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The Age of the Opening of the Ice-Free Corridor and Implications for the Peopling of the Americas

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Abstract

The "Clovis-first" model for the peopling of the Americas by ~13.4 ka has long invoked the "Ice-Free Corridor" (IFC) between the retreating margins of the Cordilleran and Laurentide ice sheets as the migration route from Alaska and the Yukon down to the Great Plains. New evidence from archaeology and ancient genomics, however, now suggests that pre-Clovis migrations occurred by at least ~15.5-16.0 ka, or earlier than most recent assessments of the age of IFC opening at ~14-15 ka, lending support to use of a Pacific coast migration route instead. Uncertainties in ages from the IFC used in these assessments, however, allow for an earlier IFC opening which would be consistent with the availability of the IFC as a migration route by ~15.5-16.0 ka. Here we use 64 new cosmogenic (^{10}Be) exposure ages to closely date the age of the full opening of the IFC at 13.8±0.5 ka. Our results thus clearly establish that the IFC was not available for the first peopling of the Americas after the Last Glacial Maximum, whereas extensive geochronological data from the Pacific coast support its earlier availability as a coastal migration route.

Significance

The Ice-Free Corridor (IFC) has long played a key role in hypotheses about the peopling of the Americas. Earlier assessments of its age suggested that the IFC was available for a "Clovis-first" migration but subsequent developments now suggest a pre-Clovis occupation of the Americas that occurred before the opening of the IFC, thus supporting a Pacific coastal migration route instead. However, large uncertainties in existing ages from the IFC cannot preclude its availability as a route for the first migrations. Resolving this debate over migration route is important for addressing the questions of when and how the first Americans arrived. We report new cosmogenic-nuclide exposure ages that show that final opening of the IFC occurred well after pre-Clovis occupation.

Main Text

Introduction

The "Ice-Free Corridor" (IFC), which developed as a contiguous ice-free area along the eastern front of the Rocky Mountains as the coalescent margins of the late-Pleistocene Cordilleran and Laurentide Ice Sheets separated and retreated (Fig. 1), has long played a central role in hypotheses about the peopling of the Americas (1-3). Upham (4) first proposed the existence of an IFC during the last glaciation, while Johnston (5) first proposed its use as a travel route from Beringia down to the Great Plains. Subsequent discovery of the Clovis cultural complex, which is dated as early as ~13,400 calibrated 14C years ago (~13.40 cal ka BP) (6, 7), was considered to be the oldest archaeological horizon in North America, forming the basis for the "Clovis-first" model for the migration south of the ice sheets that occurred by way of the IFC. At the same time, initial ^{14}C ages from the IFC supported its availability as a migration route for Clovis people (8-10).

Several subsequent developments, however, have challenged the Clovis-first model as well as the corresponding role of the IFC in the peopling of the Americas. Challenges to the Clovis-first model have been largely driven by archeological (11-16) and genomic (17-19) studies that now provide compelling evidence for pre-Clovis occupation of the Americas south of the ice sheets by at least 15.5-16.0 ka (e.g., based on ages of ~15.6 cal ka BP from the Cooper's Ferry site [Idaho] (14) and estimates from genomic evidence of ~15.7 ka [95% confidence interval 17.5-14.6 ka] (19)). At the same time, assessments of newer age constraints have concluded that the IFC did not open until 14-15 ka (19-24). Moreover, ancient genomic and radiocarbon evidence indicate that the corridor only became suitable for human travel and subsistence (i.e., biologically viable) by ~13.2 ka or earlier (25, 26), with other studies proposing even later IFC viability after ~12.6 ka (27). These developments have lent support to a proposed migration route for pre-Clovis people from Beringia down the western Canadian coast (the "coastal corridor") that largely bypassed the ice sheets (28-30). While some have suggested that the IFC route should not yet be rejected until the archaeological record supports the coastal corridor route (21, 31, 32), we note that no compelling archaeological evidence has yet been found to support a first migration through the IFC.

Despite broad agreement that the IFC was not unglaciated along its full length until 14-15 ka (19-24), existing ages used to support this time window are largely based on dating methods, many with large uncertainties, that include some lag between the time of deglaciation and the formation of the dated record (i.e., minimum-limiting ages) (26, 33). As we discuss further below, these same data can thus be used to argue for an earlier opening of the IFC that was available as a first-migration pathway. Similarly, arguments regarding the viability of the IFC to support first migrations are also based on dated organics that provide only minimum-limiting ages for biological productivity (25, 27). Uncertainties in existing data thus suggest that the IFC cannot yet be excluded as a potential route for pre-Clovis occupation. Resolving this debate over migration route is important for addressing the questions of when and how the first Americans arrived in regions south of the continental ice sheets.

To narrow these uncertainties in current understanding of the age of the IFC opening, we first assess a compilation of ages that are commonly cited (in part or in entirety) to support the 14-15 ka time window for the age of the IFC opening (Figs. 1, 2) (26). We then use 64 new ^{10}Be surface exposure ages from six locations spanning ~1,200 km of the Cordilleran-Laurentide suture zone that separated to produce the IFC (Fig. 1) to directly date the opening of the IFC with sufficient precision to establish whether it was available for the first peopling of the Americas south of the ice sheets.

Results

Previous Dating of the Ice-Free Corridor

Existing ages used to constrain the age of IFC opening include calibrated ^{14}C ages that have been previously screened in order to remove those known potentially commonly to be contaminated and thus result in spurious results (e.g., bulk sediments, terrestrial shells) (26) (*SI Appendix*, Table S2), a compilation of luminescence ages on sand dunes from Alberta (33) (*SI Appendix*, Table S3), and cosmogenic nuclide (^{10}Be) exposure ages on erratics from the southern section of the CIS-LIS suture zone (34) (*SI Appendix*, Table S4). We exclude four ^{10}Be ages from this latter study in our analysis here because they are from sites immediately adjacent to two of our sampling sites, and so instead include them with our new ^{10}Be ages from those sites. We assess all ages according to their proximity to the Cordilleran-Laurentide suture zone (Fig. 1), with the expectation that they should become younger with increasing lateral distance from the ice-sheet suture zone.

^{14}C ages typically provide only minimum-limiting ages on ice-margin retreat, owing to the unknown amount of time that lapsed between deglaciation and accumulation of reliably datable organic material (e.g., terrestrial plants) (35, 36). Of the 29 calibrated ^{14}C dates from seven sites that are within or proximal to the suture zone (Fig. 1), all but one are ≤13.5 cal ka BP in age, with no latitudinal trend (Fig. 2). Another 20 dates from two sites that are 200-400 km east of the suture zone are also ≤13.5 cal ka BP and show no longitudinal trend. Only one date is >13.5 cal ka BP (AA43652) and has been used to support the opening of the IFC by 15.0±0.2 cal ka BP (32). This date, however, was measured on a standard collagen extraction from taiga vole bones that were redeposited by a low-energy mud flow. Another age on vole bones from the same unit are stratigraphically below but ~1,600 years younger than the 15.0±0.2 cal ka BP age. ^{14}C ages on organics above and below the bone-bearing unit suggest the debris flow occurred during the middle Holocene (37). Given the potential for contamination of the collagen from old carbonate as well as the lack of stratigraphic integrity and provenance of the bones, this age provides a poor constraint on IFC opening (26). However, given their minimum-limiting nature, the remaining 48 dates do not preclude the opening of the IFC well before 13.5 cal ka BP. For example, other studies of Laurentide Ice-Sheet retreat that combined ^{10}Be ages with minimum-limiting ^{14}C ages found millennial-scale lags between the timing of ice retreat and the oldest ^{14}C-dated material (36, 38, 39).

Luminescence ages on sand dunes in Alberta have been central to recent assessments of the age of the IFC (24, 26, 31-33), but these are even more problematic than the redeposited vole bone fragments. For example, the sampled sites cover a broad region of Alberta that extends from ~150 km to 1,000 km east of the ice-sheet suture zone (Fig. 1), thus only providing minimum-limiting ages on the initial opening of the IFC. The fact that sediment sources for the sand dunes were largely derived from glacial lake sediments that became exposed following lake drainage (33) further limits their ability to date the initial opening of the IFC. Figure 2 shows that ages from within relatively small regions can span 3.5-4.5 kyr and that uncertainties on individual luminescence dates are high (mean 1SE uncertainty is ±1.1 kyr for 46 luminescence ages in ref. (33)). In many cases, ages that are more proximal to the suture zone are younger than, or similar to, ages that are more distal, equivalent to a stratigraphic age reversal. Assuming full bleaching, the oldest luminescence age from the IFC zone should provide the closest constraint on ice-margin retreat. This would place the IFC as open before 15.3±1.3 ka for the optically stimulated luminescence method (33) or 15.7±1.6 ka for the infrared stimulated luminescence method (40).

The mean of ^{10}Be exposure ages on erratics from sites extending between 49.1°N to 53.4°N has been used to argue that the southern sector of the IFC had opened by 14.9±0.9 ka (14, 22, 24, 34). However, because these sites are spaced tens to more than 200 km apart, the ages of these erratics should not be averaged together to determine the millennial- to centennial-scale timing of ice-margin retreat. We recalculated these ages following the same protocols as for our new ^{10}Be ages (*SI Appendix*, Methods). Of the 11 dates considered here (excluding the four ages we combine with our ^{10}Be ages (*SI Appendix*, Table S1) and another age identified as a clear outlier because of its Holocene age), five sites have only one ^{10}Be age and another three sites have only two ^{10}Be ages, making outlier identification for each site difficult. If considered to contain no geologic scatter, these isolated ^{10}Be ages would place IFC opening at 18.0±0.8 ka (n=1) at

~49.1°N, 15.5±0.9 ka (n=2) at ~50.3°N, and 17.6±0.9 ka (n=1) at 53.4°N; the remaining eight ages fall within this range. While the ~17.6 ka age appears to be out of stratigraphic order, one cannot exclude this age due to ^{10}Be inheritance without a larger number of samples from the same site.

New Cosmogenic Exposure Ages From the Ice-Free Corridor

To directly date the opening of the IFC with century-scale precision, we collected multiple samples for ^{10}Be surface exposure dating from each of six sites (*SI Appendix*, Fig. S1, S2) along a 1,200-km-long, south-north transect (~50-59°N) where mapping identified the confluence of the Cordilleran and Laurentide Ice Sheets (41-43) (Fig. 1). These ages date the onset of ice-free conditions in association with ice-sheet separation and thus the initial opening of the IFC at that location. To exclude the possibility that samples were exhumed from moraine degradation, we sampled glacially transported boulders resting on bedrock and, at site BCN, glacially eroded bedrock (Fig. 3). Five of the sites are on topographic highs above the elevations of former proglacial lakes (44), and there is no evidence of lake cover at the one site on the plains of west-central Alberta (ABC) (34, 42). We collected >10 samples at five of the sites and five samples from a sixth site (BCC) to assess geologic scatter. Given their proximity to our two southernmost sites (ABS, ABC), we also include four ^{10}Be ages from Ref. (34) (Fig. 1, *SI Appendix*, Fig. S1, Table S1).

We calculated individual ^{10}Be ages using the Arctic production rate (45) and Lal/Stone time-varying scaling (46). We use the Arctic production rate calibration data set (45) for our high-latitude sites as opposed to the global production rate dataset (46) because it better accounts for regional variability of the cosmic ray flux and associated production rate. We note, however, that the exposure ages calculated using the global production rate calibration data set are, on average, only 4% younger than our preferred exposure ages, which is within the 1σ external uncertainties.

We made no snow cover, vegetation, or erosion corrections. Given the major climate shifts of the last 14,000 years, it is impossible to know the snow-cover history of the sites, but several factors mitigate the effect of snow cover: snow has a low density and thus low shielding of cosmic rays; we sampled from the tops of boulders, where snow cover is more likely to blow off by wind; and we find excellent agreement between boulders and bedrock samples at site BCN where the former should have a lesser impact from snow cover than the latter. Vegetation similarly changed over the last 14,000 years, but as with snow cover, it has a low density and thus low shielding of cosmic rays. We sampled boulder surfaces that showed little-to-no erosion, but typical erosion rates (<1 mm ka^{-1}) suggest that erosion is not an issue at these timescales (47). We accounted for changes in sample elevation from isostatic uplift by using an iterative approach with isostatic rebound models (48) and new ice-sheet simulations (49). After removing outliers based on the constraints that samples cannot date from older than the Last Glacial Maximum (LGM, 26.5-19 ka) or be from the Holocene (<11.7 ka), we calculated the timing and uncertainty of deglaciation at each site using the arithmetic mean and standard error (Fig. 2; *SI Appendix*, Table S1 and Fig. S4), with the latter also including production rate uncertainty and reported as the external uncertainty to facilitate comparison with other dating methods for IFC opening.

Our ^{10}Be ages suggest that the IFC opened first at 15.4±0.7 ka at our southernmost site (ABS, 50.0°N, n=9). The IFC then progressively opened from the north and the south, with our mean age of 14.8±0.7 ka at site ABC (52.2°N, n=10) being (within uncertainty) the same as ^{10}Be ages from our two northern sites that suggest the northern section of the IFC began to open (14.4±0.6 ka, BCN, 58.7°N, n=10; 14.5±0.7 ka, BCC, 56.1°N, n=4) (Fig. 2). The center of the IFC then opened at 14.2±0.6 ka at site ABN (53.9°N, n=11) and lastly at 13.8±0.5 ka at site BCS (56.1°N) (Fig. 2), with the latter mean age being particularly robust as it is based on 15 ^{10}Be ages with no outliers. Indeed, the standard error at this site is only ±0.1 ka (±0.7%), with the remaining ±0.4 ka coming from the production rate uncertainty of ±3.8% (45). A Monte Carlo experiment using the distribution of ^{10}Be exposure ages from the BCS site suggests that ~>50 exposure ages are required to drive the site standard error below ±0.1 kyr (*SI Appendix*, Fig. S4), indicating that our analyses for this site are at the practical limit of precision for this direct dating technique and the ±0.5 ka external uncertainty cannot be realistically improved upon without reduction in production rate uncertainty. Finally, we note that site BCS (56.1°N, 122.2°W) is located just west of two sites (Charlie Lake, 56.3°N, 120.9°W; Spring Lake, 55.5'N, 119.6'W) where evidence of steppe vegetation and a variety of animals first appears ~12.6 ka (27), suggesting that the final opening of the IFC occurred ~1.2 kyr before this area became biologically viable.

Figure 2 compares our new ^{10}Be ages with the existing chronology for the IFC assessed above. Except for the calibrated ^{14}C age on the taiga vole bones (AA43652), all calibrated ^{14}C ages are younger than the mean ^{10}Be ages, consistent with the ^{14}C ages being minimum-limiting ages on deglaciation. At the same time, the calibrated ^{14}C age on taiga vole bones is ~1 kyr older than the mean ^{10}Be age of 13.8±0.5 ka from the nearby

BCS site and ~2.2 kyr older than nearby sites recording the first colonization of the area by plants and animals (27), which is consistent with the bones being contaminated by from old carbonate (26). Many luminescence ages that are proximal to, but still east of, the central IFC area are older than the mean ^{10}Be ages for deglaciation from these latitudes, further identifying age reversals that are possibly due to mixing with incompletely bleached glaciofluvial or glaciolacustrine sand prior to burial. Published ^{10}Be ages from the southern IFC include two that are significantly older than our mean ages and one (8.6±0.3 ka, not shown) that is significantly younger (34). The remaining ages are similar to our mean ages, but again cannot be combined as a single population to calculate a mean age because of the large distances between the sites. Of the two published ages included with our ABS ages, one is an outlier (181±4 ka) and the other (15.8±0.5 ka) is similar to the mean age (15.4±0.7 ka). Of the two published ages included with our ABC ages, one is also an outlier (24.2±0.9 ka) whereas the other age (16.4±0.6 ka) is significantly older than the mean age (14.8±0.7 ka), providing an example of how a single age affected by geologic scatter can provide an inaccurate age for IFC opening.

Discussion

Our new ^{10}Be chronology closely dates the final opening of the IFC as occurring at 13.8±0.5 ka (Fig. 4A), establishing that the IFC was not available as a migration route for the peopling of the Americas that had occurred before ~15.6 ka suggested by current archaeological and ancient genomic evidence (Fig. 3B). In contrast, multiple ^{14}C and ^{10}Be ages (50-54) from the coastal corridor (*SI Appendix*, Tables S5, S6) indicate that retreat of the western margin of the Cordilleran Ice Sheet and associated postglacial uplift occurred early enough to have provided a migration route for people prior to the earliest known archaeological sites south of the ice sheets (Fig. 4A). We note that these first peoples would likely still have faced considerable difficulties in navigating the largely glaciated coastline (50). Further dating of western CIS margin retreat and relative sea level change will improve our understanding of the paleogeography of this coastal corridor, which can then serve as a guide in the search for the archaeological evidence that is required to confirm this coastal migration route.

Methods

Field sampling

We collected multiple samples for ^{10}Be surface exposure dating from each of six sites located along a 1,200-km-long south-north transect (~50-59°N) (*SI Appendix*, Figures S1, S2) where mapping identifies the confluence of the Cordilleran and Laurentide Ice Sheets (41, 42, 55) (Fig. 1). The ^{10}Be ages at each site date the onset of ice-free conditions from ice-sheet separation and thus the initial opening of the IFC at that location. This contrasts with existing geochronological data used to constrain the age of IFC opening which only minimum-limiting ages on ice-margin retreat since they record some unknown amount of time between deglaciation and accumulation of reliably datable material as well as the fact that many dated sites extend from ~150 km to 1,000 km east of the ice-sheet suture zone.

Samples for ^{10}Be surface exposure ages from boulders on bedrock were collected at five sites (ABS, ABC, ABN, BCS, BCC) with a sixth site (BCN) consisting of a mixture of boulder-on-bedrock samples (n=4) and glacier-scoured bedrock samples (n=6). Sampling followed prior methods used to document ice-sheet-scale changes in ice margins and area of the IFC (38, 56) (4, 5). Each of these sites is located near the mapped confluence of the Cordilleran-Laurentide Ice Sheets (Fig. 1) and was chosen for its simple deglacial history, with the exposure of the boulder surface being due to separation of the two ice sheets with no potential cover by proglacial lakes.

ABS is the southernmost site (50.1°N, 113.8°W, ~1200 m above modern sea level); we collected 10 samples from this sample site and include two additional ages from Ref. (34) (ALT-MM-15-08, ALT-MM-15-09) (*SI Appendix*, Figure S1). All boulders are quartzite except ABS-10-16 which is granitic. At the ABC site (52.2°N, 114.8°W, ~1100 m above modern sea level), we collected samples from 12 quartzite boulders and combined them with two ages from Ref. (34) (ALT-MM-15-14, ALT-MM-15-15) (*SI Appendix*, Figure S1). ABN (54.0°N, 119.0°W, ~1800 m above modern sea level) consists of 12 quartz-rich sandstone boulders (*SI Appendix*, Figure S1). At BCS (56.1°N, 122.2°W, ~1100 m above modern sea level), we sampled 15 sandstone boulders resting on bedrock (*SI Appendix*, Figure S2) while we found only five samples for collection at BCC (57.5°N, 122.9°W, ~1200 m above modern sea level) (*SI Appendix*, Figure S2). For BCN (58.7°N, 123.8°W, ~1000 m above modern sea level), we sampled only four sandstone boulders (BCN-4-16, BCN-5-16, BCN-7-16, BCN-8-16), which we supplemented with an additional six sandstone bedrock samples to give a total of 10 samples (*SI Appendix*, Figure S2).

^{10}Be target preparation and measurement

Thirty-four samples were prepared at PRIME Laboratory at Purdue University (6=ABS, 8=ABC, 5=ABN, 5=BCS, 5=BCC, 5=BCN) following standard techniques (www.physics.purdue.edu/primelab/) with another 30 samples prepared at CosmIC Laboratories at Imperial College London (4=ABS, 4=ABC, 7=ABN, 10=BCS, 0=BCC, 5=BCN) using standard procedures (8). ^{10}Be concentrations and uncertainties are provided in *SI Appendix*, Table S1.

Age calculation and isostatic rebound

We calculated ^{10}Be ages using the Lal/Stone time-varying scaling (46) and the Arctic ^{10}Be production rate (45). Use of another scaling (LSD; (57)) does not change our results or conclusions. We do not correct for changes in atmospheric pressure as this has been shown to have a negligible impact on the production rate once the total time since deglaciation is considered (38, 56). Because the Cordilleran-Laurentide Ice-Sheet suture zone has undergone extensive isostatic rebound following deglaciation (48, 49), we estimate the impact of rebound on the surface exposure ages and correct for this influence on the final age (58). This is accomplished using new ice-sheet model simulations following Ref. (49).

We calculated average deglacial ages for each site following the methods of Refs. (38, 56) and include the four additional ^{10}Be ages from Ref. (34) that are adjacent to ABS and ABC (*SI Appendix*, Figure S3). Outliers that are either at least as old as the Last Glacial Maximum (LGM) (>19 ka) or Holocene (<11.7 ka) in age were identified and excluded, which excluded nine samples from the 68 samples, two of which are from Ref. (34). ABS contained three pre-LGM outliers while ABC had four LGM-age outliers (*SI Appendix*, Figure S3). One sample at ABN and another at BCC were identified as

Holocene-age outliers (*SI Appendix*, Figure S3). Following exclusion of these nine outlier samples, we determined the arithmetic mean and standard error for each site, which produced the largest uncertainty in the mean, making this a conservative approach (38). We then added the ^{10}Be production rate uncertainty of ±3.8% to the standard error in quadrature to determine the external uncertainty of the mean for the timing of deglaciation and the opening of the Ice-Free Corridor.

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Figure 1. Map showing extent of Cordilleran and Laurentide Ice Sheets after initial opening of Ice-Free Corridor and location of dated sites. Margins of Cordilleran (CIS) and Laurentide (LIS) ice sheets at 14.2 cal ka from Ref. (54) and locations of sites with ages discussed in text. Sites with ^{14}C ages shown as blue and gray circles, with the former sites occurring more proximal to ice-margin retreat and opening of initial Ice-Free Corridor (IFC) or coastal corridor, and latter sites occurring more distal to initial IFC. Sites with luminescence ages shown as orange and gray diamonds, with the former sites occurring more proximal to ice-margin retreat and opening of the IFC, and latter sites occurring more distal to the initial IFC. Sites with ^{10}Be ages shown as squares, with published ages shown as blue squares constraining retreat of western Cordilleran Ice-Sheet margin (52, 53), and green squares constraining opening of southern IFC (34), and our new ages shown as brown squares (with underlined text indicating site name) constraining opening of the IFC. Inset map shows our sample locations within the context of the approximate location of the suture zone (thick dashed line) of the CIS and LIS at the Last Glacial Maximum ~21 ka. AB = Alberta, BC = British Columbia.

Figure 2. Compilation of ages used to constrain the timing of the opening of the Ice-Free Corridor (IFC). Sites with ^{14}C ages shown as blue and gray circles (2σ uncertainty), with the former sites occurring more proximal to Cordilleran-Laurentide ice-sheet suture zone and latter sites occurring more distal to ice-sheet suture zone (26) (*SI Appendix*, Table S2). Sites with luminescence ages shown as orange and gray diamonds (1σ uncertainty), with the former sites occurring more proximal to Cordilleran-Laurentide ice-sheet suture zone and latter sites occurring more distal to ice-sheet suture zone (26) (*SI Appendix*, Table S3). Sites with ^{10}Be ages shown as squares (1σ

uncertainty), with published ages as green squares constraining opening of southern IFC (34) (*SI Appendix*, Table S4) and our new ages as brown squares (with corresponding site location names ABS-BCN) constraining opening of the IFC (*SI Appendix*, Table S1).

Figure 3. Photographs of representative glacial erratics sampled for cosmogenic ^{10}Be dating. (**A**) Sample ABC-5-16. (**B**) Sample ABS-1-16.

Figure 4. Age constraints on opening of Ice-Free Corridor (IFC), coastal corridor, and first peopling of the Americas south of the ice sheets. (**A**) Sites with ^{14}C (2σ uncertainty) and ^{10}Be (1σ uncertainty) ages constraining retreat of western margin of the Cordilleran Ice Sheet and emergence of ice-free areas shown as blue circles and squares, respectively (51-54) (*SI Appendix*, Tables S5, S6). Sites with ^{10}Be ages constraining opening of the IFC shown as brown squares (1σ uncertainty) (this study). (**B**) Age constraints from ancient genomics (19) and archaeological sites for first peopling of the Americas south of the ice sheets. Ages from archaeological sites (*SI Appendix*, Table S7) labelled as Paisley Caves, OR (PC) (12), the Page-Ladson site, FL (PL) (15), the Debra L. Friedkin site, TX (DF) (16), and the Cooper's Ferry site, ID (CF) (14).

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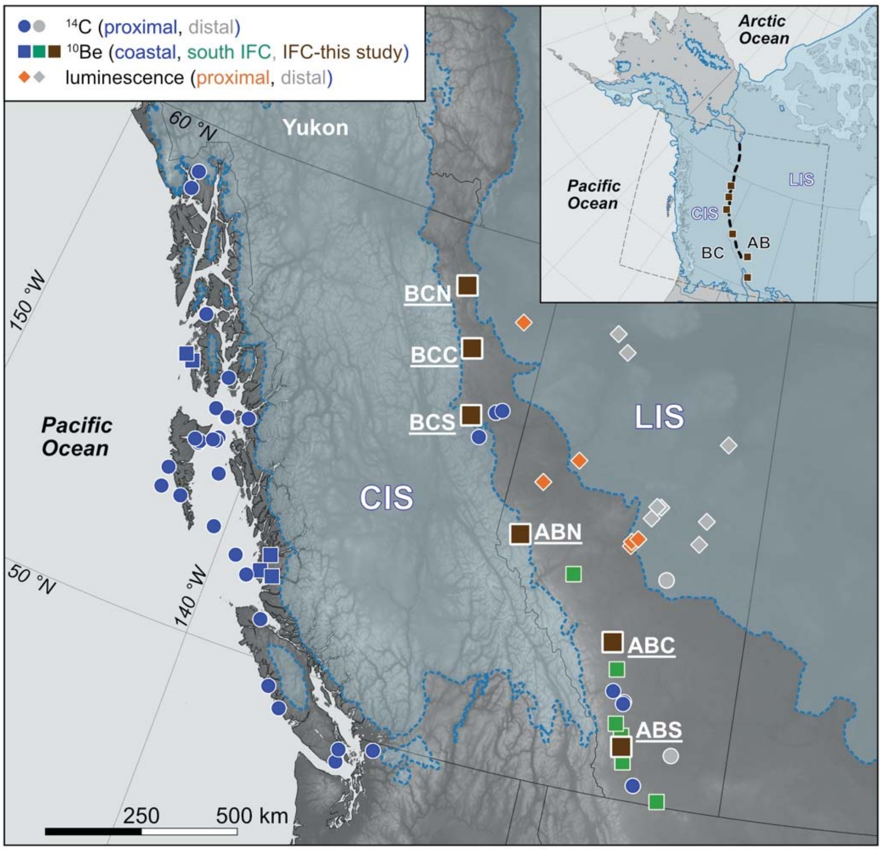
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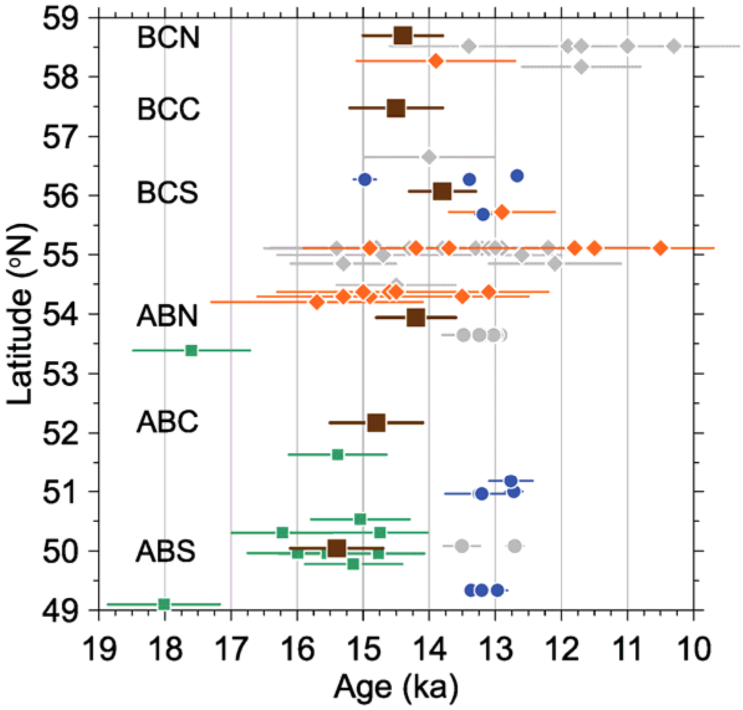
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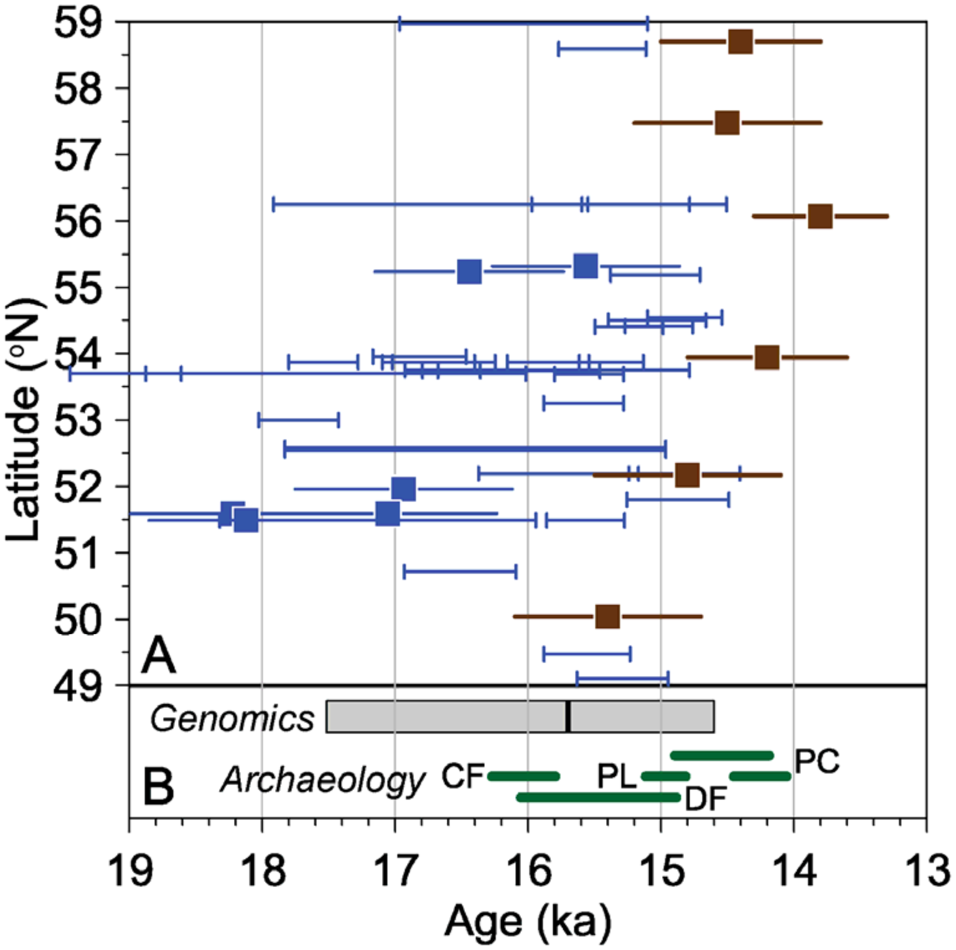
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