

## Title

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

## Authors

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## 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)<sup>1,2</sup> but that more widespread occupation began during a period of abrupt warming, Greenland Interstadial 1 (~14.7-12.9 ka b2k)<sup>3</sup>. 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)<sup>4</sup>—which spread across North America. This narrative, known as the ‘Clovis-first’ model, was widely accepted for most of the 20<sup>th</sup> century as it effectively answered most questions associated with the peopling of the Americas—when, why, and from where<sup>5</sup>. 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’<sup>6,7</sup>)<sup>7-21</sup> and distinct technological industries that occur coevally<sup>22-27</sup>. An earlier dispersal route along the Pacific Coast, is currently considered the most likely means by which people moved into the Americas<sup>28-31</sup> (but see reference <sup>32</sup>).

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<sup>33,34</sup>, 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)<sup>35</sup> 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<sup>3</sup> (Figs. 2-3). Although GICC05 and the current radiocarbon dating calibration curve (IntCal13<sup>36</sup>) are not synchronous, between 14,000 and 11,000 years before present (AD 1950), the estimated offset is less than ~50 years<sup>37</sup>. 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<sup>1,2</sup>). 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<sup>38</sup>) 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<sup>3</sup>. Following these, age estimates for Hebior (15,615-13,975 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 48<sup>th</sup> 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<sup>39-41</sup>, with evidence for high hydrological and ecological variability<sup>42-47</sup>. 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<sup>48-50</sup>. The connection to Europe lies in purported typological and manufacturing similarities between Solutrean (appearing ~25-24,000 cal BP<sup>51,52</sup>) 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<sup>53–56</sup>. 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 48<sup>th</sup> parallel (N) occurred either; (i) during the latter part of Marine Isotope Stage (MIS) 3 (57–29 ka)<sup>57</sup>, when ice and sea level estimates<sup>58–60</sup> indicate that land passage through Beringia was unlikely or interrupted, and an ice-free corridor between LIS and CIS was probably present<sup>60</sup> (with evidence of terrestrial landscapes occurring 48–40 ka<sup>61</sup>) or; (ii) during the LGM terminus, when the Bering land bridge was viable but the ice-free corridor inaccessible<sup>62,63</sup>. 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<sup>64</sup>). It is also more compatible with current genetic findings, which suggest that ancestral Native Americans experienced genetic isolation in eastern Beringia during the LGM<sup>65</sup> and diverged from Ancient Beringians at 22–18.1 ka<sup>66,67</sup>. 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<sup>68</sup>. 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<sup>6,68</sup> (but see reference<sup>69</sup>).

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<sup>3</sup>—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<sup>70</sup>, Y chromosome<sup>71</sup> and autosomal<sup>72</sup> 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<sup>66,73–76</sup> (Southern and Northern), which probably occurred outside of Eastern Beringia and south of the North American ice sheets<sup>66,67,73</sup>, at ~17.5–14.6 ka<sup>67</sup>.

Technologically, the relationship between pre-Clovis and Clovis is uncertain<sup>6,68</sup>, whilst the Western Stemmed tradition has been linked with multiple pre-Clovis<sup>19,20,30</sup> and circum-Pacific sites<sup>29,77</sup> 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<sup>20</sup>. 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<sup>68</sup>, with the exception of the pre-Clovis component at Paisley Caves, where mitochondrial DNA data corresponds to Native American founding haplogroups<sup>16</sup>, and Anzick, a burial site representing Clovis and the Southern Native American lineage<sup>74</sup>. 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<sup>78,79</sup>, perhaps occurring after the western retreat of the CIS ~18–17 ka<sup>64,80,81</sup> and the Alaska Peninsula Glacier Complex ~17 ka, as well as the likely establishment of productive ecosystems in the North Pacific coast ~17 ka<sup>64</sup>.

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

recent studies are either in support<sup>85</sup> or suggest other factors, such as climate, ecological change and an extraterrestrial impact, as main or joint contributors<sup>86–93</sup>. Our results show that human presence in the continent precedes the majority of last appearance dates (LADs) for extinct genera in North America<sup>94</sup>, 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<sup>16</sup> to improve Bayesian models (see reference<sup>95</sup>). 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<sup>96</sup> 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<sup>97–104</sup>—should allow for the chronological assessment of local archaeological sites<sup>7,9,10,22,26,27,105–114</sup> 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<sup>63</sup>, and the Beringian coastline during the LGM approximated from reference<sup>115</sup>.

**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<sup>54</sup> and is noted with a yellow band, whilst GI-1 (dark gray band) and GS-1 (light gray band) follow reference<sup>3</sup>.  $\delta^{18}\text{O}$  data according to the Greenland ice core timescale (GICC05)<sup>35</sup>. 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<sup>54</sup> and is noted with a yellow band, whilst GI-1 (dark gray band) and GS-1 (light gray band) follows reference<sup>3</sup>.  $\delta^{18}\text{O}$  data is according to the Greenland ice core timescale (GICC05)<sup>35</sup>. 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 <sup>94</sup>. 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<sup>3</sup>. 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<sup>34</sup>, and the IntCal13 calibration curve<sup>36</sup>. 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<sup>116</sup>. 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<sup>117,118</sup>. 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<sup>119</sup>. 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 <sup>34</sup>). 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<sup>120</sup>. 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 <sup>120</sup>). 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<sup>121,122</sup>)<sup>123</sup>. 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<sup>124</sup>), 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 Silverman'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<sup>125</sup>.

### **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<sup>126,127</sup> or HYP<sup>128</sup> protocols were used—recent studies show these to provide more reliable measurements, particularly for contaminated bone<sup>4,15,129,130</sup>. 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<sup>131</sup> 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<sup>132</sup>).

**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.

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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’.  $\delta^{18}\text{O}$  data according to the Greenland ice core timescale (GICC05)<sup>35</sup>.

**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’.  $\delta^{18}\text{O}$  data according to the Greenland ice core timescale (GICC05)<sup>35</sup>.

**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’.  $\delta^{18}\text{O}$  data according to the Greenland ice core timescale (GICC05)<sup>35</sup>.

**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.

#### **References**

1. Mix, A. C., Bard, E. & Schneider, R. Environmental processes of the ice age: land, oceans, glaciers (EPILOG). *Quat. Sci. Rev.* **20**, 627–657 (2001).
2. Clark, P. U. *et al.* The Last Glacial Maximum. *Science* **325**, 710–714 (2009).

3. Rasmussen, S. O. *et al.* A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quat. Sci. Rev.* **106**, 14–28 (2014).
4. Waters, M. R. & Stafford, T. W., Jr. Redefining the age of Clovis: implications for the peopling of the Americas. *Science* **315**, 1122–1126 (2007).
5. Meltzer, D. J. *The Great Paleolithic War: How Science Forged an Understanding of America's Ice Age Past.* (University of Chicago Press, 2015).
6. Haynes, G. The Millennium before Clovis. *PaleoAmerica* **1**, 134–162 (2015).
7. Dillehay, T. D. *Monte Verde, a Late Pleistocene Settlement in Chile: The archaeological context and interpretation.* (Smithsonian Institution Press, 1997).
8. Meltzer, D. J. *et al.* On the Pleistocene Antiquity of Monte Verde, Southern Chile. *Am. Antiq.* **62**, 659–663 (1997).
9. Dillehay, T. D. *et al.* Simple technologies and diverse food strategies of the Late Pleistocene and Early Holocene at Huaca Prieta, Coastal Peru. *Sci Adv* **3**, e1602778 (2017).
10. Dillehay, T. D. *et al.* A late pleistocene human presence at Huaca Prieta, Peru, and early Pacific Coastal adaptations. *Quat. Res.* **77**, 418–423 (2012).
11. Davis, L. G. *et al.* Late Upper Paleolithic occupation at Cooper's Ferry, Idaho, USA, ~16,000 years ago. *Science* **365**, 891–897 (2019).
12. Waters, M. R. *et al.* Pre-Clovis Mastodon Hunting 13,800 Years Ago at the Manis Site, Washington. *Science* **334**, 351–353 (2011).
13. Hill, C. L. & Davis, L. B. Stratigraphy, AMS radiocarbon age, and stable isotope biogeochemistry of the Lindsay Mammoth, eastern Montana. *Current Research in the Pleistocene* **15**, 109–112 (1998).
14. Davis, L. B. & Wilson, M. C. The late Pleistocene Lindsay mammoth (24DW501), eastern Montana: Possible man-mammoth association. *Current Research in the Pleistocene* **2**, 97–98



(1985).

15. Devièse, T. *et al.* Increasing accuracy for the radiocarbon dating of sites occupied by the first Americans. *Quaternary Science Research* **198**, 171–180 (2018).
16. Gilbert, M. T. P. *et al.* DNA from pre-Clovis human coprolites in Oregon, North America. *Science* **320**, 786–789 (2008).
17. Halligan, J. J. *et al.* Pre-Clovis occupation 14,550 years ago at the Page-Ladson site, Florida, and the peopling of the Americas. *Sci Adv* **2**, e1600375 (2016).
18. Feathers, J. K., Rhodes, E. J., Huot, S. & Mcavoy, J. M. Luminescence dating of sand deposits related to late Pleistocene human occupation at the Cactus Hill Site, Virginia, USA. *Quat. Geochronol.* **1**, 167–187 (2006/8).
19. Williams, T. J. *et al.* Evidence of an early projectile point technology in North America at the Gault Site, Texas, USA. *Sci Adv* **4**, eaar5954 (2018).
20. Waters, M. R. *et al.* Pre-Clovis projectile points at the Debra L. Friedkin site, Texas—Implications for the Late Pleistocene peopling of the Americas. *Science Advances* **4**, eaat4505 (2018).
21. Adovasio, J. M., Donahue, J. & Stuckenrath, R. The Meadowcroft Rockshelter Radiocarbon Chronology 1975-1990. *Am. Antiq.* **55**, 348–354 (1990).
22. Sandweiss, D. H. *et al.* Quebrada jaguay: early south american maritime adaptations. *Science* **281**, 1830–1832 (1998).
23. Goebel, T. & Keene, J. L. Are Great Basin stemmed points as old as Clovis in the Intermountain West? A review of the geochronological evidence. *Archaeology in the Great Basin and Southwest: Papers in Honor of Don D. Fowler* 35–60 (2014).
24. Méndez, C., Jackson, D., Seguel, R. & Delaunay, A. N. Early high-quality lithic procurement in the semiarid north of Chile. *Current Research in the Pleistocene* **27**, 19–21 (2010).
25. Méndez, C. & Jackson, D. Terminal Pleistocene lithic technology and use of space in Central

- Chile. *Chungara, Revista de Antropología Chilena* (2015).
26. Jones, K. B., Hodgins, G. W. L. & Sandweiss, D. H. Radiocarbon Chronometry of Site QJ-280, Quebrada Jaguay, a Terminal Pleistocene to Early Holocene Fishing Site in Southern Peru. *The Journal of Island and Coastal Archaeology* 1–19 (2017).
  27. Roosevelt, A. C. *et al.* Paleoindian Cave Dwellers in the Amazon: The Peopling of the Americas. *Science* **272**, 373–384 (1996).
  28. Erlandson, J. M. *et al.* The Kelp Highway Hypothesis: Marine Ecology, the Coastal Migration Theory, and the Peopling of the Americas. *The Journal of Island and Coastal Archaeology* **2**, 161–174 (2007).
  29. Erlandson, J. M. & Braje, T. J. From Asia to the Americas by boat? Paleogeography, paleoecology, and stemmed points of the northwest Pacific. *Quat. Int.* **239**, 28–37 (2011).
  30. Davis, L. G. *et al.* Late Upper Paleolithic Occupation at Cooper’s Ferry, Idaho, USA Shows Americas Settled Before ~16,000 Years Ago. *Science* (2019).
  31. Braje, T. J., Dillehay, T. D., Erlandson, J. M., Klein, R. G. & Rick, T. C. Finding the first Americans. *Science* **358**, 592–594 (2017).
  32. Potter, B. A. *et al.* Current evidence allows multiple models for the peopling of the Americas. *Sci Adv* **4**, eaat5473 (2018).
  33. Bronk Ramsey, C. Development of the radiocarbon program OxCal. *Radiocarbon* **43**, 355–363 (2001).
  34. Bronk Ramsey, C. Bayesian Analysis of Radiocarbon Dates. *Radiocarbon* **51**, 337–360 (2009).
  35. Rasmussen, S. O. *et al.* A new Greenland ice core chronology for the last glacial termination. *J. Geophys. Res.* **111**, 527 (2006).
  36. Reimer, P. J. *et al.* IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. *Radiocarbon* **55**, 1869–1887 (2013).
  37. Adolphi, F. *et al.* Connecting the Greenland ice-core and U/ Th timescales via cosmogenic

- radionuclides: testing the synchronicity of Dansgaard--Oeschger events. *Clim. Past* **14**, (2018).
38. Bourgeon, L., Burke, A. & Higham, T. Earliest Human Presence in North America Dated to the Last Glacial Maximum: New Radiocarbon Dates from Bluefish Caves, Canada. *PLoS One* **12**, e0169486 (2017).
  39. Ray, N. & Adams, J. A GIS-based vegetation map of the world at the last glacial maximum (25,000-15,000 BP). *Internet archaeology* (2001).
  40. Jackson, S. T. *et al.* Vegetation and environment in Eastern North America during the Last Glacial Maximum. *Quat. Sci. Rev.* **19**, 489–508 (2000).
  41. Williams, J. W. Variations in tree cover in North America since the last glacial maximum. *Glob. Planet. Change* **35**, 1–23 (2003).
  42. Lyle, M. *et al.* Out of the tropics: the Pacific, Great Basin lakes, and late Pleistocene water cycle in the western United States. *Science* **337**, 1629–1633 (2012).
  43. Goebel, T., Hockett, B., Adams, K. D., Rhode, D. & Graf, K. Climate, environment, and humans in North America's Great Basin during the Younger Dryas, 12,900–11,600 calendar years ago. *Quat. Int.* **242**, 479–501 (2011).
  44. Menking, K. M., Anderson, R. Y., Shafike, N. G., Syed, K. H. & Allen, B. D. Wetter or colder during the Last Glacial Maximum? Revisiting the pluvial lake question in southwestern North America. *Quat. Res.* **62**, 280–288 (2004).
  45. Kirby, M. E. *et al.* A late Wisconsin (32--10k cal a BP) history of pluvials, droughts and vegetation in the Pacific south-west United States (Lake Elsinore, CA). *J. Quat. Sci.* **33**, 238–254 (2018).
  46. Ibarra, D. E. *et al.* Warm and cold wet states in the western United States during the Pliocene–Pleistocene. *Geology* **46**, 355–358 (2018).
  47. Feakins, S. J., Wu, M. S., Ponton, C. & Tierney, J. E. Biomarkers reveal abrupt switches in hydroclimate during the last glacial in southern California. *Earth Planet. Sci. Lett.* **515**,

- 164–172 (2019).
48. Stanford, D. J. & Bradley, B. A. *Across Atlantic Ice: The Origin of America's Clovis Culture*. (Univ of California Press, 2013).
  49. Bradley, B. & Stanford, D. The North Atlantic ice-edge corridor: A possible Palaeolithic route to the New World. *World Archaeol.* **36**, 459–478 (2004).
  50. Oppenheimer, S., Bradley, B. & Stanford, D. Solutrean hypothesis: genetics, the mammoth in the room. *World Archaeol.* **46**, 752–774 (2014).
  51. Straus, L. G. The human occupation of southwestern Europe during the Last Glacial Maximum: Solutrean cultural adaptations in France and Iberia. *J. Anthropol. Res.* **71**, 465–492 (2015).
  52. Aubry, T. & Almeida, M. Analyse critique des bases chronostratigraphiques de la structuration du Solutréen. *Le Solutréen* **40**, 37e52 (2013).
  53. Straus, L. G., Meltzer, D. J. & Goebel, T. Ice Age Atlantis? Exploring the Solutrean-Clovis 'connection'. *World Archaeol.* **37**, 507–532 (2005).
  54. Clark, G. A. Deconstructing the North Atlantic Connection. *The Settlement of the American Continents* 103–112 (2004).
  55. Eren, M. I., Patten, R. J., O'Brien, M. J. & Meltzer, D. J. Refuting the technological cornerstone of the Ice-Age Atlantic crossing hypothesis. *J. Archaeol. Sci.* **40**, 2934–2941 (2013).
  56. Raff, J. A. & Bolnick, D. A. Does Mitochondrial Haplogroup X Indicate Ancient Trans-Atlantic Migration to the Americas? A Critical Re-Evaluation. *PaleoAmerica* **1**, 297–304 (2015).
  57. Lisiecki, L. E. & Raymo, M. E. A Pliocene-Pleistocene stack of 57 globally distributed benthic  $\delta^{18}\text{O}$  records. *Paleoceanography* **20**, (2005).
  58. Spratt, R. M. & Lisiecki, L. E. A Late Pleistocene sea level stack. *Clim. Past* **12**, 1079–1092

(2016).

59. Pico, T., Mitrovica, J. X., Ferrier, K. L. & Braun, J. Global ice volume during MIS 3 inferred from a sea-level analysis of sedimentary core records in the Yellow River Delta. *Quat. Sci. Rev.* **152**, 72–79 (2016).
60. Batchelor, C. L. *et al.* The configuration of Northern Hemisphere ice sheets through the Quaternary. *Nat. Commun.* **10**, 3713 (2019).
61. Dalton, A. S., Finkelstein, S. A., Barnett, P. J. & Forman, S. L. Constraining the Late Pleistocene history of the Laurentide Ice Sheet by dating the Missinaibi Formation, Hudson Bay Lowlands, Canada. *Quat. Sci. Rev.* **146**, 288–299 (2016).
62. Pico, T., Mitrovica, J. X. & Mix, A. C. Sea level fingerprinting of the Bering Strait flooding history detects the source of the Younger Dryas climate event. *Sci Adv* **6**, eaay2935 (2020).
63. Dyke, A. S. An outline of North American deglaciation with emphasis on central and northern Canada. *Developments in Quaternary Sciences* **2**, 373–424 (2004).
64. Lesnek, A. J., Briner, J. P., Lindqvist, C., Baichtal, J. F. & Heaton, T. H. Deglaciation of the Pacific coastal corridor directly preceded the human colonization of the Americas. *Sci Adv* **4**, eaar5040 (2018).
65. Tamm, E. *et al.* Beringian standstill and spread of Native American founders. *PLoS One* **2**, e829 (2007).
66. Moreno-Mayar, J. V. *et al.* Early human dispersals within the Americas. *Science* **362**, eaav2621 (2018).
67. Moreno-Mayar, J. V. *et al.* Terminal Pleistocene Alaskan genome reveals first founding population of Native Americans. *Nature* **553**, 203–207 (2018).
68. Ardelean, C. F. *et al.* Evidence of human occupation in Mexico around the Last Glacial Maximum. *Nature* (2020).
69. Goodyear, A. C. Evidence of Pre-Clovis Sites in the Eastern United States. in *Paleoamerican*

*Origins: Beyond Clovis* (eds. Bonnichenen, R., Lepper, B. T., Standford, D. & Waters, M. R.) 103–112 (2005).

70. Llamas, B. *et al.* Ancient mitochondrial DNA provides high-resolution time scale of the peopling of the Americas. *Sci Adv* **2**, e1501385 (2016).
71. Pinotti, T. *et al.* Y Chromosome Sequences Reveal a Short Beringian Standstill, Rapid Expansion, and early Population structure of Native American Founders. *Curr. Biol.* **29**, 149–157.e3 (2019).
72. Bergström, A. *et al.* Insights into human genetic variation and population history from 929 diverse genomes. *Science* **367**, (2020).
73. Raghavan, M. *et al.* Genomic evidence for the Pleistocene and recent population history of Native Americans. *Science* **349**, aab3884 (2015).
74. Rasmussen, M. *et al.* The genome of a Late Pleistocene human from a Clovis burial site in western Montana. *Nature* **506**, 225–229 (2014).
75. Reich, D. *et al.* Reconstructing Native American population history. *Nature* **488**, 370–374 (2012).
76. Scheib, C. L. *et al.* Ancient human parallel lineages within North America contributed to a coastal expansion. *Science* **360**, 1024–1027 (2018).
77. Williams, T. J. & Madsen, D. B. The Upper Paleolithic of the Americas. *PaleoAmerica* 1–19 (2019).
78. Pedersen, M. W. *et al.* Postglacial viability and colonization in North America’s ice-free corridor. *Nature* **537**, 45–49 (2016).
79. Heintzman, P. D. *et al.* Bison phylogeography constrains dispersal and viability of the Ice Free Corridor in western Canada. *Proc. Natl. Acad. Sci. U. S. A.* **113**, 8057–8063 (2016).
80. Darvill, C. M., Menounos, B., Goehring, B. M., Lian, O. B. & Caffee, M. W. Retreat of the western Cordilleran Ice Sheet margin during the last deglaciation. *Geophys. Res. Lett.* **45**,

9710–9720 (2018).

81. Taylor, M. A., Hendy, I. L. & Pak, D. K. Deglacial ocean warming and marine margin retreat of the Cordilleran Ice Sheet in the North Pacific Ocean. *Earth Planet. Sci. Lett.* **403**, 89–98 (2014).
82. *Pleistocene extinctions: The search for a cause.* (Yale University Press, 1967).
83. Martin, P. S. The discovery of America. *Science* **179**, 969–974 (1973).
84. Edwards, W. E. The late-Pleistocene extinction and diminution in size of many mammalian species. *Pleistocene extinctions: the search for a cause. Edited by PS Martin and HE Wright, Jr. Yale University Press, New Haven, Conn* 141–154 (1967).
85. Surovell, T. A., Pelton, S. R., Anderson-Sprecher, R. & Myers, A. D. Test of Martin’s overkill hypothesis using radiocarbon dates on extinct megafauna. *Proc. Natl. Acad. Sci. U. S. A.* **113**, 886–891 (2016).
86. Robinson, G. S., Pigott Burney, L. & Burney, D. A. Landscape Paleocology and megafaunal extinction in southwestern New York state. *Ecol. Monogr.* **75**, 295–315 (2005).
87. Guthrie, R. D. New carbon dates link climatic change with human colonization and Pleistocene extinctions. *Nature* **441**, 207–209 (2006).
88. Lorenzen, E. D. *et al.* Species-specific responses of Late Quaternary megafauna to climate and humans. *Nature* **479**, 359–364 (2011).
89. Prescott, G. W., Williams, D. R., Balmford, A., Green, R. E. & Manica, A. Quantitative global analysis of the role of climate and people in explaining late Quaternary megafaunal extinctions. *Proc. Natl. Acad. Sci. U. S. A.* **109**, 4527–4531 (2012).
90. Cooper, A. *et al.* Abrupt warming events drove Late Pleistocene Holarctic megafaunal turnover. *Science* **349**, 602–606 (2015).
91. Araujo, B. B. A., Oliveira-Santos, L. G. R., Lima-Ribeiro, M. S., Diniz-Filho, J. A. F. & Fernandez, F. A. S. Bigger kill than chill: The uneven roles of humans and climate on late

- Quaternary megafaunal extinctions. *Quat. Int.* **431**, 216–222 (2017).
92. Firestone, R. B. *et al.* Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. *Proceedings of the National Academy of Sciences* vol. 104 16016–16021 (2007).
93. Broughton, J. M. & Weitzel, E. M. Population reconstructions for humans and megafauna suggest mixed causes for North American Pleistocene extinctions. *Nat. Commun.* **9**, 5441 (2018).
94. Grayson, D. K. & Meltzer, D. J. Revisiting Paleoindian exploitation of extinct North American mammals. *J. Archaeol. Sci.* **56**, 177–193 (2015).
95. Buck, C. E. & Bard, E. A calendar chronology for Pleistocene mammoth and horse extinction in North America based on Bayesian radiocarbon calibration. *Quat. Sci. Rev.* **26**, 2031–2035 (2007).
96. Slon, V. *et al.* Neandertal and Denisovan DNA from Pleistocene sediments. *Science* **356**, 605–608 (2017).
97. Bueno, L., Prates, L., Politis, G. G. & Steele, J. A Late Pleistocene/early Holocene archaeological 14C database for South America and the Isthmus of Panama: Palaeoenvironmental contexts and demographic interpretations. *Quat. Int.* 1–2 (2013).
98. Cooke, R., Ranere, A., Pearson, G. & Dickau, R. Radiocarbon chronology of early human settlement on the Isthmus of Panama (13,000–7000 BP) with comments on cultural affinities, environments, subsistence, and technological change. *Quat. Int.* **301**, 3–22 (2013).
99. Rademaker, K., Bromley, G. R. M. & Sandweiss, D. H. Peru archaeological radiocarbon database, 13,000–7000 14C B.P. *Quat. Int.* **301**, 34–45 (2013).
100. Capriles, J. M. & Albarracín-Jordan, J. The earliest human occupations in Bolivia: A review of the archaeological evidence. *Quat. Int.* **301**, 46–59 (2013).
101. Méndez Melgar, C. Terminal Pleistocene/early Holocene 14C dates from archaeological sites



- in Chile: Critical chronological issues for the initial peopling of the region. *Quat. Int.* **301**, 60–73 (2013).
102. Bueno, L., Dias, A. S. & Steele, J. The Late Pleistocene/Early Holocene archaeological record in Brazil: A geo-referenced database. *Quat. Int.* **301**, 74–93 (2013).
103. López Mazz, J. M. Early human occupation of Uruguay: Radiocarbon database and archaeological implications. *Quat. Int.* **301**, 94–103 (2013).
104. Prates, L., Politis, G. & Steele, J. Radiocarbon chronology of the early human occupation of Argentina. *Quat. Int.* **301**, 104–122 (2013).
105. Casamiquela, R., Montané, J. & Santana, R. Convivencia del hombre con el mastodonte en Chile central. *Noticiario Mensual del Museo Nacional de Historia Natural* **11**, 1–6 (1967).
106. Montané, J. Paleo-Indian remains from laguna de tagua tagua, central chile. *Science* **161**, 1137–1138 (1968).
107. Nuñez, L. *et al.* Cuenca de Taguatagua en Chile: el ambiente del Pleistoceno superior y ocupaciones humanas. *Revista Chilena de Historia Natural* **67**, 503–519 (1994).
108. Jackson, D., Méndez, C., Núñez, L. & Jackson, D. Procesamiento de fauna extinta durante la transición Pleistoceno-Holoceno en el centro-norte de Chile. *Boletín de Arqueología PUCP* 315–336 (2011).
109. Montane, J. Primera fecha radiocarbónica de Tagua-Tagua. *Not. Mens. Mus. Nac. Hist. Nat.* **139**, (1968).
110. Reitz, E. J., McInnis, H. E., Sandweiss, D. H. & Others. Terminal Pleistocene and Early Holocene fishing strategies at Quebrada Jaguay and the Ring Site, southern Peru. *Journal of Archaeological Science: Reports* **8**, 447–453 (2016).
111. Jackson, D., Méndez, C., Seguel, R., Maldonado, A. & Vargas, G. Initial Occupation of the Pacific Coast of Chile during Late Pleistocene Times. *Curr. Anthropol.* **48**, 725–731 (2007).
112. Roosevelt, A. C. Relatório preliminar sobre o levantamento e escavações na Caverna da Pedra

- Pintada, Monte Alegre, Pará, Brasil. *Segunda etapa de campo do projeto arqueológico Santarém* (1991).
113. Michab, M. *et al.* Luminescence dates for the Paleoindian site of Pedra Pintada, Brazil. *Quat. Sci. Rev.* **17**, 1041–1046 (1998).
114. Dillehay, T. D. *et al.* Monte Verde: seaweed, food, medicine, and the peopling of South America. *Science* **320**, 784–786 (2008).
115. Bond, J. D. Paleodrainage map of Beringia. (2019).
116. Harris, E. C. *Principles of Archaeological Stratigraphy*. (Elsevier, 2014).
117. Gelfand, A. E. & Smith, A. F. M. Sampling-Based Approaches to Calculating Marginal Densities. *J. Am. Stat. Assoc.* **85**, 398–409 (1990).
118. Gilks, W. R., Richardson, S. & Spiegelhalter, D. *Markov chain Monte Carlo in practice*. (Chapman and Hall/CRC, 1995).
119. Bronk Ramsey, C. Radiocarbon Calibration and Analysis of Stratigraphy: The OxCal Program. *Radiocarbon* **37**, 425–430 (1995).
120. Bronk Ramsey, C. Dealing with Outliers and Offsets in Radiocarbon Dating. *Radiocarbon* **51**, 1023–1045 (2009).
121. Rosenblatt, M. Remarks on Some Nonparametric Estimates of a Density Function. *Ann. Math. Stat.* **27**, 832–837 (1956).
122. Parzen, E. On Estimation of a Probability Density Function and Mode. *Ann. Math. Stat.* **33**, 1065–1076 (1962).
123. Bronk Ramsey, C. Methods for Summarizing Radiocarbon Datasets. *Radiocarbon* **59**, 1809–1833 (2017).
124. Silverman, B. W. *Density Estimation for Statistics and Data Analysis*. (Chapman and Hall, 1986).
125. Bronk Ramsey, C. OxCal 4.3 Manual. *OxCal 4.3 Manual*

[https://c14.arch.ox.ac.uk/oxcalhelp/hlp\\_contents.html](https://c14.arch.ox.ac.uk/oxcalhelp/hlp_contents.html).

126. Stafford, T. W., Jr, Duhamel, R. C., Haynes, C. V., Jr & Brendel, K. Isolation of proline and hydroxyproline from fossil bone. *Life Sci.* **31**, 931–938 (1982).
127. Stafford, T. W., Brendel, K. & Duhamel, R. C. Radiocarbon, <sup>13</sup>C and <sup>15</sup>N analysis of fossil bone: Removal of humates with XAD-2 resin. *Geochim. Cosmochim. Acta* **52**, 2257–2267 (1988).
128. Deviese, T., Comeskey, D., McCullagh, J., Bronk Ramsey, C. & Higham, T. New protocol for compound specific radiocarbon analysis of archaeological bones. *Rapid Commun. Mass Spectrom.* **32**, 373–379 (2017).
129. Becerra-Valdivia, L. *et al.* Reassessing the chronology of the archaeological site of Anzick. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 7000–7003 (2018).
130. Waters, M. R., Stafford, T. W., Jr, Kooyman, B. & Hills, L. V. Late Pleistocene horse and camel hunting at the southern margin of the ice-free corridor: reassessing the age of Wally’s Beach, Canada. *Proc. Natl. Acad. Sci. U. S. A.* **112**, 4263–4267 (2015).
131. Bronk Ramsey, C., Housley, R. A., Lane, C. S., Smith, V. C. & Pollard, A. M. The RESET tephra database and associated analytical tools. *Quat. Sci. Rev.* **118**, 33–47 (2015).
132. Derek Hamilton, W. & Krus, A. M. The myths and realities of Bayesian chronological modeling revealed. *Am. Antiq.* **83**, 187–203 (2018).