Title

The timing and impact of the earliest human arrival in North America

Authors

Lorena Becerra-Valdivia[1,2] and Thomas Higham[1]

[1]Oxford Radiocarbon Accelerator Unit, Research Laboratory for Archaeology and History of Art, University of Oxford, Dyson Perrins Building, South Parks Road, OX1 3QY, Oxford, United Kingdom.
[2]Chronos ^{14}C-Cycle Facility, SSEAU, Mark Wainwright Analytical Centre Room G61, Chemical Sciences Building (F10), UNSW, Sydney, NSW 2052, Australia.

Summary

The peopling of the Americas marks a major expansion of humans across the planet. Questions regarding the timing and mechanisms of this dispersal remain, however, and the previously accepted model, termed 'Clovis-first', has been effectively refuted. Given that a robust chronological framework is required in mapping human dispersal(s), we have analysed chronometric data from 42 North American and Beringian archaeological sites using a Bayesian age modelling approach and use the resulting framework to elucidate spatio-temporal patterns. These are integrated with genetic and climatic evidence. The data obtained show that humans were probably already present before, during, and immediately after the Last Glacial Maximum (LGM; ~26.5-19 ka)[1,2] but that more widespread occupation began during a period of abrupt warming, Greenland Interstadial 1 (~14.7-12.9 ka b2k)[3]. We also identify the near-synchronous commencement of Beringian, Clovis and Western Stemmed cultural traditions, and an overlap of each with the last appearance dates for 18 extinct faunal genera. Our analysis suggests that the widespread expansion of humans through North America was a key factor in the extinction of large terrestrial mammals occurring at the time.

Main Text

Until recently, the prevailing paradigm for initial human dispersal into the Americas held that the first Americans were big-game hunters who entered the continent ~13 thousand years ago (ka) from Asia via Beringia, moving southwards through an ice-free corridor between the Laurentide and Cordilleran Ice Sheets (LIS and CIS). Once below the 48th parallel north (N), it was suggested that these human groups developed a material tradition named 'Clovis'—dated to between 13,250-12,800 years before 1950 (cal BP)[4]—which spread across North America. This narrative, known as the 'Clovis-first' model, was widely accepted for most of the 20th century as it effectively answered most questions associated with the peopling of the Americas—when, why, and from where[5]. The Clovis-first model has been refuted, however, by new archaeological and chronometric data demonstrating the existence of sites that predate Clovis (often termed 'pre-Clovis' or 'older-than-Clovis'[6,7])[7–21] and distinct technological industries that occur coevally[22–27]. An earlier dispersal route along the Pacific Coast, is currently considered the most likely means by which people moved into the Americas[28–31] (but see reference [32]).

To understand the pattern of initial human dispersals in a more refined manner, we have analysed chronometric data from a large number of North American and Beringian archaeological sites, using

Bayesian statistical methods. The results enable us to propose a new chronology-based model for the peopling of North America.

High-precision chronometric models were built using Bayesian age modelling on the OxCal 4.3 platform[33,34], based on archaeo-chronometric information obtained from 42 archaeological sites (see Supplementary Information; Table S1). This approach enables the incorporation of absolute chronometric data, in this case radiocarbon and luminescence ages, with stratigraphic and other relative age information (see Methods). The sites we have analysed include cultural components that fall, according to the literature, within one of three technological traditions (Clovis, Western Stemmed, and Beringian; see Supplementary Information) or, as defined here, two exclusively temporal categories (pre-Clovis and 'Clovis-coeval'; Fig. 1). Probability density functions (PDFs) corresponding with temporal start boundaries or age estimates for each site and tradition were generated from the models (see Methods and Supplementary Information; Table S2), and are reported below at a 95.4% confidence/credible interval (CI). In addition, we used kernel density estimate (KDE) methods, which estimate the underlying distribution of a dataset, to visualise the spatial and temporal distribution of the data (see Methods). We used the Greenland ice core timescale (GICC05)[35] to place our results in the context of past climatic changes, particularly the period comprising the Greenland Interstadial 1 (GI-1) and Greenland Stadial 1 (GS-1)—beginning at ~14.7 thousand years before AD 2000 (b2k) and ending at ~11.7 ka b2k[3] (Figs. 2-3). Although GICC05 and the current radiocarbon dating calibration curve (IntCal13[36]) are not synchronous, between 14,000 and 11,000 years before present (AD 1950), the estimated offset is less than ~50 years[37]. Given the temporal resolution of this study, the effect of this offset is therefore negligible.

Modelled start boundaries for pre-Clovis sites show the earliest evidence for cultural occupation at Chiquihuite Cave [Stratigraphic Component (SC) C], Mexico, at 33,150-31,405 cal BP, prior to the Last Glacial Maximum (LGM; 26.5 to 20-19 ka[1,2]). Later, several sites appear to be occupied during, or immediately after, the LGM. These include Gault (26,435-17,385 cal BP), Meadowcroft Rockshelter (24,335-18,620 cal BP) and Cactus Hill (20,585-18,970 cal BP) (Fig. 2a). In eastern Beringia, Bluefish Caves is represented by a single date obtained on a humanly-modified bone sample (24,035-23,310 cal BP[38]) dating squarely to the LGM. Start boundaries for Chiquihuite Cave SC-B (16,605-15,615 years cal BP), Cooper's Ferry (16,560-15,285 cal BP) and Debra L. Friedkin (16,315-14,660 cal BP) suggest occupations at these sites began after the LGM and near to GI-1—a warmer period of sudden, short-lived climate[3]. Following these, age estimates for Hebior (15,615-13975 cal BP), Schaefer (15,020-13,710 cal BP), Paisley Caves (14,755-13,780 cal BP), Page-Ladson (14,710-14,450 cal BP), Lindsay (14,625-13,945 cal BP) and Manis (13,795-13,745 cal BP) fall within or near GI-1. Chronometric data (n=215) from these fourteen pre-Clovis components yielded a distribution with a peak centred on ~14,250 cal BP, which represents the bulk of the chronometric evidence (Fig. 2b). For later lithic traditions—Beringian, Western Stemmed and Clovis—modelled start boundaries obtained suggest these began between 14,955-13,895, 14,860-13,065 and 14,210-13,495 cal BP, respectively (Fig. 3; Extended Data Figs. 1-3).

Apart from pre-LGM evidence, currently limited to Chiquihuite Cave (SC-C), the analysis shows that several archaeological sequences in North America—Bluefish Caves, Gault, Meadowcroft and Cactus Hill—begin during, or immediately after, the LGM and, south of the 48th parallel (N), concentrate in the east (Fig. 1; Fig 4a-b). Whilst global climate was generally cooler and drier during the LGM, areas south of the North American ice sheets were relatively open and temperate[39–41], with evidence for high hydrological and ecological variability[42–47]. The distribution of early mid-latitude sites led some to argue that North America was originally colonised by southwestern Europeans arriving via a transatlantic ice-corridor during the LGM; the so-called Solutrean Hypothesis[48–50]. The connection to Europe lies in purported typological and manufacturing similarities between Solutrean (appearing ~25-24,000 cal BP[51,52]) and Clovis lithic

technologies, as well as evidence for pre-Columbian West Eurasian genetic admixture. This hypothesis, however, has been rejected on technological and genetic grounds[53–56]. If transatlantic migration is set aside and an Asian origin assumed, the antiquity and distribution of these sites suggest that the initial crossing of the 48th parallel (N) occurred either; (i) during the latter part of Marine Isotope Stage (MIS) 3 (57-29 ka)[57], when ice and sea level estimates[58–60] indicate that land passage through Beringia was unlikely or interrupted, and an ice-free corridor between LIS and CIS was probably present[60] (with evidence of terrestrial landscapes occurring 48-40 ka[61]) or; (ii) during the LGM terminus, when the Bering land bridge was viable but the ice-free corridor inacessible[62,63]. Both possibilities suggest the earliest arrivals to North America had some degree of littoral adaptation. The latter scenario would have required movement along the Pacific Coast, perhaps before the CIS reached its maximum extent (~20-17 ka[64]). It is also more compatible with current genetic findings, which suggest that ancestral Native Americans experienced genetic isolation in eastern Beringia during the LGM[65] and diverged from Ancient Beringians at 22-18.1 ka[66,67]. This assumes the pre-Clovis occupants of Gault, Meadowcroft and Cactus Hill were of Native American ancestry. Evidence from Chiquihuite Cave's SC-C suggests the presence of an earlier human group, but their genetic ancestry is yet unknown[68]. Once in mid-latitude North America, the paucity (only twelve archaeological sites), distribution (Fig. 1) and characteristics of pre-Clovis evidence suggest that humans had unique adaptational behaviours and were spread widely. Lithic industries at Chiquihuite Cave, Gault, Meadowcroft and Cactus Hill, for example, are largely unrelated[6,68] (but see reference [69]).

Bayesian age modelling shows that the start dates of the Beringian, Western Stemmed and Clovis traditions are statistically indistinguishable (see Supplementary Information, section 5) and occur near-synchronously, largely coinciding with GI-1 (Fig. 3)—a warmer period of sudden, short-lived climate[3]—and a peak in the modelled chronometric data (Extended Data Fig. 4d-f). This suggests a probable increase in population density at this time, supported by mitochondrial[70], Y chromosome[71] and autosomal[72] evidence for marked population growth at ~16-15 ka. In addition, the age estimates also likely follow or coincide with a split of the ancestral Native American lineage into two branches[66,73–76] (Southern and Northern), which probably occurred outside of Eastern Beringia and south of the North American ice sheets[66,67,73], at ~17.5-14.6 ka[67].

Technologically, the relationship between pre-Clovis and Clovis is uncertain[6,68], whilst the Western Stemmed tradition has been linked with multiple pre-Clovis[19,20,30] and circum-Pacific sites[29,77] due to perceived similarities in stemmed point technologies. Recently, however, evidence from the Debra L. Friedkin site has been argued to show the progression from stemmed to fluted (Clovis) technology, with a triangular lanceolate point noted as a possible link between the two[20]. Genetically, the connection between pre-Clovis populations and the makers of Clovis and Western Stemmed traditions requires further research. This is because genetic information from other Clovis-coeval or pre-Clovis archaeological sites has yet to be obtained[68], with the exception of the pre-Clovis component at Paisley Caves, where mitochondrial DNA data corresponds to Native American founding haplogroups[16], and Anzick, a burial site representing Clovis and the Southern Native American lineage[74]. It is likely, however, that these groups and the initial arrivals are somehow related, otherwise, a minimum of two Pleistocene-aged migrations should be expected. Given our results, if there were a later dispersal event into the Americas, this would most likely predate GI-1 and estimates for the earliest bioavailability of the ice-free corridor, at ~13,000 cal BP[78,79], perhaps occurring after the western retreat of the CIS ~18-17 ka[64,80,81] and the Alaska Peninsula Glacier Complex ~17 ka, as well as the likely establishment of productive ecosystems in the North Pacific coast ~17 ka[64].

Humans arriving in North America have been previously linked with the extinction of 37 faunal genera; the overkill hypothesis popularized by P. Martin[82–84]. Depending on the analysis, more

recent studies are either in support[85] or suggest other factors, such as climate, ecological change and an extraterrestrial impact, as main or joint contributors[86–93]. Our results show that human presence in the continent precedes the majority of last appearance dates (LADs) for extinct genera in North America[94], including *Camelops*, *Cuvieronius*, *Equus, Mammut*, and *Mammuthus*. When these are summarized in a probability density distribution, the highest peak (containing 18 of the 24 dates included) occurs during the GI-1/GS-1 boundary and overlaps with the start boundaries obtained for Clovis and Western Stemmed traditions (Fig. 3). This raises the distinct possibility that widespread human expansion in population and space was a key factor in the extinction of large terrestrial mammals. To better understand the relationship between human arrival, faunal extinctions, and the climate changes that may have also played a role, we require improved demographic histories for each extinct genus and species, as well as more robust chronometric data[16] to improve Bayesian models (see reference [95]). Results from the latter would allow formal integration with the archaeological age estimates in this study and their combined, quantitative analysis.

Our analysis of the timing of initial human dispersals into Beringia and North America suggests that people were present in different settings before, during, and immediately following the LGM, prior to the commencement of more widespread occupation and human population growth during GI-1. Pre-LGM evidence is currently limited to one archaeological site (Chiquihuite Cave). If population continuity is assumed, this pattern is consistent with phases of human exploration and colonization, and the degree of genetic structure already present in North America by GI-1. The bio-cultural relationship between humans represented by pre-Clovis sites and later North American and Beringian traditions, however, is largely unknown. The analysis of ancient human DNA from sediments[96] has the potential to increase our knowledge and shed light on these questions. Finally, although this study focused on Beringia and North America, continued investigations in Central and South America—for which Late Pleistocene data is comparatively limited[97–104]—should allow for the chronological assessment of local archaeological sites[7,9,10,22,26,27,105–114] and the development of continent-wide spatio-temporal models. Future research will enable the chronological model described here to be tested, and its precision and accuracy improved as new data is integrated.

[add 30 first refs]

Fig. 1 | Map showing the location of the 42 archaeological sites included in this study. The extent of the ice-free corridor at 12,500 cal BP is according to reference [63], and the Beringian coastline during the LGM approximated from reference [115].

Fig. 2 | Start boundaries or age estimates for fourteen pre-Clovis sites/components (a) and a summarized distribution of chronometric data (i.e., dates; n=215; b) within these. In (**a**), the LGM span is according to reference [54] and is noted with a yellow band, whilst GI-1 (dark gray band) and GS-1 (light gray band) follow reference [3]. $\delta^{18}O$ data according to the Greenland ice core timescale (GICC05)[35]. Brackets beneath each age estimate show 95.4% CI. In (**b**), the light gray crosses show the median values of the calibrated date ranges, whilst the black crosses show the medians of the marginal posterior distributions for each event from the KDE model analysis. Within this distribution, data are concentrated around a single peak at ~14,250 cal BP. Results suggest that humans were initially present in North America before, during, or immediately after the LGM.

Fig. 3 | Start boundaries for Clovis, Western Stemmed and Beringian traditions, and a summarized distribution of last appearance dates (LADs) for 24 extinct mammal genera in North America. The LGM span is according to reference [54] and is noted with a yellow band, whilst GI-1 (dark gray band) and GS-1 (light gray band) follows reference [3]. $\delta^{18}O$ data is according to the Greenland ice core timescale (GICC05)[35]. Brackets beneath each age estimate show 95.4% CI. In the summarized distribution panel, the light gray crosses show the median values of the calibrated

dates, whilst the black crosses show the medians of the marginal posterior distributions for each event from the KDE model analysis. LAD data is entered as compiled in reference [94]. Results suggest that the onset of the three traditions is largely coincident with GI-1, a globally warmer period of drastic, short-lived climate changes[3]. Moreover, the highest density peak for the KDE model overlaps with the start of Clovis and Western traditions and coincides with the GI-1/GS-1 interface. This suggests that human expansion was strongly involved in North American Pleistocene extinctions.

METHODS

Previously published archaeo-chronometric data for 41 archaeological sites (see Supplementary Information; Table S1) were used to construct site- and tradition-level models using OxCal 4.3, a Bayesian modelling program[34], and the IntCal13 calibration curve[36]. In OxCal, models are built using Chronological Query Language (CQL), which is identified here in Courier New font.

Bayesian age modelling and non-MCMC functions in OxCal

Bayesian age modelling is a statistical tool that enables the analysis of chronometric data (standardized likelihoods) in the context of existing, pertinent knowledge (prior), and the results obtained (posterior). Priors can include absolute, e.g., historical accounts, or relative information, e.g., stratigraphy[116]. Results are expressed as probability density functions (PDFs) through the use of a random sampling technique, Markov Chain Monte Carlo (MCMC), that utilizes a mixture of Metropolis-Hastings algorithm and Gibbs Sampling[117,118]. The program is set to initially analyse 30,000 iterations, with convergence checked every 3,000 (a 'pass') and new starting points at every 6,000. If convergence is less than 95%, the pass interval is increased by a factor of two until convergence is satisfactory[119]. As preset, PDFs are quoted as age ranges including the 68.2, 95.4 or 99.7% most likely results based on the prior (the highest posterior density range). In plots, these are identifiable over individual calibrated radiocarbon likelihoods or non-radiocarbon measurements as a darker distribution. Bayesian age modelling assumes that time can be divided into units and treats archaeological events as groups defined by start and end boundaries. In this sense, a group can be incorporated into OxCal as a `Phase` within a `Sequence` constrained by two `Boundary` commands. A `Phase` contains a group with unrelated, unordered items, whilst those in a `Sequence` follow an order. The type of group can be defined by the type of boundary used (`Boundary`, `Zero_Boundary`, `Tau_Boundary` or `Sigma_Boundary`) and the distribution each denotes—uniform, ramped, exponential or normal (Figure 4 in reference [34]). A `Boundary` at the start and end of a group, for example, defines a uniform phase and assumes, a priori, that all events included are equally likely to occur anywhere within the two boundaries. An outlier analysis approach [`Outlier_Model()` and `Outlier()`] can be used to address the assumption that all dates are correct. This defines the distribution and scale of outliers, and assigns each date a prior probability of being an outlier. The '`General`' outlier model, for example, draws outliers from a Student's t-distribution with 5 degrees of freedom to account for extreme outliers, and sets the scale of offset to range widely, between 10^0 to 10^4 years[120]. The analysis then identifies outliers by assessing the fit of chronometric data within the prior framework, and down-weights them automatically according to their degree of offset. This approach is more objective than manual exclusion of dates and has a similar output (Fig. 9 in reference [120]). In archaeology, outlier analysis can be used to assess agreement between chronometric data and stratigraphic evidence, often yielding important information regarding site-specific processes, e.g., geological unconformity or bioturbation.

In OxCal, there are a number of MCMC and non-MCMC functions that are relevant to archaeological investigations. These can be used to produce age estimates for archaeological

features (`Date` within a `Phase`; this produces a distribution for the dated events), the commencement of an occupational phase (start `Boundary`), or test goodness of fit between multiple dates relating to the same moment in time (`R_Combine` and `Combine`). Modeling the start of an archaeological occupation is particularly useful in the study of human dispersals, as human presence precedes an archaeological event. In addition, `KDE_Model` and `KDE_Plot` can be used to estimate the underlying distribution of datasets using kernel density estimation (KDE[121,122])[123]. `KDE_Model`, in particular, is an MCMC approach that can be applied to sets of related dates. This uses a normal kernel, assumes a normal distribution (estimating bandwidth according to Silverman's rule[124]), applies a shaping parameter to the bandwidth to overcome over-smoothing of multi-modal distributions, and treats events within a grouping as dependent. Default kernel and factor (applied relative to Siverman's rule) parameters in OxCal are N(0,1) and U(0,1), accordingly.

Further details, including mathematical notation, can be found online in the OxCal manual[125].

Model construction and visualisation

Archaeological sites with dated stratified sequences were incorporated into single or multiple uniform phases, and start boundaries were used as temporal markers of human presence (see Supplementary Information). Unstratified sites containing roughly synchronous archaeological events—directly dated human burials with associated (dated) artifacts or faunal remains subjected to human predation—were included in a single, uniform `Phase`, and a `Date` function was used to provide an age estimate. For these, if applicable and available, only the latest bone collagen dates obtained through XAD[126,127] or HYP[128] protocols were used—recent studies show these to provide more reliable measurements, particularly for contaminated bone[4,15,129,130]. If these sites were best or solely represented by a single measurement, a calibrated date was employed. All modelled dates were assigned a 0.05 probability of being an outlier (unless otherwise specified), and 'General' and 'SSimple' models were used (using default parameters). We relied on outlier analysis to objectively identify and down-weight outliers within the models. Following these methods, site-specific age estimates (start boundaries, `Date` functions, or calibrated dates) were obtained for all archaeological sites (Supplementary Information, Table S2). Where appropriate, these were incorporated into uniform phases to build tradition-level models and PDFs for the start of Beringian, Western Stemmed and Clovis traditions were obtained (Extended Data Figs. 1-3). This allowed for the comparison of different traditions spatio-temporally, as informed by the statistical assessment of individual archaeological sequences. To visualise the temporal and/or spatial distribution of chronometric data, KDE methods were applied using the `KDE_Model` function (using default parameters noted above; in Figs. 2-4) and spatial KDE analysis within the mapping package (see reference [131] for a description of the algorithm) to identify clusters within the model output (in Extended Data Fig. 4). All age estimates are noted to 95.4% confidence or credible (for Bayesian model output) interval, unless otherwise specified, and rounded to five years (following a convention explained in reference [132]).

Data availability The data that support the findings of this study are available from the main text or Supplementary Information.

Code availability Code for OxCal are noted within the Supplementary Information file.

[Insert leftover references here]

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Author contributions L.B-V compiled archaeo-chronometric data and built Bayesian age models. L.B-V and T.H analysed modelled output and wrote the manuscript.

Competing interests The authors declare no competing interests.

Additional information
Supplementary Information is available for this paper.
Correspondence and requests for materials should be addressed to L.B-V. (l.becerravaldivia@unsw.edu.au)
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Extended Data Fig. 1 | Bayesian age model and start boundary for the Beringian tradition (14,955-13,895 cal BP). In the right pane, the estimate has been rounded to 50. Outlier analysis output is noted as 'O:posterior probability/prior probability'. $\delta^{18}O$ data according to the Greenland ice core timescale (GICC05)[35].

Extended Data Fig. 2 | Bayesian age model and start boundary for the Western Stemmed tradition (14,860-13,065 cal BP). Outlier analysis output is noted as 'O:posterior probability/prior probability'. $\delta^{18}O$ data according to the Greenland ice core timescale (GICC05)[35].

Extended Data Fig. 3 | Bayesian age model and start boundary for Clovis (14,210-13,495 cal BP). Outlier analysis output is noted as 'O:posterior probability/prior probability'. $\delta^{18}O$ data according to the Greenland ice core timescale (GICC05)[35].

Extended Data Fig. 4 | Spatio-temporal slices (a-f) of chronometric data (colored circles; i.e., dates; n=451) belonging to the cultural components analysed, with a spatial KDE analysis (white outlines). Chronometric data was summarized using a '`KDE_Model`' analysis (see Methods). For each date, differences in circle size reflect increasing/decreasing probabilities at a 95.4% CI, and follow the color scheme in Fig. 1. The spatial KDE analysis shows a marked increase in the frequency and distribution of the data immediately, before and during GI-1.

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