Paleoindian demography and the extraterrestrial impact hypothesis

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Recently it has been suggested that one or more large extraterrestrial (ET) objects struck northern North America 12,900 ± 100 calendar years before present (calBP) [Firestone RB, *et al.* (2007) *Proc Natl Acad Sci USA* 104: 16016–16021]. This impact is claimed to have triggered the Younger Dryas major cooling event and resulted in the extinction of the North American megafauna. The impact is also claimed to have caused major cultural changes and population decline among the Paleoindians. Here, we report a study in which ≈1,500 radiocarbon dates from archaeological sites in Canada and the United States were used to test the hypothesis that the ET resulted in population decline among the Paleoindians. Following recent studies [e.g., Gamble C, Davies W, Pettitt P, Hazelwood L, Richards M (2005) *Camb Archaeol J* 15:193–223), the summed probability distribution of the calibrated dates was used to identify probable changes in human population size between 15,000 and 9,000 calBP. Subsequently, potential biases were evaluated by modeling and spatial analysis of the dated occupations. The results of the analyses were not consistent with the predictions of extraterrestrial impact hypothesis. No evidence of a population decline among the Paleoindians at 12,900 ± 100 calBP was found. Thus, minimally, the study suggests the extraterrestrial impact hypothesis should be amended.

comet | Clovis | population decline | radiocarbon | summed probability distribution

Recently Firestone *et al.* (1) have suggested that one or more large low-density extraterrestrial (ET) objects impacted or exploded over northern North America 12,900 ± 100 calendar years before present (calBP) with massive effects. Firestone *et al.* argue that the impact destabilized the Laurentide continental ice sheet, and that this triggered the most significant cooling event in the Holocene, the Younger Dryas. They also argue that the impact was accompanied by a high-temperature shock wave, changes in pressure that would have resulted in hurricane force winds, and extensive groundcover burning from the impact and superheated ejecta. Together, these caused a continent-wide environmental collapse, which, in turn, resulted in the extinction of the North American megafauna and major cultural changes and population decline among the Paleoindians.

Firestone *et al.* (1) outline two lines of evidence that they believe indicate there was an ET impact over northern North America 12,900 ± 100 calBP. One is the so-called black mat that has been found at Younger Dryas-age archeological and paleontological sites across North America. This layer contains a large amount of charcoal and soot, which Firestone *et al.* suggest is consistent with extensive groundcover burning. The other line of evidence concerns the composition of a layer found immediately below the black mat at 10 key sites. Firestone *et al.*'s analyses of this layer demonstrate it contains several classes of particle that they contend are consistent with an ET impact. These include magnetic grains with iridium, magnetic microspherules, carbon spherules, glass-like carbon containing nanodiamonds, and fullerenes with ET helium.

The evidence Firestone *et al.* (1) put forward in support of the proposed effect of the ET impact on the North American megafauna and the Paleoindians is much more limited. They simply point to the apparent temporal proximity between the black mat, the onset of the Younger Dryas, the disappearance of the North American megafauna, and changes in the Paleoindian archaeological record. With this situation in mind, we used a sample of ≈1,500 radiocarbon dates from Paleoindian archaeological sites in Canada and the United States to test the hypothesis that the Paleoindians experienced a population bottleneck ≈12,900 ± 100 calBP.

We employed a method that has been used recently to investigate prehistoric population history (e.g., refs. 2–5). This method entails calibrating a large sample of radiocarbon dates, and then computing the dates' summed probability distribution. The major peaks and troughs in the summed probability distribution are taken to reflect fluctuations in population size. We reasoned that if Firestone *et al.* (1) are correct and the Paleoindians experienced a population bottleneck as a result of an ET-impact-triggered environmental collapse, then a plot of the summed probabilities of the calibrated Paleoindian dates should exhibit a major trough that starts at 12,900 ± 100 calBP.

Although the summed probability distribution method is capable of yielding important insights, it is not without shortcomings. One problem is that, although major peaks and troughs in a summed probability distribution can be reasonably interpreted in terms of demography, it is difficult to determine whether minor fluctuations are caused by changes in demography or reflect the "wiggles" in the curve used to calibrate the dates. To address this problem, we carried out χ^2 tests in which we compared the spatial distribution of calibrated dates in the 300 years before the ET impact with the spatial distribution of calibrated dates at the time of and shortly after the ET impact. Given the size and environmental diversity of North America, it is unlikely that the ET impact affected all Paleoindian populations equally. Specifically, the proposed population bottleneck is likely to have been more pronounced in the northern part of the continent than in the southern part. Thus, the putative ET impact can be expected to affect both the summed probability distribution and the spatial distribution of the dates. In contrast, wiggles in the calibration curve have the potential to affect the summed probability distribution, but there is no reason to expect them to influence the spatial distribution of the dates.

Recently, Surovell and Brantingham (6) have highlighted another problem with the summed probability distribution method. They show that time-dependent site destruction can result in summed probability distribution patterns that mimic the patterns expected to result from demographic changes. With this in mind, we used a simulation model to evaluate the likelihood that the results of our summed probability distribution analysis

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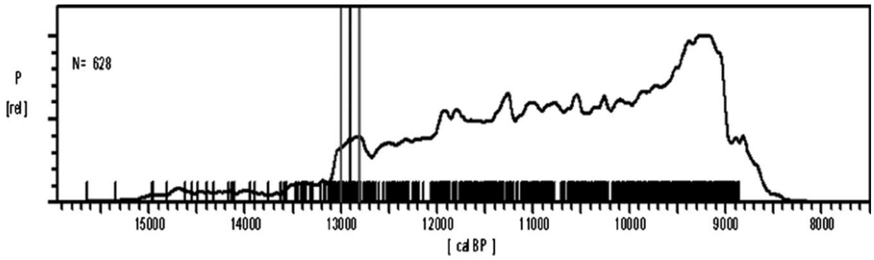

Fig. 1. Summed probability distributions of radiocarbon-dated occupations in Canada and the United States between 15,000 and 9,000 calBP with the age of the hypothesized ET impact at 12,900 calBP (black vertical line) and the ± 100-year error range (gray vertical lines) assumed by Firestone *et al.* (1) demarcated.

of the calibrated Paleoindian dates are biased by time-dependent site destruction.

Results and Discussion

Fig. 1 shows the summed probabilities of the calibrated radiocarbon dates for the period from ≈15,000 to 9,000 calBP. The shape of the summed probability distribution suggests slow population growth between 15,000 and 13,100 calBP, which is likely the period of the initial colonization of North America by humans migrating from East Asia via Beringia and an ice-free corridor between the Laurentide and Cordilleran ice sheet and/or along the coasts of Beringia and the Pacific Northwest (7–10). Thus, the slow population growth during this period may reflect small groups of initial colonists or possibly multiple failed attempts at colonization. Subsequently, there is a period of rapid population growth. Lasting from 13,100 to 13,000 calBP, this population growth coincides with the efflorescence of Clovis in North America (11, 12). Thereafter, population increases reasonably steadily until ≈9,500 calBP, when another period of rapid population increase occurs. Shortly before 9,000 calBP, the curve drops dramatically. This last drop is an artifact of our dataset, which does not include radiocarbon ages younger than 8,000 ^{14}C BP.

Between 13,000 and 9,500 calBP, the summed probability distribution exhibits a number of troughs. One of these begins at 12,800 calBP, which is within the error range of the date for the ET impact used by Firestone *et al.* (1). However, the trough in question is not only short but also relatively minor in scale. It lasted only 100 years and is no more pronounced than some of the other troughs that occur in the 13,000–9,500 calBP period (e.g., the one that occurs ≈11,300 calBP). As such, it is not consistent with a population bottleneck.

Although the depth and duration of the trough that begins at 12,800 calBP are inconsistent with a population bottleneck, it is possible that the trough represents a decline in population and therefore supports a weaker version of Firestone *et al.*'s (1) hypothesis. However, this possibility is not consistent with the results of our spatial analysis of the radiocarbon dates. Fig. 2 shows the geographic distribution of 74 radiocarbon dates from three time periods: the 300 years before the proposed ET impact (13,299–13,000 calBP), the 300 years during which the impact is hypothesized to have occurred and its direct effects are likely to have been most severe (12,999–12,700 calBP), and the subsequent 300 years (12,699–12,400 calBP). Given that the ET impact is proposed to have occurred north of the Great Lakes, if the trough represents a population decline, there should be significantly fewer Paleoindian radiocarbon dates in northern latitudes during the second time period compared with the first and third time periods. This is not the case. A χ^2 test revealed no statistical difference in the counts of radiocarbon dates in the six blocks of latitude and longitude between the first and second periods ($\chi^2 = 8.13$, $P = 0.15$). Similarly, no statistical difference was found in the counts of radiocarbon dates in the six blocks of latitude and longitude between the second and third periods ($\chi^2 = 3.83$, $P = 0.57$). Redistributing the blocks using different longitudinal boundaries (see *Methods*) did not alter the results of the χ^2 test. This result suggests that the trough in the summed probability distribution that begins at 12,800 calBP is a conse-

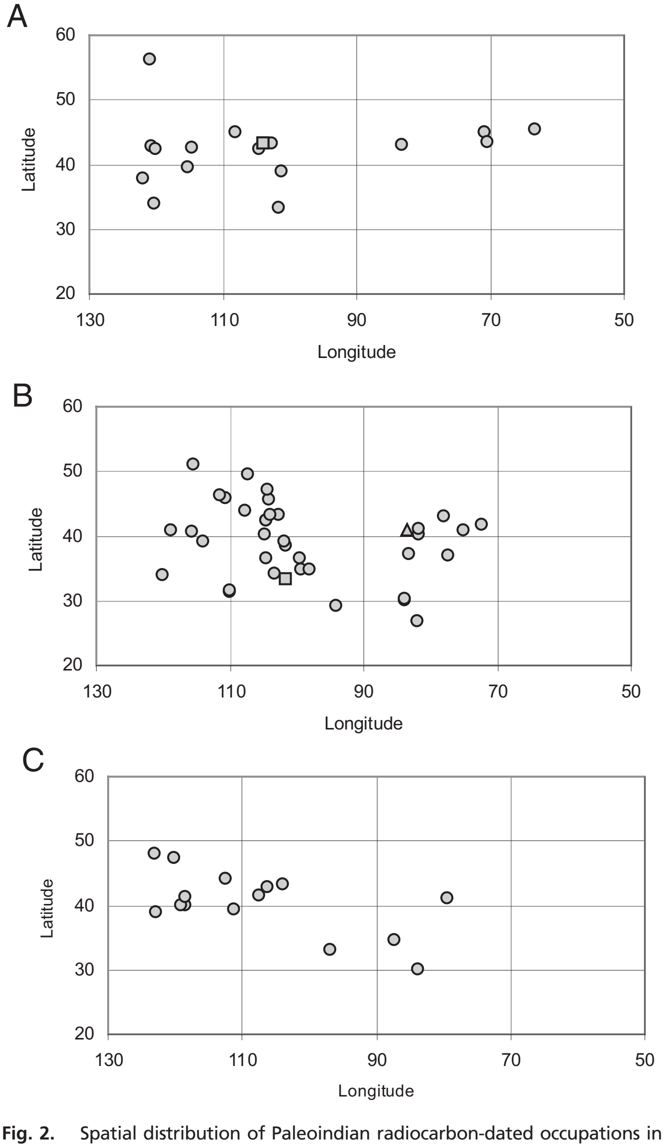

Fig. 2. Spatial distribution of Paleoindian radiocarbon-dated occupations in Canada and the United States by degrees west longitude and degrees north latitude. (*A*) Radiocarbon-dated occupations from the period 13,299–13,000 calBP. (*B*) Radiocarbon-dated occupations from the period 12,999–12,700 calBP. (*C*) Radiocarbon-dated occupations from the period 12,699–12,400 calBP. Circles show locations of a radiocarbon-dated occupation, squares show the location of two overlapping radiocarbon-dated occupations, and triangles show the location of three overlapping radiocarbon-dated occupations.

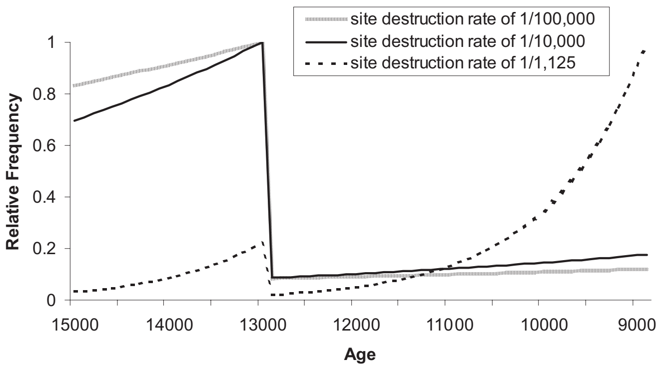

Fig. 3. Results from simulated population growth and taphonomic bias showing the relative frequency of radiocarbon-dated occupations before and after a population bottleneck event 12,900 years ago. The results from three separate simulations with varying degrees of taphonomic bias are shown. The gray stippled line shows an extremely low taphonomic rate of 1 in 100,000 sites destroyed per year. The black line shows a taphonomic rate of 1 in 10,000 sites destroyed per year, and the dashed line shows the highest taphonomic rate of 1 in 1,125 sites destroyed per year, at which at least one complete site remained in any of the time periods.

quence of a wiggle in the calibration curve rather than a decline in population.

The simulation experiments suggested that time-dependent site destruction processes are unlikely to have masked a population bottleneck. We began with a taphonomic rate of 1 in 100,000 sites destroyed per year, which Surovell and Brantingham (6) suggest is an extremely low rate of site destruction. This taphonomic rate would yield a clear signal of the population bottleneck at 12,900 calBP followed by modest population growth (Fig. 3). We then increased the taphonomic rate to 1 in 10,000 sites destroyed per year. This rate would also result in a clear signal of the population bottleneck (Fig. 3). Lastly, we identified the highest plausible taphonomic rate, which was defined as the highest rate compatible with the recovery of at least one complete site in each time period. The highest plausible taphonomic rate was determined to be 1 in 1,125 sites destroyed per year. We found that a population bottleneck would still be visible with this rate (Fig. 3). Sensitivity testing indicated that the results did not depend on the size of the starting population. Thus, the simulation experiments suggest that, even with high rates of site destruction, if a population bottleneck had occurred, it would be visible in the summed probability distribution of calibrated Paleoindian radiocarbon dates.

In sum, then, the results of our analyses support neither Firestone *et al.*'s (1) original suggestion that the Paleoindians experienced a populations bottleneck as a result of an ET impact at 12,900 ± 100 calBP, nor a weaker hypothesis in which Paleoindian population simply declined or migrated south because of the proposed impact.

The results of our analysis are consistent with recent comments by Pinter and Ishman (13) and Haynes (14). Pinter and Ishman reject Firestone *et al.*'s (1) claim that there was a devastating ET impact north of the Great Lakes at 12,900 ± 100 calBP. Pinter and Ishman contend that the particles Firestone *et al.* use to support their claim are in fact ubiquitous, and that the amounts Firestone *et al.* recovered from the layer beneath the black mat are more consistent with micrometeorite ablation fallout than with a major ET impact. Pinter and Ishman also outline what they consider to be major problems with Firestone *et al.*'s interpretation of the black mat as a burning horizon, and their suggestion that an impact produced the Carolina Bays. In addition, Pinter and Ishman cast doubt on the link Firestone *et al.* propose between the ET impact and the extinction of the megafauna. Haynes argues that "something major happened" in North America at 12,900 calBP, but he is skeptical that an ET impact initiated the Younger Dryas and caused the megafaunal extinctions.

Clearly, if Pinter and Ishman (13) are correct, the reason we failed to find evidence of a Paleoindian population bottleneck at the time of the proposed ET impact is that there was no ET impact. However, this explanation is not the only one that is consistent with our results. There are two other potential explanations for our failure to find evidence for a decline in the size of the Paleoindian population at 12,900 ± 100 calBP. One is that a major ET impact occurred and had significant, continent-wide ecological effects, including the extinction of the megafauna, but did not devastate the Paleoindians for some reason. The other is that an ET impact occurred but was much smaller than the one proposed by Firestone *et al.* (1) and therefore had only local effects. Determining which of these hypotheses is correct will require further research.

Methods

A total of 1,509 radiocarbon dates from archaeological sites in Canada and the United States were used in the study. The dates span the period 13,000 to 8,000 ^{14}C BP. Twenty-three of these dates were obtained from Hamilton and Buchanan (11) and Waters and Stafford (12). The remaining dates were obtained from the Canadian Archaeological Radiocarbon Database (ref. 15; www.canadianarchaeology.ca/radiocarbon/card/card.htm). We removed radiocarbon dates labeled as anomalous in the latter source. These are radiocarbon dates that were either too young or old in relation to the accepted target age. Following methods discussed by Shennan and Edinborough (4) we used a pooled mean date for site occupations or discrete cultural components (Shennan and Edinborough use the term ''phase;'' here, we use the term ''occupation'') with multiple radiocarbon assays. We did this to prevent occupations with multiple dates from biasing the results. Pooled mean dates were calculated from uncalibrated dates by using the Calib 5.1 program (16). We pooled radiocarbon dates from 237 Paleoindian occupations with multiple dates. The resulting database consists of 628 radiocarbon dates [supporting information (SI) Table S1]. It should be noted that we did not independently assess the validity of individual radiocarbon dates. Undoubtedly there are dates in our sample that some investigators may consider erroneous. However, we contend that, given the large size of the sample and the removal of dates identified as anomalous, a small number of erroneous dates will not alter the broad trends in the data.

Summed Probability Distribution Analysis. The single and pooled mean uncalibrated radiocarbon dates in our sample were calibrated in CALPAL (ref. 17; www.calpal.de) by using the Intcal04.14 curve (18). The probabilities of these calibrated dates were then summed and plotted along the abscissa according to calendar age BP.

Spatial Distribution Analysis. To test for statistical differences in the spatial distribution of radiocarbon-dated occupations in the three time periods, we compared the number of occupations in each period in six blocks of latitude and longitude by using a χ^2 test. We defined blocks as 10° of latitude, between 30° and 50° of latitude, by 20° of longitude, between 70° and 130° of longitude. We ignored the three radiocarbon-dated occupations above 50° of latitude and the four below 30° of latitude. It is worth noting that the southern boundary of the Laurentide ice sheet is estimated to have been at or slightly below the 50th parallel ≈12,900 cal BP (19). In the region of the Great Lakes it may have dipped as far south as the 45th parallel (19). Therefore, the paucity of radiocarbon-dated occupations in these areas is attributable to the lack of habitable land. To check whether the way in which the blocks were defined influenced the results of the statistical test we shifted the longitudinal boundaries from 70–130° to 60–120° to create a different set of blocks and subjected the counts to a χ^2 test.

Assessing Taphonomic Bias. We used a model developed by Surovell and Brantingham (6) to assess whether time-dependent site destruction could obliterate evidence of a population bottleneck at 12,900 ± 100 calBP. Surovell and Brantingham's model assumes a constant rate of site destruction through time. The relationship between the taphonomic rate (λ) and occupations is expressed as:

$$n = n_t e^{-\lambda t},$$

where n_t is the number of occupations created at time t, λ is the constant rate of site destruction, and t is the time elapsed from initial deposition of the occupations to the present.

We simulated a period of exponential population growth for 6,000 years (15,000–9,000 calBP), the approximate duration of the Paleoindian period. At 12,900 calBP we created a population bottleneck by reducing the population to 1,000, after which we allowed for exponential population growth to proceed again in the following time periods. This bottleneck represents a 91.5% decline in the population. Population growth before, and after, the bottleneck was modeled with the following equation:

$$n_t = Ke^{\alpha t},$$

where K is the number of occupations and α is the population growth rate. α was set at 0.00008 based on Pennington's (20) estimate for hunter–gatherer population growth rates. Initially, the starting population size was set at 10,000. Subsequently, we used starting population sizes of 5,400 and 1,000 based on the estimations of Kitchen *et al.* (21), which they derived from genetic models for Paleoindian founding populations of 15,000 years ago. We began with a taphonomic rate of 1 in 100,000 sites destroyed per year ($\lambda = 1/100{,}000$), which Surovell and Brantingham (6) suggest is extremely low. We then increased the taphonomic rate to 1 in 10,000 sites destroyed per year ($\lambda = 1/10{,}000$). Lastly, we identified the highest plausible taphonomic rate, which was defined as the highest rate compatible with the recovery of at least one complete site in each time period. The highest plausible taphonomic rate was determined to be 1 in 1,125 sites destroyed per year ($\lambda = 1/1{,}125$). To make the results of the simulations comparable with the results of our analysis of the summed probability distribution for the real Paleoindian dates, we converted the numbers of simulated radiocarbon-dated occupations per time period to relative frequencies.

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