±0.0033	1.3115±0.0027	17,340	0.8725±0.0033	1.3116±0.0027	112.3±0.8	1.428±0.003

CM-292-08	0.0177	3.75	177.6	0.022	3.7E-5±4.8E-6	0.8729±0.0034	1.3123±0.0028	23,823	0.8729±0.0034	1.3123±0.0028	112.3±0.9	1.429±0.003
CM-292-09	0.0151	4.5	174.4	0.022	3.7E-5±5.7E-6	0.8618±0.0037	1.3101±0.0028	23,344	0.8618±0.0037	1.3101±0.0028	110.3±0.9	1.423±0.003
CM-292-10	0.0143	5.25	174.4	0.024	4.1E-5±6.1E-6	0.8563±0.0033	1.3012±0.0027	20,806	0.8563±0.0033	1.3012±0.0027	110.5±0.8	1.411±0.003
CM-292-11	0.0136	6.2	170.5	0.029	5.2E-5±6.6E-6	0.8537±0.0034	1.3065±0.0030	16,394	0.8537±0.0034	1.3065±0.0030	109.1±0.8	1.417±0.004
CM-292-12	0.0127	7	166.9	0.022	3.9E-5±7.1E-6	0.8520±0.0036	1.3117±0.0031	21,991	0.8520±0.0036	1.3117±0.0031	108.0±0.9	1.423±0.004
CM-292-13	0.0128	7.9	165.2	0.025	4.6E-5±7.2E-6	0.8513±0.0032	1.3058±0.0027	18,404	0.8513±0.0032	1.3058±0.0027	108.7±0.8	1.416±0.003
CM-292-14	0.0157	8.8	162.7	0.021	3.9E-5±5.9E-6	0.8452±0.0033	1.3101±0.0028	21,934	0.8452±0.0033	1.3101±0.0028	106.8±0.8	1.419±0.003
CM-292-15	0.0162	9.5	166.4	0.017	2.8E-5±5.6E-6	0.8470±0.0034	1.3076±0.0030	29,957	0.847±0.0034	1.3076±0.0030	107.6±0.8	1.417±0.004
CM-292-16	0.0127	10.3	165.3	0.023	4.1E-5±7.2E-6	0.8438±0.0032	1.3104±0.0027	20,572	0.8438±0.0032	1.3104±0.0027	106.5±0.8	1.419±0.003
CM-292-17	0.0137	11.1	167.2	0.025	4.5E-5±6.6E-6	0.8464±0.0041	1.3090±0.0027	18,796	0.8463±0.0041	1.3090±0.0027	107.2±0.9	1.418±0.003
CM-292-18	0.0133	12	170.4	0.024	4.2E-5±6.7E-6	0.8521±0.0048	1.3081±0.0030	20,261	0.8521±0.0048	1.3081±0.0030	108.6±1.1	1.419±0.004
CM-292-19	0.0029	13	173.6	0.206	3.9E-4±3.1E-5	0.8779±0.0153	1.3100±0.0047	2,277	0.8779±0.0153	1.3101±0.0047	113.7±3.4	1.427±0.007
CM-292-20	0.0039	13.9	172.1	0.107	2.0E-4±2.3E-5	0.8769±0.0063	1.3100±0.0028	4,378	0.8769±0.0063	1.3101±0.0028	113.5±1.4	1.427±0.004
CM-292-21	0.0166	14.7	173.7	0.022	3.7E-5±5.3E-6	0.8680±0.0034	1.3119±0.0029	23,615	0.8680±0.0034	1.3119±0.0029	111.3±0.9	1.427±0.004
CM-292-22	0.0147	15.7	176.3	0.028	4.7E-5±5.8E-6	0.8735±0.0037	1.3120±0.0027	18,609	0.8735±0.0037	1.3120±0.0027	112.5±0.9	1.429±0.003
CM-292-23	0.0142	16.7	176.7	0.070	1.2E-4±6.1E-6	0.8806±0.0046	1.3145±0.0027	7,025	0.8806±0.0046	1.3146±0.0027	113.6±1.1	1.433±0.003
CM-292-24	0.0137	17.5	179.1	0.029	4.8E-5±6.2E-6	0.8673±0.0035	1.3216±0.0030	18,078	0.8672±0.0035	1.3216±0.0030	109.7±0.9	1.438±0.004
CM-292-25	0.0150	18.2	171.0	0.034	6.1E-5±5.9E-6	0.8963±0.0036	1.3219±0.0030	14,733	0.8963±0.0036	1.3219±0.0030	115.8±0.9	1.446±0.004
CM-292-26	0.0145	19.5	179.4	0.030	5.0E-5±5.8E-6	0.8805±0.0034	1.3217±0.0029	17,748	0.8805±0.0034	1.3217±0.0029	112.4±0.8	1.442±0.004
CM-292-27	0.0154	20.5	180.8	0.043	7.3E-5±5.5E-6	0.9069±0.0037	1.3298±0.0028	12,375	0.9069±0.0037	1.3298±0.0028	116.8±0.9	1.459±0.003
CM-292-28	0.0140	21.3	181.7	0.071	1.2E-4±6.0E-6	0.9131±0.0035	1.3341±0.0028	7,372	0.9131±0.0035	1.3342±0.0028	117.4±0.9	1.466±0.003
CM-292-29	0.0088	22	165.4	0.207	4.1E-4±1.1E-5	0.9238±0.0044	1.3395±0.0029	2,262	0.9238±0.0044	1.3396±0.0029	118.9±1.1	1.475±0.004
CM-292-30	0.0121	22.8	159.6	0.462	9.5E-4±8.2E-6	0.9574±0.0038	1.3386±0.0029	1,008	0.9573±0.0038	1.3389±0.0029	126.6±1.1	1.484±0.004

Shallow groundwater from Sweetwater Authority water well SW, zones 5 and 6; 32.65889°N, -117.0855571°; Samples collected 10/15-16/2009

SDSW5	105.663	0.00084	1.446±0.003	
SDSW6	44.803	0.00338	1.538±0.004	

SECTION 9. ASIAN ORIGINS OF EARLY HUMANS ON THE WEST COAST OF NORTH AMERICA

Climatic conditions during the last interglacial period (Marine Isotope Stage 5e [MIS 5e]) would have allowed entry of early hominins into North America⁷⁶. This was the warmest interglacial period in the middle and late Pleistocene and one of the warmest during the entire Pleistocene Epoch. This period of global climatic warming allowed vertebrates from mid-latitude North America to range into more northerly latitudes and to higher elevations. For example, mastodons and sloths dispersed north above the Arctic Circle in Alaska, USA and the Yukon, Canada⁷⁷ and moved to higher elevations in the Rocky Mountains. After glacial retreat near the end of MIS 6 and the beginning of MIS 5 these taxa lived at an elevation of 2705 m (amsl) in central Colorado, USA⁷⁸, representing their northern-most limit in North America, as well as the highest elevation record for sloth and the second highest record for mastodons. Related to this northward movement of mammals is the discovery of a single capybara (*Hydrochoerus*) tooth (SDNHM 143879) at the CM site. This is the northwestern-most record for the genus and is far outside of its modern range in South America and northwest of the late Pleistocene distribution of capybara in northeastern Sonora, Mexico⁷⁹. The occurrence of capybara at the CM site suggests a warmer and wetter climate in this area at that time, conditions consistent with those of MIS 5e.

Hominins in Eurasia during MIS 5 include *Homo sapiens*, *Homo neanderthalensis*, *Homo* sp. (Denisova), *Homo floresiensis* and *Homo erectus*^{80, 81}. These taxa, except *Homo floresiensis*, could have dispersed into northeastern Asia as temperatures increased at the end of MIS 6 and during the Last Interglacial MIS 5⁸². Plausible dispersal routes for hominins to arrive on the west coast of North America at the end of MIS 6 include a land route across Beringia prior to 135 ka⁸³ and a coastal water route along the coasts of Asia, Beringia and North America. If Beringia was

partially submerged, the inland route would have required traversing a narrow water passage separating present-day Siberia from Alaska; a maximum of an 80-km crossing with Diomed Islands midway.

The continuous presence of hominins beginning ~300 ka in southern Siberia at the end of the Lower Paleolithic, although many of the sites are not well-dated⁸⁴, provides a potential source of populations that could disperse eastward. By adapting to conditions in southern Siberia, hominins could have extended their range further northeast to cross Beringia during interglacial intervals. The southern edge of the Beringian land bridge at its maximum extent is estimated to have been close to 63° N, about 200 km further north than the Diring Yuriakh site situated at 60° N in Siberia. The best age estimate for the lower level of the site containing stone tools is based upon TL dates of 267-366 ka⁸⁵. However, the geoarchaeological position and age (especially of the oldest stone artefacts) have been questioned⁸⁶. It is noteworthy that fossil remains of a cold-adapted female hominin, possibly an archaic *Homo sapiens*, have been discovered in Manchuria, China (40° 34' N). Animal teeth at the site were dated to ~ 260 ka by electron-spin resonance and uranium series dating⁸⁷. It is not yet known how far north these cold-adapted hominins dispersed, but they may be responsible for archaeological sites like Diring Yuriakh and other Early Paleolithic sites in southern Siberia.

At Denisova Cave (51.4° N) in southcentral Siberia, *Homo neanderthalensis* is first evidenced by the appearance of Middle Paleolithic stone tools in Stratum 22 with bracketing radio thermoluminescence (RTL) ages of 282 ± 56 and 171 ± 43 ka⁸⁸. Biostratigraphic and paleomagnetic data (Blake polarity episode) correlate more recent Denisova Cave Middle Paleolithic stone tool industries with MIS 5⁸⁶. Thus, there are several possible hominin candidates (late *Homo erectus*, Neanderthals or archaic *Homo sapiens*) resident in eastern Asia

that could have entered North America via Beringia and dispersed to the west coast of North America at 130 ka. Another possibility is that the little-known Denisovans, related most closely to Neanderthals⁸⁹, and known only from DNA studies at Denisova Cave, were the first hominins to reach North America.

In support of a coastal dispersal route is indirect evidence for the use of watercraft by hominins more than 100 ka. For example, the biogeographic barrier in Southeast Asia called the Wallace Line is marked by a deep ocean trench that limits most terrestrial species from dispersing from mainland Asia and western Indonesia to islands in eastern Indonesia. However, hominins crossed this barrier at least two times before 100 ka. The oldest recorded evidence is the presence of stone tools dating to 1.1 Ma⁹⁰ (probably made by ancestors of *Homo floresiensis*) on the island of Flores (lowest sea level sea crossing at Lombok Strait, ~19 km⁹¹). Additional evidence is provided by the presence of stone tools made by archaic humans (possibly *H. erectus*, or *Homo* sp. (Denisova)) at sites on the island of Sulawesi (lowest sea level sea crossing at Makassar Strait, ~42 km⁹¹) dating to between 118 and 194 ka⁹². In the Mediterranean Sea, there is evidence of an early hominin reaching Crete more than 130 ka based on the presence of Palaeolithic artefacts found there⁹³. Thus, early hominins using watercraft appear to have had the capacity to cross relatively narrow expanses of ocean before 100 ka ago. Based on this capacity, early hominins could have followed the east coast of Asia northward as the climate warmed at the beginning of MIS 5. They then could have followed the southern coast of Beringia, or crossed a short distance of open water between present-day Siberia and Alaska if the land connection had recently been submerged. A route south along the west coast of North America would then have brought them to the latitude of the CM site.

Three hominin groups are candidates for making the journey to North America by simple watercraft during the latest middle Pleistocene⁸⁰. The first is an archaic human (*Homo neanderthalensis*, *Homo sp.* (Denisovans) or *Homo erectus*). Neanderthals and “Denisovans” were probably present in northeastern Asia during MIS 5, and potentially capable of sea crossings. *Homo erectus* or their descendants were present in eastern mainland Asia at this time with potential sea-crossing capacity, since they are candidates for reaching the islands of Flores and Sulawesi^{90, 91, 92}. A more remote possibility is that *Homo sapiens* made the journey. Recent discoveries suggest that *Homo sapiens* was present in southern China sometime between 80 and 120 ka^{94, 95}. The CM site is well-dated to 130.7 +/- 9.4 ka. This time period is consistent with the onset of sea-level high stand conditions during MIS 5e dated by corals from tectonically stable areas^{96, 97, 98}. Higher temperatures and rapid sea-level rises associated with Termination II deglaciation may have facilitated coastal migration routes.

Another possible hominin group making the journey to North America is identified by DNA studies of remote Native Americans in Amazonia and the Central Brazilian Plateau. This study found traces of DNA from an unknown Population Y related to Australasians^{99, 100}. This DNA type is not present in Mesoamerican or North American Native American populations. The authors state “The arrival of Population Y ancestry in the Americas must in any scenario have been ancient: while Population Y shows a distant genetic affinity to Andamanese, Australian and New Guinean populations, it is not particularly closely related to any of them, suggesting that the source of Population Y in Eurasia no longer exists; furthermore, we detect no long-range admixture linkage disequilibrium in Amazonians as would be expected if the Population Y migrations had occurred within the last few thousand years.” This earlier dispersal event appears to be unrelated to the migration or migrations of later populations that became the Native

Americans and therefore must have occurred at an earlier date. Thus, Population Y, a group distantly related to modern Australasians but with no modern analog population in southeast Asia or Australia, may have arrived in the Americas quite early. Of course, Population Y could be the same early *Homo sapiens* group discussed previously.

The CM site currently is the only locality in North America that supports such an early hominin dispersal. This speculative discussion poses the challenge to initiate archaeological research in MIS 5e and MIS 6-age geological deposits in North America.

SECTION 10. REFERENCES CITED IN SUPPLEMENTARY INFORMATION SECTIONS

1. Deméré, T.A., Cerutti, R.A. & Majors, C.P. *State Route 54 Paleontological Mitigation Program: Final Report*. (San Diego Natural History Museum, 1995).
2. Kennedy, M.P. & Tan, S.S. Geology of National City, Imperial Beach, and Otay Mesa quadrangles, southern San Diego Metropolitan area, California. *Calif. Div. Mines and Geology, Map Sheet 29* (1977).
3. Kern, J.P. Origin and history of upper Pleistocene marine terraces, San Diego, California. *Bull. Geol. Soc. Amer.* **88**, 1553-1566 (1977).
4. Kern, J.P. & Rockwell, T.K. in *Quaternary Coasts of the United States: Marine and Lacustrine Systems* (eds C.H. Fletcher, III and J.F. Wehmiller), 377-382 (SEPM Special Publication 48 1992).
5. Ku, T-L. & Kern J.P. Uranium-series age of the upper Pleistocene Nestor terrace, San Diego, California. *Bull. Geol. Soc. Amer.* **85**, 1713-1716 (1974).
6. Kraus, M.J. & Hasiotis, S.T. Significance of different modes of rhizolith preservation to interpreting paleoenvironmental and paleohydrologic settings: Examples from Paleogene

- paleosols, Bighorn Basin, Wyoming, U.S.A. *J. of Sedimentary Research*. **76**, 633-646 (2006).
7. Holen, S.R. & Talley, R.H. The April Fools' Mammoth Site (14JW101), Lovewell Reservoir, Jewell County, Kansas. *Denver Museum of Nature & Science, Archaeological Series Technical Report* 2003-02 (2003).
 8. Johnson, E. in *Advances in Archaeological Method and Theory*, vol. 8. (ed M.B. Shiffer) 157-235, (Academic Press. 1985).
 9. Lyman, R.L. *Vertebrate Taphonomy* (Cambridge Univ. Press, 1994).
 10. Behrensmeyer, A.K. Taphonomic and ecologic information from bone weathering. *Paleobiology* **4**, 150-162 (1978).
 11. Egeland, C. & Domínguez-Rodrigo, M. Taphonomic perspectives on hominid site use and foraging strategies during Bed II times at Olduvai Gorge, Tanzania. *Journal of Human Evolution* **55**, 1031-1052 (2008).
 12. Morlan, R.E. Toward the definition of criteria for the recognition of artificial bone alterations. *Quaternary Research* **22**, 160–171 (1984).
 13. Haynes, G. Frequencies of spiral and green-bone fractures of ungulate limb bones in modern surface assemblages. *American Antiquity* **48**, 102–114 (1984).
 14. Holen, S.R. Taphonomy of two last glacial maximum mammoth sites in the central Great Plains: a preliminary report. *Quaternary International* **142-143**, 30-44 (2006).
 15. Holen, S.R. The age and taphonomy of mammoths at Lovewell Reservoir, Jewell County, Kansas, USA. *Quaternary International* **169-170**, 51-63 (2007).

16. Holen, S.R. & Holen, K. in *IV Simposio Internacianal: El hombre temprano en America*, (eds J.C. Jimenez Lopez, C. Serrano Sanchez, A. Gonzalez Gonzalez, & F.J. Aguilar Arellano) 85-105 (Instituto Nacional de Anthropologia and Historia 2012).
17. Holen, S. R. & Holen, K. in *Paleoamerican Odyssey* (eds K.E. Graf, C.V. Ketron & M.R. Waters) 429-444 (Center for the Study of the First Americans, 2013).
18. Fisher, D.C. Taphonomic Analysis of Late Pleistocene Mastodon Occurrences: Evidence of Butchery by North American Paleo-Indians *Paleobiology* **10**, 338-357 (1984).
19. Diedrich, C.J. Late Pleistocene Eemian hyena and steppe lion feeding strategies on their largest prey – *Palaeoloxodon antiquus* Falconer and Cautley 1845 at the straight-tusked elephant graveyard and Neanderthal site Newmark-Nord Lake 1, Central Germany. *Archaeological and Anthropological Sciences* **6**, 271-291 (2014).
20. Binford, L. R. *Bones: Ancient Men and Modern Myths*. (Academic Press, 1981).
21. Haynes, G. in *Recent Developments in Environmental Analysis in Old and New World Archaeology* (ed. R.E. Webb) 151-169 (BAR International Series 416, 1988).
22. Crader, D. in *Animals and Archeology, Vol. 1. Hunters and Their Prey*. (eds J. Clutton-Brock, & C. Grigson) 107–141 (BAR International Series No. 163, 1983).
23. Haynes, G. Longitudinal studies of African elephant death and bone deposits. *Journal of Archaeological Science* **15**, 131–157 (1988).
24. Krasinski, K.E. *Broken bones and cutmarks: taphonomic analyses and implications for the peopling of North America*. Ph.D. Dissertation, University of Nevada, Reno, U.S.A. (2010).

25. Domínguez-Rodrigo, M., Pickering, T.R. & Bunn, H.T. Configurational approach to identifying the earliest hominin butchers. *Proceeding of the National Academy of Sciences* **107**, 20929-20934 (2010).
26. Semenov, S.A. *Prehistoric Technology* (Adams & Dart, 1964).
27. Leakey, M.D. *Olduvai Gorge. Vol. 3. Excavations in Beds I and II, 1960-1963.* (Cambridge University Press 1971).
28. de Heinzelin, J. et al. Environment and behavior of 2.5-million-year-old Bouri Hominids. *Science* **284**, 625-629 (1999).
29. Backwell, L. R. & d’Errico, F. The first use of bone tools: a reappraisal of the evidence from Olduvai Gorge, Tanzania. *Palaeontologia Africana* **40**, 95-158 (2004).
30. Walker, S.J. *Paleolithic bone handaxes: On the evidence for the knapping of bone artifacts by premodern hominids and the implications for hominid behavioral and cognitive evolution.* Dissertation, Department of Archaeology, The University of Reading (1999).
31. Beyene, Y. et al. The characteristics and chronology of the earliest Acheulean at Konzo, Ethiopia. *Proceedings of the National Academy of Sciences* **110**, 1584-1591 (2013).
32. Zutovski, K. & Barkai, R. The use of elephant bones for making Acheulian handaxes: A fresh look at old bones. *Quaternary International* doi:10.1016/j.quaint.2015.01.033 (2015).
33. Wei, G. et al. First discovery of bone handaxe in China. *Quaternary International* doi.org/10.1016/j.quaint.2014.12.022 (2015).

34. Ono, A., Orikasa, A. & Nakamura, Y. Palaeolithic Bone Tools from the 10th Excavation Season at Tategahana, Lake Nojiri, Central North Japan. *The Quaternary Research* **29**, 90-103 (1999), (In Japanese).
35. Domínguez-Rodrigo, M. et al. On meat eating and human evolution: A taphonomic analysis of BK4b (Upper Bed II, Olduvai Gorge, Tanzania) and its bearing on hominin megafaunal consumption. *Quaternary International* **322-323**, 129-152 (2014).
36. Espigares, M.P. et al. *Homo* vs. *Pachycrocuta*: Earliest evidence of competition for an elephant between scavengers at Fuente Nueva-3 (Orce, Spain). *Quaternary International* **295**, 113-125 (2013).
37. Pobiner, B.L., Rogers, M.J., Monahan, C.M., & Harris, J.W.K. New evidence for hominin carcass processing strategies at 1.5. Ma, Koobi Fora, Kenya. *Journal of Human Evolution* **55**, 103-130 (2008).
38. Hannus, L.A. in *Bone Modification* (eds R. Bonnicksen, M.H. Sorg) 395–412 (Center for the Study of First Americans, 1989).
39. Stanford, D. J., Wedel, W. R., & Scott, G. R. Archaeological Investigations of the Lamb Spring Site. *Southwestern Lore* **47**, 14-27 (1981).
40. Miller, S.J. in *Bone Modification* (eds R. Bonnicksen, M.H. Sorg) 395–412 (Center for the Study of First Americans, 1989).
41. Steele, D.G. & Carlson, D.L. in *Bone Modification* (eds R. Bonnicksen, M.H. Sorg) 395–412 (Center for the Study of First Americans, 1989).
42. Fisher, D.C. Taphonomic analysis of late Pleistocene mastodon occurrences: evidence of butchery by North American Paleo-Indians. *Paleobiology* **10**, 338-357 (1984).

43. Fisher, D.C. in *The Evolution of Human Hunting* (eds M.H. Nitecki & D.V. Nitecki) 309–421 (Plenum Press, 1987).
44. Shipman, P., Fisher, D.C. & Rose, J.J. Mastodon butchery: microscopic evidence of carcass processing and bone tool use. *Paleobiology* **10**, 358–365 (1984).
45. Holen, S.R. & Holen, K. Testing the hypothesis of human-induced fracture and flaking patterns on Last Glacial Maximum mammoth limb bone: experimental replication using hammerstones to break and flake a modern African elephant femur. *Program and Abstracts, 64th Plains Anthropological Conference*, 68 (2006).
46. Stanford, D.J., Bonnicksen, R. & Morlan, R.E. The Ginsberg experiment: modern and prehistoric evidence of a bone-flaking technology. *Science* **212**, 438–39 (1981).
47. Haynes, G. & Krasinski, K.E. Taphonomic fieldwork in southern Africa and its application in studies of the earliest peopling of North America. *Journal of Taphonomy* **8**, 181–202 (2010).
48. Dominguez-Rodrigo, M. & Barba, R. New estimates of tooth mark and percussion mark frequencies at FLK Zinj site: the carnivore-hominid-carnivore hypothesis falsified. *Journal of Human Evolution* **50**, 170–194 (2006).
49. Capaldo, S.D. & Blumenshine, R.J. A quantitative diagnosis of notches made by hammerstone percussion and carnivore gnawing on bovid long bones. *American Antiquity* **59**, 724–728 (1994).
50. Galan, A. B., Rodríguez, M., de Juana, S. & Domínguez-Rodrigo, M. A new experimental study on percussion marks and notches and their bearing on the interpretation of hammerstone-broken faunal assemblages. *Journal of Archaeological Science* **36**, 776–784 (2009).

51. de la Torre, I., Benito-Calvo, A., Arroyo, A., Zupancich, A. & Proffitt, T. Experimental protocols for the study of battered stone anvils from Olduvai Gorge (Tanzania). *Journal of Archaeological Science* **40**, 313-332 (2013).
52. Caruana, M.V. et al. Quantifying traces of tool use: a novel morphometric analysis of damage patterns on percussive tools. PLoS ONE 9(11):e113856.doi:10.1371/journal.pone.0113856 (2014).
53. Yustos, P.S. et al. Production and use of percussive stone tools in the Early Stone Age: Experimental approach to the lithic record of Olduvai Gorge, Tanzania. *Journal of Archaeological Science Reports* **2**, 367-383 (2015).
54. Voorhies, M. *Taphonomy and Populations Dynamics of an Early Pliocene Vertebrate Fauna, Knox County, Nebraska*. (Contributions to Geology, Special Paper 1, University of Wyoming, 1969).
55. McDaniel, G. in *Fossil Treasures of the Anza-Borrego Desert* (eds G.T. Jefferson and L. Lindsay), 217-233 (Sunbelt Publications 2006).
56. Stepleton, E. The Trenton stegomastodon: *Morrillia barbouri* makes its best (and last?) appearance! (University of Nebraska State Museum, Vertebrate Paleontology Collections and Research, 2010). <http://museum.unl.edu/research/vertpaleo/stego.html>.
57. Gust, S., Scott, K. & Richards, C. Paleontological monitoring report for the Arboleda Drive freeway project State Route 99, Merced County, California. Submitted to the State of California Department of Transportation, Manuscript on File Colorado Desert District Stout Research Center Library Archive, Borrego Springs 144 p. (2012).

58. Fisher, D. C. in *Mastodon Paleobiology, Taphonomy, and Palaeoenvironment in the Late Pleistocene of New York State: Studies on the Hyde Park, Chemung, and North Java Sites* (eds W.D. Allmon & P.L. Nester) 197–290 (Paleontological Research Institution, 2008).
59. Murray, A.S. & Wintle, A.G. The single aliquot regenerative dose protocol: potential for improvements in reliability. *Radiation Measurements* **37**, 377–381 (2003).
60. Bailey, R.M., Armitage, S.J. & Stokes, S. An investigation of pulsed-irradiation regeneration of quartz OSL and its implications for the precision and accuracy of optical dating (Paper II). *Radiation Measurements* **39**, 347–359 (2005).
61. Jain, M., Botter-Jensen, L. & Singhvi, A. K. Dose evaluation using multiple-aliquot quartz OSL: test of methods and a new protocol for improved accuracy and precision. *Radiation Measurements* **37**, 67–80 (2003).
62. Aitken, M. J. & Bowman, S. G. E. Thermoluminescent dating: assessment of alpha particle contribution. *Archaeometry* **17**, 132–138 (1975).
63. Prescott, J.R. & Hutton, J.T. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. *Radiation Measurements* **23**, 497–500 (1994).
64. Ludwig, K.R. & Titterton, D.M. Calculation of $^{230}\text{Th}/\text{U}$ isochrones, ages, and errors. *Geochim. Cosmochim. Acta*, **58**, 5031–5042 (1994).
65. Millard, A.T. & Hedges, R.E.M. A diffusion-adsorption model of uranium uptake by archaeological bone. *Geochim. Cosmochim. Acta*, **60**, 2139–2152 (1996).
66. Pike, A.W.G., Hedges, R.E.M & van Calsteren, P. U-series dating of bone using the diffusion-adsorption model. *Geochim. Cosmochim. Acta* **66**, 4273–4286 (2002).

67. Pike, A.W.G. & Pettitt, P.B. U-series dating and human evolution. *Reviews Mineral. Geochem.* **52**, 607–630 (2003).
68. Grün, R. et al. U-series and ESR analyses of bones and teeth relating to the human burials from Skhul. *J. Human Evol.* **49**, 316–334 (2005).
69. Grün, R., Aubert, M., Joannes-Boyau, R. & Moncel, M-H. High resolution analysis of uranium and thorium concentration as well as U-series isotope distributions in a Neanderthal tooth from Payre (Ardèche, France) using laser ablation ICP-MS. *Geochim. Cosmochim. Acta* **72**, 5278–5290 (2008).
70. Grün, R., Eggins, S., Kinsley, L., Moseley, H. & Sambridge, M. Laser ablation U-series analysis of fossil bones and teeth. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* **416**, 150–167 (2014).
71. Tandon, L., Iyengar, G.V. & Parr, R.M. A review of radiologically important trace elements in human bones. *Appl. Radiat. Isot.* **49**, 903–910 (1998).
72. Larivière, D. et al. Age dependence of natural uranium and thorium concentrations in bone. *Health Phys.* **92**, 119 (2007).
73. Larivière, D., Tolmachev, S.Y., Kochermin, V. & Johnson, S. Uranium bone content as an indicator of chronic environmental exposure from drinking water. *J. Environ. Radioact.* **121**, 98–103 (2013).
74. Sambridge, M., Grün, R., & Eggins, S. U-series dating of bone in an open system: The diffusion-adsorption-decay model. *Quatern. Geochron.* **9**, 42–53 (2012).
75. Paces, J.B., Ludwig, K.R., Peterman, Z.E. & Neymark, L.A. $^{234}\text{U}/^{238}\text{U}$ evidence for local recharge and patterns of ground-water flow in the vicinity of Yucca Mountain, Nevada, USA. *Appl. Geochem.* **17**, 751–779 (2002).

76. Shackleton, N.J., Sánchez-Goñi, M.F., Pailler, D. & Lancelot, Y. Marine Isotope Substage 5e and the Eemian Interglacial. *Global and Planetary Change* **36**, 151-155 (2003).
77. Zazula, G.D. et al. American mastodon extirpation in the Arctic and Subarctic predates human colonization and terminal Pleistocene climate change. *Journal of the National Academy of Sciences* **111**, 18460-18465 (2014).
78. Fisher D. C. et al. Taxonomic overview and tusk growth analyses of Ziegler Reservoir proboscideans. *Quaternary Research* **82**, 518–532 (2014).
79. Mead, J. I. et al. Tropical Marsh and Savanna of the Late Pleistocene in Northeastern Sonora, Mexico. *The Southwestern Naturalist* **51**, 226-239 (2006).
80. Boivin, N., Fuller, D.Q., Dennell, R., Allaby, R. & Petraglia M.D. Human dispersal across diverse environments of Asia during the Upper Pleistocene. *Quaternary International* **300**, 32–47 (2013).
81. Sutikna, T. et al. Revised stratigraphy and chronology for *Homo floresiensis* at Liang Bua in Indonesia. *Nature* **532**, 748-752 (2016).
82. Rovere, A. et al. The analysis of Last Interglacial (MIS 5e) relative sea-level indicators: Reconstructing sea-level in a warmer world. *Earth-Science Reviews* **159**, 404–427 (2016).
83. Hu, A. et al. Influence of Bering Strait flow and North Atlantic circulation on glacial sea-level changes. *Nature Geoscience* **3**, 118–121 (2010).
84. Derevianko, A.P., Postnov, E.V., Rybin, E.P., Kuzmin, Y.V. & Keates, G. The Pleistocene peopling of Siberia: A review of environmental and behavioral aspects. *Indo-Pacific Prehistory Association Bulletin* **25**, 57-68 (2005).

85. Waters, M. R., Forman, S.L. & Pierson, J.M. Diring Yuriakh: A Lower Paleolithic site in Central Siberia. *Science* **275**, 1281-1284 (1997).
86. Kuzmin, Y.V. & Krivonogov, S.K. More about Diring Yuriakh: Unsolved geoarchaeological problems at the “Lower” Paleolithic site in central Siberia. *Geoarchaeology* **14**, 351-359 (1999).
87. Rosenberg, K.R. et al. Body size, body proportions, and encephalization in a Middle Pleistocene archaic human from northern China". *Proceedings of the National Academy of Sciences* **103**, 3552–3556 (2006).
88. Derevianko, A.P., Markin, S.V. & Shunkov, M.V. The Sibiryachikha facies of the Middle Paleolithic of the Altai. *Archaeology Ethnology & Anthropology of Eurasia* **41.1**, 89–103 (2013).
89. Prufer, K. et al. The complete genome sequence of a Neanderthal from the Altai Mountains *Nature* **505**, 43–49 (2014).
90. Brumm, A. et al. Hominins on Flores, Indonesia, by one million years ago. *Nature* **464**, 748-752 (2010).
91. Birdsell, J. in *Sunda and Sahul* (eds. J. Allen, J. Golson & R. Jones) 113-168 (Academic Press, 1977).
92. van den Bergh, G.D. et al. Earliest hominin occupation of Sulawesi, Indonesia. *Nature* **529**, 208-211 (2016).
93. Runnels, C. Early Palaeolithic on the Greek Islands? *Journal of Mediterranean Archaeology* **27.2**, 211-230 (2014).
94. Lui, W. et al. The earliest unequivocally modern humans in southern China. *Nature* **526**, 696-699 (2015).

95. Shen, G. et al. Mass spectrometric U-series dating of Huanglong Cave in Hubei Province, central China: Evidence for early presence of modern humans in eastern Asia. *Journal of Human Evolution* **65**, 162–167 (2013).
96. Gallup, C.D., Cheng, H., Taylor, F.W. & Edwards, R.L. Direct determination of the timing of sea level change during Termination II. *Science* **295**, 310–313 (2002).
97. Muhs, D.R. Evidence for the timing and duration of the Last Interglacial Period from high-precision uranium-series ages of corals on tectonically stable coastlines. *Quaternary Research* **58**, 36–40 (2002).
98. Thomas, A.L. et al. Penultimate deglacial sea-level timing from uranium/thorium dating of Tahitian corals. *Science* **324**, 1186–1189 (2009).
99. Skoglund, P. et al. Genetic evidence for two founding populations of the Americas. *Nature* **525**, 104–108 (2015).
100. Skoglund, P. & Reich, D. A genomic view of the peopling of the Americas. *Current Opinion in Genetics and Development*, **41** 27–35 (2016).