The Solutrean Atlantic Hypothesis: A View from the Ocean

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Abstract - One current hypothesis for the Pleistocene peopling of the Americas invokes a dispersal by European hunter-gatherers along a biologically productive "corridor" situated on the edge of the sea-ice that filled the Atlantic Ocean during the Last Glacial Maximum (LGM). In this paper, we assert that critical paleoceanographic data underpinning this hypothesis has not yet been examined in sufficient detail. To this end, we present data which show that the corridor may not have existed, and that, if it did, its suitability as a migration route is highly questionable. In addition to demonstrating that the hypothesized migration was unlikely, this highlights the importance of integrating paleoceanographic and archaeological data in studies of paleo-coastal societies.

Introduction

The timing of the initial colonization of the Americas is one of the great unsolved questions of prehistoric archaeology. For much of the last half-century, the orthodox view was dominated by proponents of the "Clovis-first" argument. According to this theory, the first colonists were Siberian hunter-gatherers who travelled to Alaska across the Bering Sea continental shelf, which at the time was exposed by lowered sea-levels. From here, they dispersed south through an ice-free corridor dividing the Laurentide and Cordilleran ice sheets which covered most of landscape above ≈50°N, before spreading rapidly across North America (Fig. 1). Their presence was manifest by a distinctive toolkit of fluted lithic points (the eponymous Clovis point) found across the continent and originally radiocarbon-dated to between 11.5–10.9 (^{14}C) ka BP (Fiedel 1999) and recently refined to 11.05–10.8 (^{14}C) ka BP (Waters and Stafford 2007). In calendar years, this equates to a maximum age span of 13.11–12.66 or 13.25–12.8 cal ka BP, depending on whether a dendrochronological or coral-based calibration is used (Waters and Stafford 2007).

However, this argument was undermined by the presence of archaeological sites scattered across the Americas that predated Clovis. Although many were demonstrated to be the product of contaminated radiocarbon dates, stratigraphic mixing, or naturally rather than anthropogenically produced artifacts, there remained several sites that resisted critique (Fiedel 2000). Notable examples include the Monte Verde (Chile, dated to 12.5–12 [^{14}C] ka BP), Meadowcroft (Pennyslvania, USA, 19–13 [^{14}C] ka BP), and Cactus Hill (Virginia, USA, dated to 16.9–15 [^{14}C] ka BP) sites (Dillehay 1997, Feathers et al. 2006, Fiedel 1992). More recently, Waters and Stafford's (2007) redating of Clovis suggests that the temporal gap between Clovis and the youngest well-dated sites in South America was a minimum of 200 to a maximum of 350 calendar years, a timeframe within which it is improbable that humans could enter North America, adapt to a wide range of environments and undertake a single migration of 14,000 km to populate South America. In short, the current evidence provides a strong indication that the Clovis people were not the first occupants of the Americas.

The presence of a pre-Clovis population in turn requires consideration of their migration route into the Americas. In this instance, the ice-free corridor hypothesis proves to be problematic. Firstly, it contains relatively little archaeological evidence. Moreover, what evidence there is postdates, or coincides with Clovis (Waguespack 2007). Secondly, it is still an open question whether it was capable of supporting past humans (Waguespack 2007). For example, Arnold (2002) has suggested that the corridor's lack of datable organic material predating 11 (^{14}C) ka BP implies it was devoid of habitable environments. Thirdly, better dating has constrained its opening between 13–12.5 (^{14}C) ka BP (Dyke et al. 2003), implying it was not a pathway available for a pre-Clovis dispersal given the age of the dated sites. In short, an alternative route into the Americas is required.

The most widely discussed alternative is a coastal route from Beringia down the Pacific Northwest coast of North America (Fig. 1). This theory was first proposed by Knut Fladmark (1979) over twenty years ago, but was not seriously considered until the last decade due to the supposition that the relevant evidence had been eroded or submerged by rising sea-levels. According to this hypothesis, migrants circumvented the Cordilleran ice sheet by using boats to hop between unglaciated sections of the coastline. Recent work has supported it by identifying such unglaciated refugia on the continental shelf off British Columbia and southern Alaska

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(Heaton et al. 1996, Hetherington et al. 2003, Mandryk et al. 2001).

Another alternative, proposed by Bruce Bradley and Dennis Stanford (2004) comes from the other direction. They propose a migration across the Atlantic by European hunter-gatherers, using boats to follow the extensive pack ice that filled the North Atlantic at the height of the last ice age, the Last Glacial Maximum (LGM) (Fig. 1). Along the way, they were sustained by the rich marine resources, particularly marine mammals such as harp seals that are argued to have congregated along the edge of the ice, hence the description of the route as an "ice-edge corridor." Their view is based primarily on lithic technology, more specifically the suggestion that Siberian sites do not have a lithic technology that resembles a Clovis precursor, and that greater technological similarities can be found between lithic assemblages from France and Spain (the Solutrean technocomplex; dated to ≈25–18 cal ka BP) and Clovis. They also believe artifacts from three pre-Clovis sites in eastern North America (Meadowcroft, Cactus Hill, and Page-Larson) are transitional between the Solutrean and Clovis, thus filling the time gap between them, while also pointing out that the earliest Clovis dates come from the southeast of North America, rather than the northwest, as might be expected given an Asian origin.

This view has been heavily critiqued on a number of fronts including: a lack of evidence for a significant marine adaptation in the Solutrean; similarities between European and North American tool types being more apparent than real; and the 5000-year time gap between the Solutrean and Clovis (Straus 2000, Straus et al. 2005). Similarly, any rebuttals have been based primarily around issues of lithic technology (Bradley and Stanford 2006).

One aspect that has not been examined in as much detail, by both proponents and opponents of the hypothesis, is the "ice-edge" corridor itself, a factor that one would presume to be critical to the success or failure of the hypothesized dispersal. Bradley and Stanford's descriptions of Solutrean marine or ice-based settlement and resource procurement systems are, as they freely admit (2004:470), informed speculation. Meanwhile, Straus et al. (2005: 517) recognized the need to test these descriptions with paleo-environmental data, but stopped short of doing so on the basis that "This is not a matter to be left to archaeologists." However, ignoring the paleo-environmental record provides a somewhat imbalanced view of the past. Even without resorting to environmental determinism, it should be clear that the human activities operate within broad practical boundaries set by the environment. Indeed, the need for an understanding of paleo-environment is well established in prehistoric archaeology in relation to terrestrial sites (e.g., Bell and Walker 2005, Van Andel and Davies 2003). It therefore begs the question why the same should not be true of the marine environment, especially considering how critical it is to the proposed dispersal. Consequently, the aim of this paper is to test the Solutrean hypothesis by primarily using relevant paleo-environmental and paleoceanographic data.

This inquiry can be framed by two broad questions:

1. Did an ice-edge corridor actually exist at the period in question?
2. If so, was it actually amenable to migration and dispersal?

The remainder of this paper will address these two questions by both reviewing North Atlantic paleoceanography and the implications of this for the

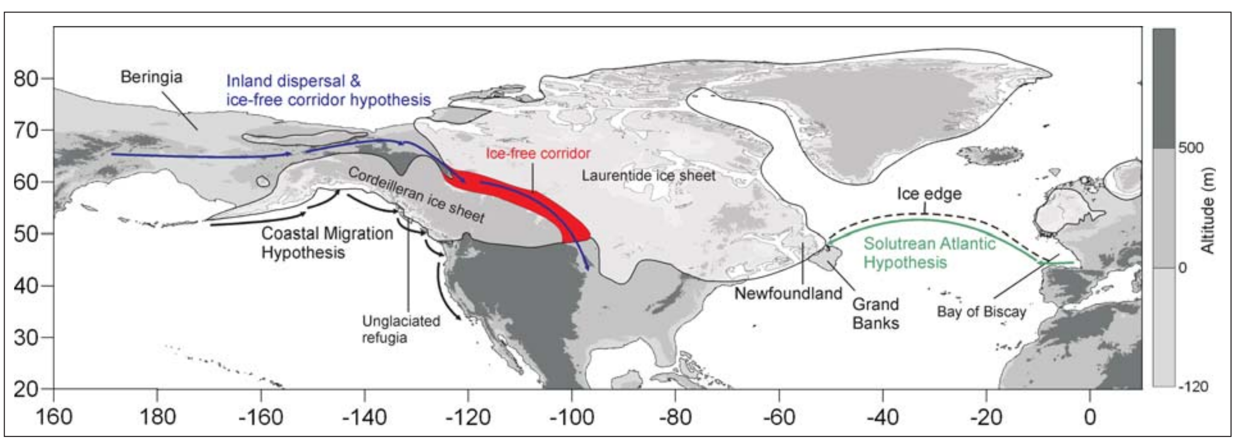


Figure 1. Competing hypotheses for routes taken by hunter-gatherers during the initial colonization of the Americas. Ice sheet limits and sea-levels are those of the Last Glacial Maximum (c.18–24 cal ka BP). Note that the ice-free corridor was only opened after the LGM (c. 16 cal ka BP). European and North American ice limits from Carr et al. (2006) and Dyke et al. (2003) respectively. The paleo-shoreline has been placed at -120 m and represents the LGM glacio-eustatic sea-level fall (Peltier and Fairbanks 2006). This depiction is therefore a first-order approximation, with areas in close proximity to the ice sheets experiencing different patterns of sea-level change (see Lambeck and Chappell 2001 for more information).

proposed dispersal. A specific focus will be placed on the conditions in the Bay of Biscay, as this borders the Solutrean heartland of southern France and the Iberian Peninsula and was therefore the most likely location for the development of a Solutrean maritime adaptation, if one occurred.

The North Atlantic at the LGM

The proposed Solutrean migration took place during the height of the last glacial period; an interval commonly referred to as the Last Glacial Maximum (LGM) and dated to between 18 and 24 cal ka BP as defined by the EPILOG project (Mix et al. 2001). During this time, high and mid-latitude conditions were much colder and drier than at present, characterized by the expansion of ice sheets, polar desert, and steppe tundra on land, and low sea surface temperatures (SSTs) and greater sea-ice extents at sea (Kutzbach et al. 1998, Ray and Adams 2001).

For many years, reconstructions of North Atlantic paleoceanography during this interval were based on the pioneering CLIMAP (Climate Long Range Investigation, Mapping, and Prediction) project (CLIMAP Project Members 1976, 1981). This work, undertaken in the 1970s, provided quantitative reconstructions of LGM terrestrial and marine climate, based on proxy records. According to this, LGM SSTs in the North Atlantic dropped dramatically relative to the present day. For example, at 50°N, they fell 12 °C below present (CLIMAP Project Members 1976). The temperature drop was particularly dramatic on the Northwest European margin as the warm North Atlantic Drift (NAD) current, which presently keeps seasonal temperatures above the latitudinal average, was deflected south. Consequently, the southern boundary of the polar front (the transition zone between cold subpolar and warm subtropical waters) was located at ≈37–43°N, approximately the same latitude as the Portuguese and North Spanish coasts (Ruddiman and McIntyre 1981). As a consequence of these lowered temperatures, the distribution of sea-ice was more extensive and believed to cover much of the North Atlantic, reaching as far south as the French Atlantic coast during the winter (CLIMAP Project Members 1981). It is this ice that Bradley and Stanford (2004) regard as the critical link in their hypothesis of trans-Atlantic migration.

In recent years, new data and more advanced scientific techniques have superseded some of the conclusions of CLIMAP. With respect to North Atlantic paleoceanography, important examples are the GLAMAP (Glacial Atlantic Ocean Mapping: Pflaumann et al. 2003) and MARGO (Multi-proxy Approach for the Reconstruction of the Glacial Ocean surface; Kucera et al. 2005) projects, both of which re-assessed LGM SSTs and sea-ice cover using new and more refined techniques of proxy reconstruction, as well as better constraints on the timing of paleoceanographic changes. One key aspect of the MARGO project was its use of multiple proxies to measure paleoceanographic change. These ranged from measurements of chemical changes in the bodies of marine micro-organisms (a reflection of climate-induced chemical changes in ocean water) to biological transfer functions which measure change on the basis that particular communities of micro-organism species can only live within particular environmental ranges. Although the different proxies provided varying quantitative estimates of paleo-SSTs (see review in De Vernal et al. 2006), they are consistent in two areas. Firstly, they show that the LGM North Atlantic was warmer, and secondly that LGM sea-ice was less extensive and much more seasonal than previously estimated by CLIMAP.

The results of the MARGO Project based on biological transfer functions for two proxies—dinocysts and planktonic foraminifera—are displayed in Figure 2. While there are quantitative differences between the two (for example, compare Figs. 2a and 2c), the overall pattern they reconstruct is consistent. More specifically, winter sea-ice extended down to ≈45–50°N at maximum. During summer, the NW European margin was seasonally ice free almost to 80°N, with rare excursions down to ≈60–65°N and quasi-permanent ice restricted to the northeast Canadian and east Greenland coasts (Figs. 2e and f). The dinocyst reconstructions also provide a quantitative estimate of ice duration, namely that winter ice only persisted for 1–3 months each year across most of the North Atlantic (Fig. 2f). Further important features to note are a broad ice-free channel inferred for the central Atlantic and that the Bay of Biscay, on average, experienced winter sea-ice for less than one month per year (De Vernal et al. 2005, De Vernal et al. 2006, Sarnthein et al. 2003). In short, the remarkable seasonality of the LGM North Atlantic contrasts with the oft-assumed concept of a perennially ice covered ocean.

The improved time resolution of recent deep-sea records has also allowed greater insight into the pattern of paleoceanographic change over time. In this instance, the majority of the evidence shows that the coldest conditions in the North Atlantic did not occur during the LGM as previously believed, but during two rapid events on either side of it; Heinrich Events 1 and 2, dated to ≈17 and 24 cal ka BP respectively (Hemming 2004). During these brief (500 ± 250 years) intervals, SSTs fell drastically and the North Atlantic was filled by ice. However, this did not take the form of a continuous sheet of sea-ice, but was comprised of massive discharges of icebergs from the North American and European ice sheets reaching as far south as 40°N. The most detailed evidence of these events comes from off the Portuguese coast where favourable conditions permit the formation of long high-resolution deep-sea records. For example, cores from this area have LGM SSTs of 13–17°C compared to lows of 5–10°C for Heinrich Events and also contain layers of ice-rafted debris (IRD) deposited by the fleet of melting icebergs (De Abreu et al. 2003, Pailler and Bard 2002).

Similar patterns prevailed in the Bay of Biscay. Here, a high-resolution record (core MD 95-2002;

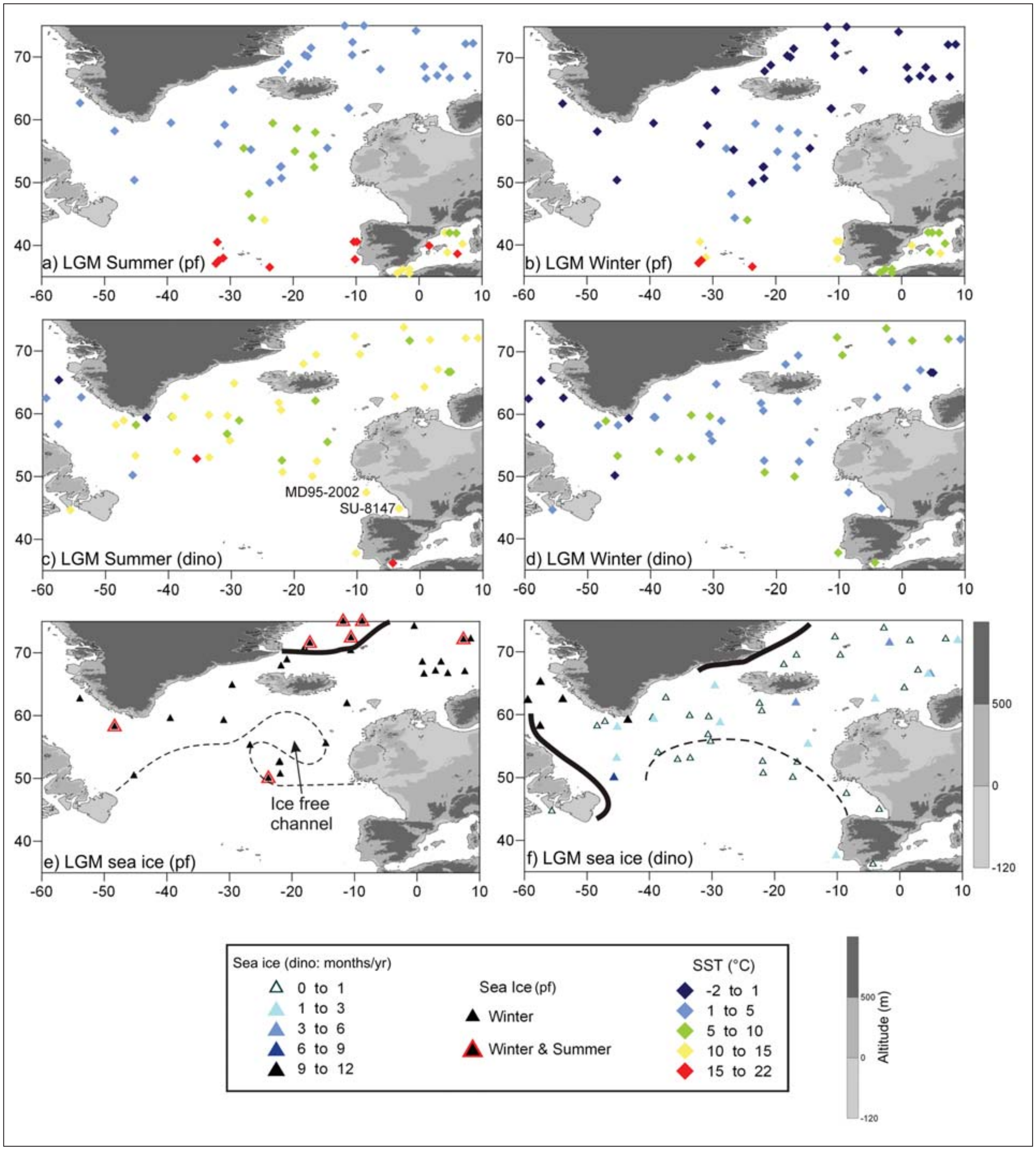


Figure 2. Quantitative reconstructions of LGM North Atlantic paleoceanography based on two different proxies: dinocysts and planktonic foraminifera. Data from De Vernal et al. (2004) and Weinelt (2004) (See also De Vernal et al. 2006, Kucera et al. 2005). a) Summer SSTs from planktonic foraminifera. b) Winter SSTs from planktonic foraminifera. c) Summer SSTs from dinocysts. d) Winter SSTs from dinocysts. e) Sea-ice extents from planktonic foraminifera: triangles show core sites with evidence of summer and winter ice. Heavy black line represents the extent of perennial ice, and dashed line is the maximum extent of winter ice (based on Sarnthein et al. 2003). f) Sea-ice extents from dinocysts: triangles show core sites with evidence of the duration of ice in months per year. Heavy black line represents the extent of perennial ice, and dashed line is the maximum extent of winter ice (based on De Vernal et al. 2006).

see Fig. 2c for core location) covers the LGM and post-LGM period and clearly demonstrates millennial-scale changes in ocean conditions (Fig. 3). This pattern is revealed firstly by the presence of IRD, which reaches maximum values during Heinrich Events 1 and 2, but drops dramatically during the intervening period—the LGM. A second proxy is the presence of the planktonic foraminifera *Neogloboquadrina pachyderma(s)*, a subpolar species which presently inhabits North Atlantic waters above 65°N. High concentrations of *N.pachyderma(s)* are therefore a clear sign of cold conditions and in this instance coincide with Heinrich Events 1 and 2 and the GS-1 stadial identified in the Greenland ice cores. Importantly, the interval between Heinrich Events 1 and 2 was characterized by lower quantities of *N.pachyderma(s)*, and can be divided into an initial cold period followed by a period of fluctuating, often warmer, temperatures brought about by the increased advection of warm North Atlantic Drift water into the Bay. A third proxy is the dinocyst *Algidasphaeridium minutum*, a species that tends to be associated with sea-ice. It is noteworthy that its highest concentrations occur before and after the LGM, substantiating the results described earlier and in Figure 2 (Eynaud 1999, Zaragosi et al. 2001).

Another important record from the Bay of Biscay is core SU8147 (see Fig. 2c for core location). Though it lacks a published radiocarbon timescale and is of lower resolution, it can be correlated to the MD95-2002 timescale by virtue of similar changes in faunal composition (Westley 2006). Importantly, this core provides quantification of the paleoceanographic changes described above. Noteworthy features are that LGM conditions were subarctic, though not low enough to form perennial sea-ice: February temperatures are believed to have ranged between 1–4 °C (±2 °C), with sea-ice cover of between 1–2 months per year at most. Conversely, during Heinrich 1, winter SSTs reached as low as 0–1 °C while sea-ice cover potentially reached up to 6 months per year. In summary, a variety of evidence from the North Atlantic indicates that LGM conditions were not as cold and icy as previously believed. Instead these circumstances were prevalent during the short stadial events on either side of it.

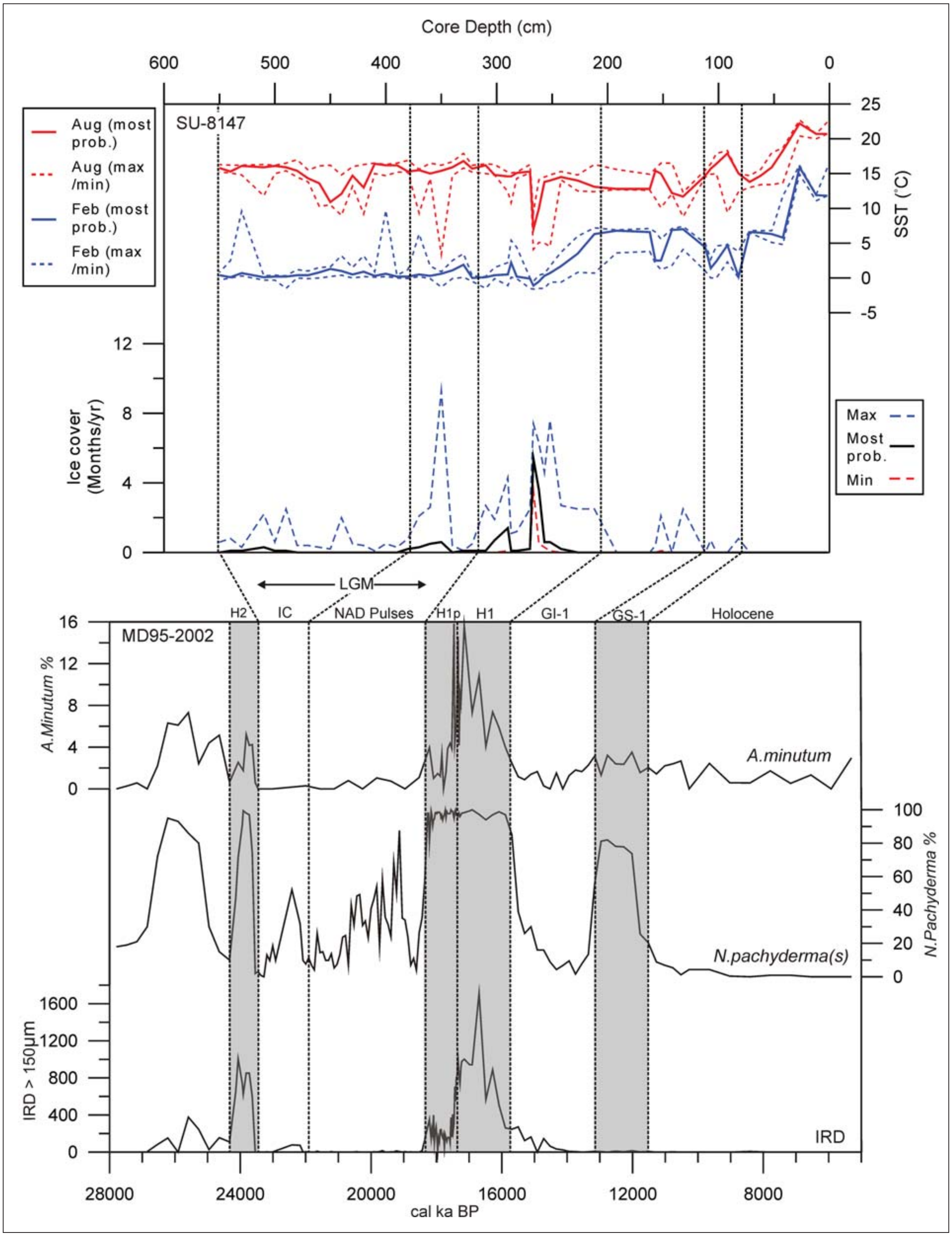
Implications for the Trans-Atlantic Crossing: Existence of the Ice-Edge Corridor

Before assessing the implications of the previous section for the hypothesized migration, it is necessary to constrain the chronology of the Solutrean accurately so as to compare it with the paleoceanographic evidence. This analysis will be done by calibrating radiocarbon dates from Solutrean sites and plotting them alongside paleoceanographic evidence calibrated on the same timescale (Fig. 4). This comparison clearly shows that Solutrean sites correlate for the most part with Heinrich Event 2 and the LGM. The first question to consider is whether sufficient ice actually existed across the Atlantic to form a migration corridor during the time period encompassed by the Solutrean.

The revised views of North Atlantic paleoceanography do indeed show that sea-ice was more extensive at the LGM relative to the present. However, they also show that the actual duration of ice cover was much less and the differences between summer and winter ice extents were much greater than previously believed. The actual duration for which the coasts of eastern North America and NW Europe were connected was probably very small—of the order of 1–3 months per year (Fig. 2). Potential migrants therefore had a very restricted time window within which to cross the ocean. Moreover, in the Bay of Biscay, extensive winter ice probably only have existed for less than a month, and possibly up to a maximum of two months per year. Focusing specifically on harp seals, regarded by Bradley and Stanford (2004) as a particularly important resource ("A Solutrean hunter must have been awe-struck when he watched for the first time a pristine seal colony stretching for as far as he could see, basking on an ice floe as it drifted towards the shore." [2004:470]), the most southerly modern extremes of harp seal congregations on ice are located in the waters of the Gulf of St. Lawrence and off northeast Newfoundland (Renouf and Bell 2006). These areas presently have ice cover 2–4 months per year (De Vernal and Hillaire-Marcel 2000). These facts lead one to question whether an intensively ice-based marine mammal hunting subsistence strategy could actually have developed in the Bay of Biscay, given its lower ice concentrations.

Admittedly, the Solutrean does overlap to a small degree with Heinrich Event 1 (more specifically, the Heinrich 1 precursor rather than the maxima of the ice-rafting event) and completely with Heinrich Event 2, during which ice extents increased considerably. Nonetheless, even if it were argued that the hypothesized dispersal took place during these events, there is still the obstacle that the Atlantic sea-ice was composed of discontinuous icebergs rather than a largely continuous and flat mass of ice, a platform less suited to the aggregation of dense concentrations of marine mammals. In addition, these were drifting south and east with the dominant wind and ocean currents, as shown by the presence of North European and Canadian IRD in the Bay of Biscay (Zaragosi et al. 2001), directly opposite to the proposed migration. Furthermore, if dispersal occurred at Heinrich 2, this would increase the time gap between Clovis and the Solutrean to more than 10,000 years, weakening the idea that the two were connected.

The greater seasonality of the LGM North Atlantic also requires us to consider the ice-edge corridor as a dynamic entity, rapidly altering its geography every year. Bradley and Stanford's (2004) view assumes a synchronous northward retreat of the ice edge so as to maintain a viable "bridge" or "corridor." They suggest that Solutrean hunters progressively moved further from the Bay of Biscay during phases of climate warming as the ice retreated north in pursuit of ice-edge dwelling seals until they inadvertently reached the other



side of the bridge. An obstacle to this route would have been the ice-free channel in the central North Atlantic identified by Sarnthein et al. (2003) and shown in Figure 2e. If this channel expanded during the initial phases of the seasonal ice melt, it would effectively split the ice-edge corridor. While the exact pattern of seasonal ice melt is still uncertain, the presence of short-duration (i.e., 0–1 month/yr) ice in the vicinity of the channel (Fig. 2f) could be taken as substantiating evidence. This scenario would then necessitate an open-water crossing to reach the other side, and if the Solutrean hunters were in fact tracking the ice edge, then northward movement up the European margin would be more likely.

The speed of seasonal ice melt is also critical if one takes into account the time required to traverse the LGM North Atlantic. Since there is little information in the Solutrean Atlantic Hypothesis on the types of boat used, the speed of the proposed migration, or the proportions of time spent on the water versus the ice, we must turn to computer simulations of LGM boat journeys developed by

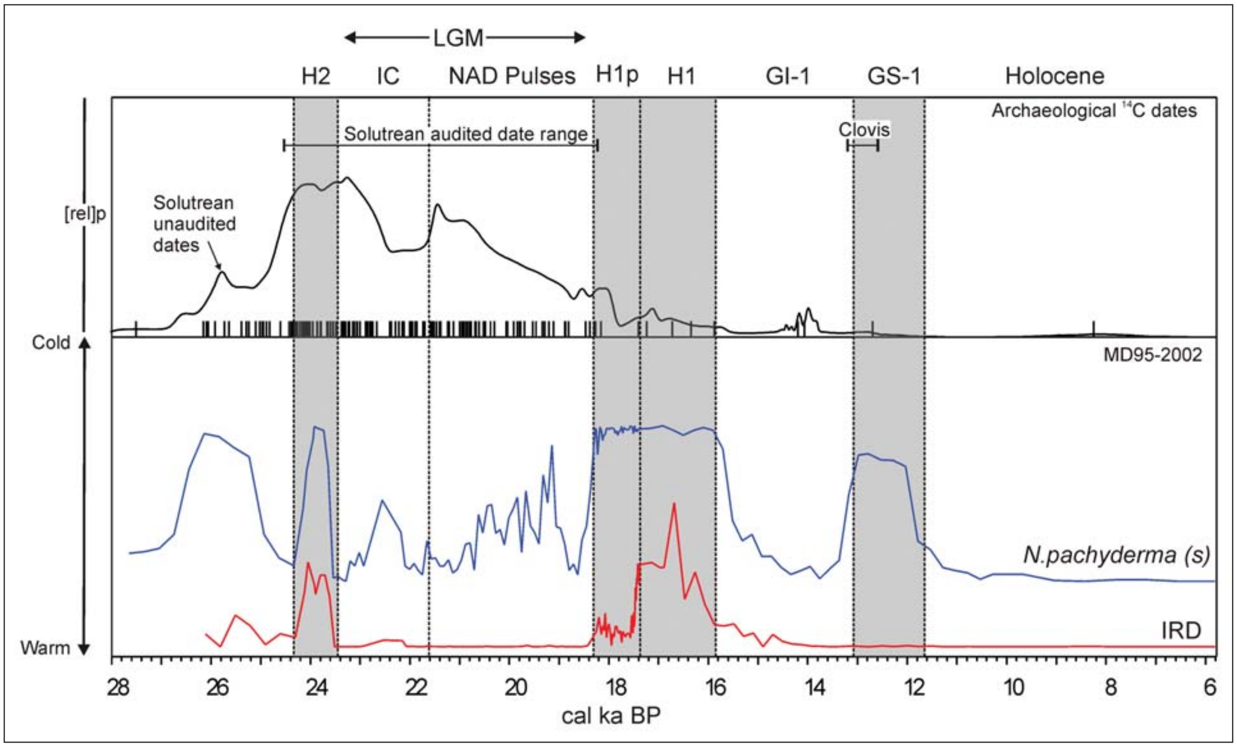


Figure 4. Relative probability distribution of radiocarbon dates from Solutrean sites plotted against the MD95-2002 paleoceanographic record. Both datasets calibrated using the CalPal Hulu 2007 curve and the CalPal program (Weninger and Jöris 2008, Weninger et al. 2007). Solutrean dates were obtained from the S2AGES database of radiocarbon dates (Gamble et al. 2005) provided courtesy of W. Davies and C. Gamble. This database contains a means of auditing dates in order to exclude poor or inaccurate dates. In this Figure, an unaudited sample has been used so as to obtain the widest possible chronological limits. Hence, the outlying dates such as in the Holocene and GS-1 are "bad" dates, resulting from issues such as sample contamination (Pettitt et al. 2003). The unaudited data provide a Solutrean duration between 26 and 18 cal ka BP, whilst the use of audited dates refines the time period to between 25 and 18 cal ka BP (based on 17 dates from 5 sites).

Figure 3 (opposite page). Late Pleistocene paleoceanographic conditions in the Bay of Biscay based on cores MD95-2002 and SU8147. MD95-2002 has a well-constrained radiocarbon-based chronology (Eynaud et al. 2007, Zaragosi et al. 2001), which in this instance has been calibrated using the CalPal Hulu 2007 curve and the CalPal program (Weninger and Jöris 2008, Weninger et al. 2007). SU8147 lacks a published radiocarbon timescale, but can be correlated with MD95-2002 on the basis of synchronous changes in microfossil communities. The pattern of paleoceanographic change allows the period to be divided into specific climatic intervals. In this case, the LGM—between 24–18 cal ka BP—can be divided into two phases: an initial cold phase (IC) and a subsequent warmer and fluctuating phase during which pulses of warm North Atlantic Drift water entered the Bay (NAD Pulses). H2 and H1 refer to Heinrich Events 1 and 2, respectively, when temperatures fell and iceberg incursion was common. H1p refers to the Heinrich 1 precursor—the interval during which iceberg rafting was initiated. GI-1 and GS-1 are respectively interstadial and stadial periods that are also visible in the Greenland ice cores. Grey bars highlight the coldest intervals. SU8147 SST and sea-ice reconstructions show the maximum, minimum, and most probable values as determined by the original investigators (Turon et al. 1995). MD95-2002 provides qualitative indications of change: IRD concentrations rise when icebergs are present, and *A. minutum* and *N. pachyderma(s)* inhabit sea-ice and subpolar environments, respectively (data courtesy of F.Eynaud).

Montenegro et al. (2006). These estimate travel times of 95 to 220 days (assuming a journey from Iberia to North America), and are a function of boat speed and the fact that dominant mid- to high-latitude winds in the North Atlantic are westerly (i.e., opposed to the proposed direction of travel) and were strengthened during the LGM. Although these models are by necessity simplifications of reality, they do provide a first approximation of the time duration involved, which even at the lowest estimate, is 1.5–3 times greater than the amount of time for which seasonal ice was present in the central and northeastern Atlantic. The implication is that by the time a group of hunters had reached the Central Atlantic, the connection to the Americas may already have been broken.

Implications for the Trans-Atlantic Crossing: Nature of the Ice-Edge Corridor

From the previous section, it is clear that only short intervals coinciding with the Solutrean were characterized by large expanses of ice. Nonetheless, even if it is assumed that this constituted sufficient ice to allow a crossing, or that it took place during Heinrich Events 1 or 2, there is an additional aspect to consider: whether the ice-edge corridor was actually amenable to migration. This revolves heavily around questions of productivity. Did sufficient marine resources exist to allow the development of a Solutrean maritime adaptation, attract it across the ocean, and then sustain it along the way?

Bradley and Stanford (2004:469) assert this was indeed the case, describing both the Bay of Biscay and ice-edge corridor as "a region with intense biological productivity, providing a major food source for much of the marine food chain." Their suggestion is based on three lines of evidence:

1. Enhanced photosynthesis of Arctic and sub-Arctic species of plankton caused by their shift to lower latitudes.
2. Increased LGM productivity resulting from the erosion of "seabed ooze" from exposed continental shelves, increased loess deposition and upwelling of intermediate waters caused by more vigorous atmospheric circulation, and increased mineral input derived from ice rafted minerals.
3. The ice-edge is a region of intense biological productivity.

In fact, each of these mechanisms is less straightforward than described above and includes several features that weaken the hypothesis. Taking the first of the lines of evidence, the shift of Arctic and sub-Arctic plankton to lower latitudes may not necessarily have increased photosynthesis per se. It may have been more a case of spreading it more evenly throughout the year rather than having intense seasonal blooms. A more important factor may have been the increased spring and summer insolation brought about by the orbital patterns of the time (Loutre et al. 2004), which would have enhanced productivity, but only during seasons when the ice was melting or absent.

Secondly, the issue of LGM productivity is a complex one with some studies suggesting greater or equal productivity compared to the Holocene, and others indicating that it was lower (Villanueva et al. 2001). The differences arise because of sample location—i.e., productivity is not uniformly distributed across the world—and the fact that different proxies provide varying estimates. Therefore, while overall LGM productivity levels seem to have been higher than present as evidenced by reduced carbon dioxide levels (which are at least partially the result of greater uptake of CO_2 due to increased phytoplankton productivity; Abrantes 2000), there are questions over where these productivity spikes were located.

Consequently, Bradley and Stanford (2004) are correct in identifying that the strong atmospheric circulation of the LGM resulted in enhanced upwelling and marine productivity in the Atlantic (Abrantes 2000, Pailler and Bard 2002). What they fail to mention is that intense coastal upwelling systems are restricted to certain areas, specifically those in which shore-parallel winds move ocean water such that cold, nutrient-rich deep water is upwelled from beneath the main current body (Pickard and Emery 1990). On the European margin, the Portuguese coast rather than the Bay of Biscay experiences such systems, and in fact represents the northernmost limit of the North Atlantic upwelling system both now and during the LGM (Vautravers and Shackleton 2006). Unlike the Portuguese margin where northerly winds generate the upwelling, the Bay of Biscay was dominated by westerly winds at the LGM (Kageyama et al. 2006), even further reducing the possibility of a strong upwelling system developing here.

Looking at the other mechanisms, it is true that loess mobilization was more prevalent during cold, dry glacial periods (Lowe and Walker 1997), and may have played a role in enhancing productivity. However, the role of icebergs is more questionable. Although IRD deposition does increase mineral input into the oceans, a number of studies have correlated episodes of iceberg rafting or increased sea-ice extent during the Pleistocene with decreased productivity (e.g., Auffret et al. 1996, Pailler and Bard 2002). Firstly, the ice reduces the amount of light available for phytoplankton photosynthesis, in turn reducing primary productivity at the base of the food chain. Secondly, melting icebergs create a cold, low salinity "lid" on the surface of the ocean. This enhanced stratification inhibits the mixing of nutrients between different water layers, further reducing productivity. It should be noted that this mechanism seems to have been particularly apparent during Heinrich Event 1 in the 40–50°N latitudinal band (i.e., the same latitude as the Bay of Biscay; Nave et al. 2007). Thirdly, mineral input requires the icebergs to melt so as to release the IRD they carry and consequently increased productivity (if not offset by the aforementioned mechanisms) only occurred at certain times of the year, creating a highly seasonal system rather than overall heightened productivity levels. In short, the times of greatest ice, when a sea-ice based adaptation might be expected to develop, seem to have been some of the least productive.

The role of eroded seabed ooze during sea-level lowstands is a similarly questionable mechanism, since the delivery of sediment eroded from land is a feature that enhances coastal productivity during both low- and highstands. Why this process is regarded as being of greater importance during the LGM is unclear. If the crucial factor is taken to be the erosion of "seabed ooze" rather than terrestrial sediment, then it is worth considering the fact that it was more common for shelves to be exposed than submerged during the last glacial. Thus, maximum shelf inundation and deposition of "seabed ooze" occurred during Marine Isotope Stage 5e (≈125 cal ka BP). Subsequently, global sea-levels fell, staying below -40m for most of the next 100,000 years. From 50 cal ka BP on, sea-levels oscillated around the -80 to -90m mark before falling to the LGM lowstand of ≈120m by 27–26 cal ka BP (Peltier and Fairbanks 2006, Siddall et al. 2003). This pattern suggests that by the time of the Solutrean, much of the deposited ooze may have already been eroded out and replaced on the subaerial shelf by terrestrial sediment. Moreover, there is an additional complication concerning the role of continental shelves in generating productivity—namely the fact that they are the most productive parts of the marine ecosystem. Their shallow depth allows sunlight to reach the seabed, promoting the growth of productive marine plant communities, and also permitting waves and currents to suspend nutrients from the seabed and transport them to the photosynthetic zone. They also play an important role as nurseries for a number of pelagic species (Mann 2000). It might therefore be expected that the reduction of shallow subtidal shelf areas by sea-level fall led to decreased productivity, or at the very least offset some of the other hypothesized productivity-increasing mechanisms put forward by the Solutrean Atlantic Hypothesis.

Finally, regarding the third argument for high productivity, there is no doubt that the ice-edge is a productive environment. After all, areas under ice are light limited and hence experience reduced primary productivity levels (see above and Smetacek and Nicol 2005). Consequently, in Arctic environments, resources either cluster at the ice edge or in polynyas (open water spaces) (e.g., Henshaw 2003). What is less clear is whether this high productivity should be considered in a relative sense—i.e., the ice edges were more productive than the surrounding ice itself, but were they more productive than coastlines and inland areas? Additionally, whether or not this level of productivity was maintained across the Atlantic is another matter, largely due to the fact that the ocean is not a uniform environment. Simply put, the ice corridor had to cross the open ocean, an environment that tends to be characterized by lower productivity than coastal areas and continental shelves, on account of increased water depths inhibiting the suspension of seabed nutrients by waves and tides and the increased distance to coastal nutrient sources (e.g., rivers). Admittedly, the North Atlantic is characterized by a band of high productivity created by a spring/summer plankton bloom that is presently situated between 45–55°N. Nevertheless, we should note the fact that this bloom would have been initiated during or after the ice melt (especially considering the duration of LGM ice extents described in section 2) and may also have shifted over time. Villanueva et al. (2001), for example, suggest that band had moved south to 37°N during the period in question, in other words away from the hypothesized ice-edge. Together with the evidence for reduced areas of productive shallow shelf at times of low sea-level (see above), this strongly suggests that all but the very beginning and end of the hypothesized dispersal took place over low productivity deep water. In short, an assumption of a much more spatio-temporally dynamic system of productivity is no less valid than one of constant high productivity. Therefore, even if its starting point was characterized by a highly productive ecosystem, it is an open question whether the rest of the route was characterized by a corridor of similarly productive ecosystems. Without this incentive, it is more likely that sea-ice based hunters stayed in productive coastal waters rather than venturing across the less productive deep ocean.

Aside from issues of productivity, there is a final crucial point to examine in our consideration of the hypothetical dispersal route: its end point. In this case, the question is, once across the Atlantic bridge, what landscape would the migrants have faced and would it have induced them to stay or even return on successive voyages? After all, the colonization of the Americas and direct link between Clovis and the Solutrean would have required an incoming population to stay and expand. Assuming the dispersal followed the ice-edge, the landing point on North America was the perennial ice which existed off the eastern Canadian coast—more specifically off Newfoundland and Labrador—coincidentally the parts of North America closest to Europe, as Bradley and Stanford (2006) point out. During the LGM, the vast majority of this area was covered by the Laurentide ice sheet with the exception of fringing areas of ice-free continental shelf exposed by glacial forebulge uplift and lowered glacio-eustatic sea-levels, such as the Grand Banks southeast of Newfoundland (Fig. 1; Shaw et al. 2002). These however were spatially quite restricted as the ice sheet extended out to the shelf edge across most of eastern Canada. By 21 cal ka BP, it had begun to break up, and it was not until ≈19–17 cal ka BP (i.e., the end of the Solutrean) that areas of shelf were ice-free (Shaw et al. 2006). Indeed, Shaw (2005) explicitly points out that this view contrasts with the image of emergent shelves depicted by Bradley and Stanford (2004: Fig. 4). Moreover, during and immediately after deglaciation, exposed shelves may have been isostatically depressed by the former weight of ice, and therefore initially flooded as the ice retreated. At this time, the mainland (i.e., presently terrestrial areas) was also still under ice and unavailable for settlement by incoming populations. Effectively, any migrants would have either been restricted to small isolated areas of exposed low-lying shelf. Further, the environment of these exposed shelf areas is also uncertain. Were they glacial refugia, such as have been found on the Pacific Northwest coast, or did their low topography make them areas of polar desert swept by intensely cold winds coming off the Laurentide ice, and susceptible to the glacio-eustatic rise in sea-level that was beginning at that time (Peltier and Fairbanks 2006)? Either way they presented a quite different landscape from the Bay of Biscay where hundreds of kilometres of open unglaciated terrain with both coastal and inland resources were readily available.

Synthesis and Conclusion

The information above reveals a number of obstacles to the hypothesized migration, specifically concerning the mechanism of dispersal: movement along the edge of the sea-ice in the North Atlantic. These can be summarized as follows:

1. There was less sea-ice at the LGM than commonly believed, with large zones of the North Atlantic and, in particular, the Bay of Biscay experiencing less than 1–2 months of sea-ice per year on average. Thus, we question whether sufficient ice existed to permit the development of an intensively ice-based subsistence strategy or to allow hunters to travel all the way across the Atlantic within a single year.
2. The greatest ice extents of the Late Pleistocene took place at Heinrich Events 1 and 2. However, both events were characterized by low marine productivity, which in turn argues against a marine-based migration. Moreover, a migration during Heinrich 2 increases the time gap between Solutrean and Clovis assemblages to 10,000 years, while the Solutrean overlap with Heinrich 1 is minimal, i.e., very few Solutrean sites actually date to 17–18 cal ka BP.
3. The pattern of LGM ice cover raises the possibility that the annual ice melt pattern may not have been synchronous across the North Atlantic. More specifically, an ice-free channel in the central Atlantic may have expanded, splitting the ice-edge. If Solutrean hunters were indeed following it, they were more likely to move north than west across the Atlantic.
4. Dominant wind and current patterns were against the direction of dispersal. Although overcoming them was not impossible (i.e., by paddling or sailing), it would have increased the journey times making it less likely that any migrants would have reached the central Atlantic while the ice-edge there was intact.
5. Consistently high marine and ice-edge productivity should be regarded as a possibility not as a given. There is no doubt that marine resources existed in the Bay of Biscay and all along the exposed Atlantic margin. However, the main contention is that evidence for the level of productivity advocated by Bradley and Stanford (2004), particularly in deep ocean waters that characterized the vast majority of the hypothesized dispersal route, is simply not there. The well-documented dynamism of Late Pleistocene climate in conjunction with the sensitivity of a sea-ice based ecosystem is more likely to have resulted in much more variable productivity levels across both space and time. Although this can be argued to have been a driver for movement (i.e., migration in response to movement of prey), it can equally be regarded as a barrier (i.e., areas of low productivity inhibit dispersal).
6. Any migrants that made it across the hypothetical ice-edge corridor were confronted by a very different landscape to the one they had left, specifically one dominated by a continental ice sheet. This environment was a harsh and potentially unproductive landscape (certainly for the areas of exposed land), and we question whether there would have been any desire to stay.

On the whole, it should be clear from the above that the paleoceanographic and paleo-environmental evidence do not provide unequivocal support for the Solutrean ice-edge expansion into the Americas. In this instance, the lack of a corridor would imply that dispersal was impossible, or that the Solutreans were capable of deepwater, trans-oceanic voyages, without any terrestrial support. In conjunction with the lack of evidence for this capability and the archaeological critiques of this hypothesis (e.g., Straus et al. 2005), it seems unlikely that this dispersal event occurred.

Nevertheless, there remain two issues arising from Bradley and Stanford's (2004) hypothesis that are well worth bearing in mind. The first concerns the role of ice, which seems to be much neglected in discussions of Paleolithic society. After all, given the recurrent stadial and glacial episodes of the Pleistocene (Van Andel 2003), more sea-ice than present may well have been the norm rather than the exception. Considering that people were living in NW Europe since at least 700 ka (Parfitt et al. 2005), were in the High Arctic (≈70°N) by 30 cal ka BP (Pitulko et al. 2004) and Beringia by at least ≈14 cal ka BP (Bever 2001), it is highly likely that they encountered sea-ice on a regular basis. This then raises questions of whether it was used, and if so, how it was used and how past people adapted as it changed over time.

Secondly, the role of ice in facilitating movement should also not be ignored. Much of the discussion on the colonization of the Americas has described a coastal or maritime migration with little discussion of what this entails beyond the use of boats. However, ice could have been very important in relation to the more commonly hypothesized Beringian and Pacific Northwest route. Here the paleo-climate evidence supports the existence of significant volumes of sea-ice in the Sea of Okhotsk, Bering Sea and Gulf of Alaska between the LGM and Clovis (e.g., De Vernal and Pedersen 1997, Katsuki and Takahashi 2005, Kienast and McKay 2001, Sakamoto et al. 2006). It is conceivable that sea-ice based travel and subsistence was an important part of a coastal adaptation here, and indeed it could have provided the uniform megapatch-type environment that some consider a prerequisite to coastal migration. Note, for example, the recent suggestion that coastal migration along the Pacific coast of the Americas was aided by a "highway" of homogenous habitats created by ubiquitous and productive kelp forests (Erlandson et al. 2007). Further, it could have also allowed circumvention of the coastal ice sheets of southern Alaska and British Columbia, although in this instance, the ice should be seen as an extension of the coastline rather than a bridge spanning the ocean.

To conclude, it is clear from the paleoceanographic and paleo-environmental data that the LGM North Atlantic does not fit the descriptions provided by the proponents of the Solutrean Atlantic Hypothesis. Although ice use and sea mammal hunting may have been important in other contexts, in this instance, the conditions militate against an ice-edge-following, maritime-adapted European population reaching the Americas. The approach and data described in this paper are relevant not only in the specific case, but also on a wider scale. For paleo-coastal societies, the nature of the offshore environment is as important as the onshore; hence, knowledge of the state of the oceans is critical to our archaeological understanding. This fact is particularly significant given that archaeological work has been consistently pushing the onset of coastal/marine resource use back into the Pleistocene (e.g., Marean et al. 2007), a period characterized by ever-increasing quantities and resolution of paleo-environmental data that show an array of environmental changes, often of large magnitude, operating both on land and at sea. Archaeologists should therefore be prepared to engage as much with the paleo-environmental and paleoceanographic records as with more conventional archaeological data. This conclusion does not necessarily mean that they should independently collect or generate the relevant data, but rather should be aware of its existence, be able to understand and integrate that information with the archaeological record in an effort to attain a more balanced view of prehistory.

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