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The Heinrich and Dansgaard-Oeschger climatic events during Marine Isotopic Stage 3: Searching for appropriate times for human colonization of the Americas

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ABSTRACT

Marine Isotope Stage 3 (MIS 3) was an interstadial stage, a relatively warm climatic period which developed roughly between 60 and 50 and 30 cal. ka BP. Several very cold periods, known as Heinrich (H) events, developed during MIS 3 as a result of partial collapse of the North American ice sheet margins, with formation of huge amounts of icebergs which, after melting in more temperate latitudes, would have inundated the North Atlantic Ocean with low salinity waters which would have impeded the reach of the Gulf Stream into the North Atlantic Ocean. Several paleoclimatic moments with relatively warmer conditions, known as the Dansgaard-Oeschger (D-O) events, took place in between the Heinrich (H) events, throughout MIS 3. These H and D-O cycles would have been very short (perhaps even only around 1 ky each in some cases) and intense, with mean annual temperatures in the area of Beringia ca. 5–8 C° higher than those active at the Last Glacial Maximum (LGM; ca. 24 cal. ka B.P.) and perhaps close to those occurring in past interglacial periods, respectively. Even though climate was warmer, total melting of the continental ice sheets did not take place; thus, global sea level was perhaps still low enough to allow the persistence of the Beringia land bridge between Siberia and North America, without any interruptions throughout the entire MIS 3. The aims of this paper are to present paleoclimatic and paleogeographic information about MIS 3 and to discuss the most favorable chronology for human displacement through Beringia. At the times of MIS 3, there would have been no coalescence between the Laurentide and Cordilleran ice sheets; thus, both the hinterland path from Beringia southwards and the coastal route would have been open and enjoying moderate climate ecosystems, and thus available for humans. In this case, it is now possible to suggest possible moments for human penetration in North America, sometime between ca. 60–50 to 28 cal. ka B.P, during one or more D-O events (most likely sometime between the D-O 16 and D-O 3 events) throughout MIS 3. Other routes of human colonization of the Americas following other routes rather than that of Siberia-Beringia, if they ever existed, are not discussed in this paper.

1. Introduction

Middle and Late Pleistocene paleoclimates are characterized by climatic cycles that include glacial (colder) and interglacial (warmer) stages, with a total duration of ca. 100 kiloyears (ky) each. The colder glacial periods, around 80–90 ky duration, are longer than the interglacial ones, which are shorter and warmer, averaging 10–20 ky. Glacial periods show significant paleoclimate variations, with colder events which are called “stadials” and warmer periods named as “interstadials”. Full glacial conditions concerning both very low global temperatures and sea level stands are achieved only during stadials. Interstadials are characterized by warmer temperatures than those during the stadials, recession of the continental ice sheets (but not total vanishing), and rising sea levels to intermediate positions in between full glacial and interglacial times. These cycles are very well exposed by the relative content of ^{18}O isotopes ($\partial^{18}O$), or other proxy elements or substances contained in ice from polar ice cores, such as those in Greenland and Antarctica, as well as the variations of the same isotopes in foraminifera and/or ostracoda found in marine sedimentary cores (for explanation of the $\partial^{18}O$ method, see Andrews, 2000; Wright, 2000). In Fig. 1, the $\partial^{18}O$ variations during the last glacial–interglacial cycle are depicted, starting with the final phases of the last interglacial. Isotope peaks pointing upwards correspond to warmer periods, whereas those pointing downwards are colder events.

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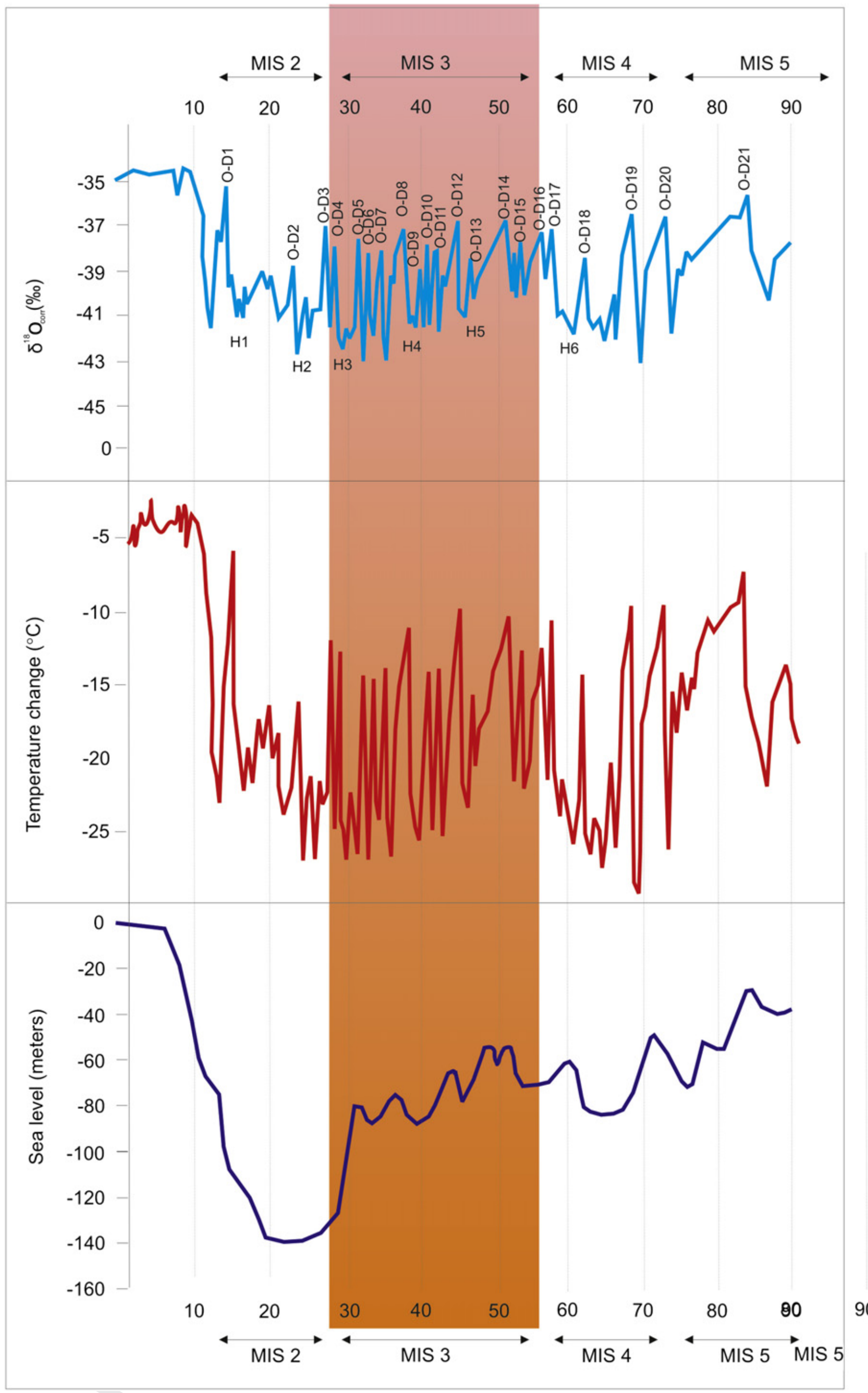

Fig. 1. Upper: ∂^{18}O contents in Greenland for MIS 5 to MIS 2 following Uriarte Cantolla (2003); middle: strong climatic variations in Greenland of up to 16 °C for MIS 5 to MIS 2 (in mean annual temperature; IPCC, 2007), lower: global sea level curve, in meters, according to Lambeck and Chappell (2001). The shaded area corresponds approximately to the actual extent of MIS 3.

The periods showing a specific trend of ∂^{18}O content are called “marine isotope stages” (MIS), and they correspond to moments with distinct global temperatures and climates. MIS 5 is the last full interglacial period and MIS 1 is the present interglacial. MIS 4 and 2 are colder, stadial events, the earlier corresponding to the process of building up of the continental ice sheets, and the latter representing the maximum of the Last Glaciation (LGM, ca. 24 cal. ka B.P.) and extending until the end of the Pleistocene (10 ^{14}C ka B.P.). MIS 3 corresponds to a long interstadial epoch which was much warmer than the following stadial period or LGM. MIS 3 lasted at least 25 ky, between approximately 60–50 and 30 cal. ka B.P.

2. The climate of North America, Beringia, and the North Atlantic Ocean during MIS 3: Heinrich and Dansgaard-Oeschger events

The region of Beringia, considered as the most probable pathway for human colonization of the Americas, is the object of

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study in this paper. This is the area comprised by the Bering Straits and the adjacent continental and submarine platform portions of both NW North America and NE Asia (Fig. 2). The paleogeography of Beringia in selected moments during the Late Pleistocene is presented in Fig. 3. The paleoclimates inferred for Beringia during the Late Pleistocene are discussed below.

During MIS 3, the North American and European ice caps receded from their outer positions achieved in MIS 4, and extensive portions of the landscape were abandoned by the ice; sea level stood between 55 and 90 m below present sea level (Fig. 3B and C; see Lambeck and Chappell, 2001), only half to three quarters of the maximum sea level depression during MIS 2. As the ice was then receding in the Northern Hemisphere, the Gulf Current was able to penetrate to higher latitudes, bringing warmer and moister air to the North Atlantic Ocean, favoring the temporary restoration of milder climates and more temperate environments (Uriarte Cantolla, 2003).

However, climate was neither stable nor homogeneous during MIS 3. Very strong, intense, and fast climatic changes took place during this period, indicated by significant $\partial^{18}O$ variations. MIS 3 was a period of moderate insolation that is in sharp contrast with the insolation troughs of MIS 4 and MIS 2 (Andrews and Dyke, 2007). Very cold periods designated as Heinrich (H) events alternated with much warmer and moister periods called as Dansgaard-Oeschger (D-O) events, in both cases named after important glaciologists of the last quarter of the 20th century (Heinrich, 1988; Uriarte Cantolla, 2003; Labeyrie et al., 2007).

During the Last Glaciation, there were at least six paleoclimatic episodes in which large amounts of glacial debris were ice-rafted and deposited at the bottom of the ocean in an area between 40° N and 55° N. The thickness of the resulting bottom sediments diminishes from west to east, and the dominant lithology types are those coming from North America and the Hudson Bay (Heinrich, 1988). Some of the icebergs reached up to 3000 km from their place of origin. The most appropriate explanatory theory is that the North American ice sheets outgrew their stable boundaries during certain moments of the Last Glaciation, reaching the outer edges of the continental shelves where they became unstable and collapsed, throwing huge amounts of icebergs into the North Atlantic Ocean. The high iceberg discharge would have interrupted the thermohaline circulation in the North Atlantic (Denton, 2000). Other opinions suggest that the ice collapse was forced by subglacial melting due to ground heat trapped under the huge ice sheets (between 2 and 3 km thick), or even that the enormous pressure of the ice sheet during maximum expansion triggered local earthquakes (Uriarte Cantolla, 2003).

The exceptional abundance of fresh water due to iceberg melting would have forced changes in the North Atlantic deep water production and limited the northernmost reach of the Gulf Stream, allowing the southward displacement of polar waters and subsequent temperature lowering (Bard et al., 2000). Once the iceberg discharge was completed, the size of the glaciers discharging along the North American coasts dramatically diminished, lowering also the supply of fresh water to the Northern Atlantic Ocean; thus, the Gulf Stream was reestablished. Therefore, a sharp increase in middle-to-high latitude temperatures took place, leading into a warm interstadial stage. These are known as the Dansgaard-Oeschger (D-O) events, in which mean annual temperature would have risen between 5 °C and 8 °C, perhaps during only a century or even less. Usually, D-O events are characterized by a rapid warming up to ca. 3–5 °C per century (Labeyrie et al., 2007). Moreover, during the D-O 19 event, around 70 ka ago, in MIS 4, the rise of temperature would have been up to 16 °C (Lang et al., 1999; Uriarte Cantolla, 2003).

During these warm events, a much larger evaporation rate and atmospheric moisture export from the Atlantic Ocean to the Pacific Ocean, across Middle America, would have taken place. These events would have forced an increase in the Atlantic Ocean salinity, and therefore a reinforcement of the thermohaline circulation and the Gulf Stream, which would have warmed the whole of the northern Atlantic, including Greenland (Peterson et al., 2000), heating very rapidly the atmosphere of the Northern Hemisphere,

Fig. 2. Beringia, location map.

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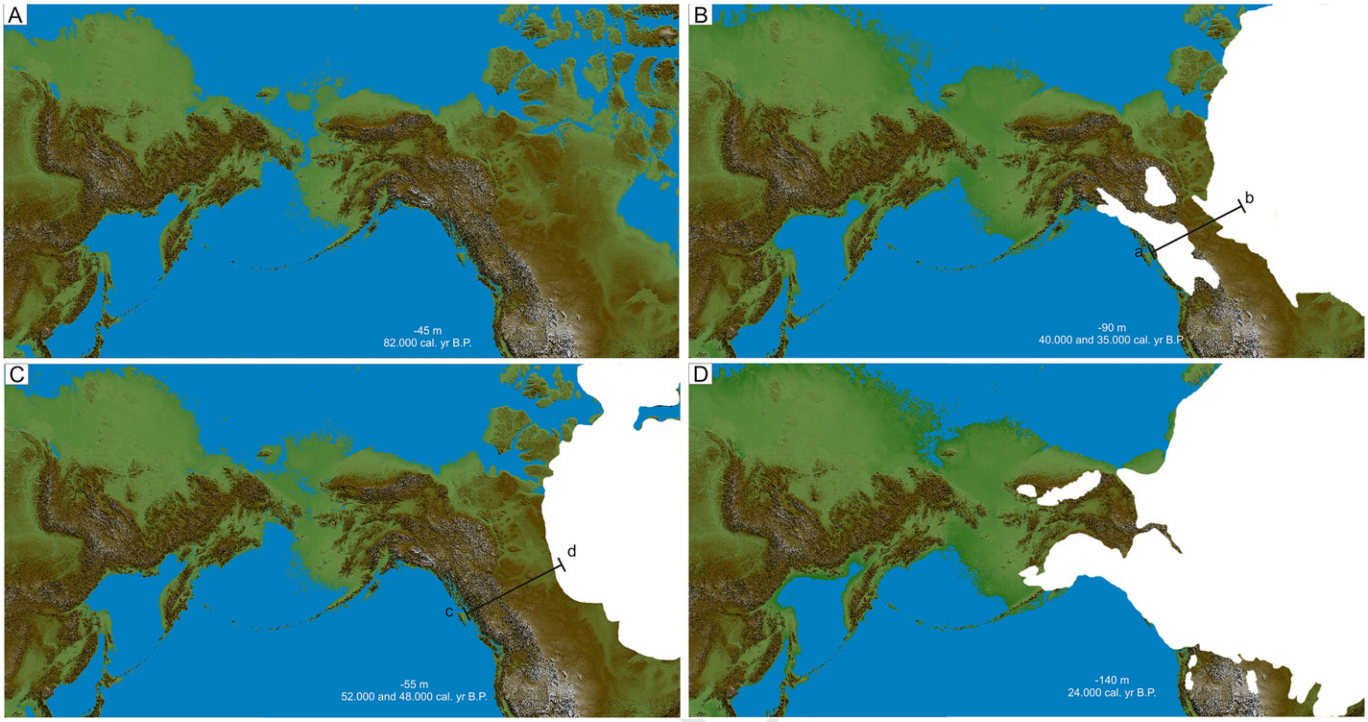

Fig. 3. (A) to (D): Paleogeography of Beringia, with ancient positions of the coastline for lower sea levels during different moments of the Late Pleistocene. Sea level information from Lambeck and Chappell (2001). Whitish areas correspond to the actual extent of the Laurentide and the Cordilleran ice sheets for the studied moments.

but without pushing a sudden rise in sea level because of their short duration. For instance, MIS 3 warm events in Greenland had rapid (even less than 1 ky) changes of up to 15 °C between peaking H and D-O subsequent episodes (Fig. 1; see Labeyrie et al., 2007, for a detailed discussion). It is of high interest to note that there are clear paleoclimatic signals about the H and D-O events both in high and low latitudes, and in both the North Atlantic and North Pacific oceans at almost identical times (Labeyrie et al., 2007).

Sea-surface temperature (SST) during the D-O events was at least 4 °C–6 °C higher than those of the LGM (ca. 24 cal. ka B.P.), suggesting that terrestrial temperatures were higher as well, indicating that mean annual temperature during these events was perhaps slightly colder than present conditions, but much warmer than full glacial conditions. This circumstance would have allowed the development of temperate forest and prairie environments in Beringia, in addition to or perhaps even replacing the usual tundra scenarios.

Six major Heinrich (H) events have been identified in MIS 2, MIS 3 and MIS 4, at approximately 17, 22, 29, 39, 45 and 61 cal. ka B.P., H1 being the younger episode and H6 the older one. H2 corresponds to the LGM. Likewise, at least 14 Dansgaard-Oeschger (D-O) events have been detected in the ∂^{18}O curves, roughly at ca. 14, 23, 27, 29, 32, 33.5, 34, 38, 40, 41, 43, 45, 47, and 52 cal. ka B.P.; not all of them were of identical magnitude, but they were clearly warmer than the LGM in all cases (Table 1). As with Heinrich events, D-O 1 is the youngest event. The total length of each H or D-O events during MIS 3 is variable, but each whole cycle was probably around 1–2 ky long in average. The longer and more intense are the D-O 8, 12 and 14 events, at ca. 38, 45 and 52 cal. ka B.P., respectively. However, violent secular transitions between events, of not more than 1–2 centuries long, have been quantified in the ∂^{18}O curves. A detailed record of these variations during the last part of MIS 3, between 30 and 46 cal. ka B.P. is presented in Fig. 4. Particularly, Vidal et al. (1999) have found two very warm D-O events at ca. 43 and 33 cal ka B.P., which would be triggered following H5 and H4 episodes, respectively. This figure illustrates the paleoclimatic and paleoenvironmental conditions both in Greenland and Antarctica, proving the global and possibly synchronous impact of these climatic changes. There are diverging opinions about such synchronicity (see, for instance, White and Steig, 1998; Vidal et al., 1999; Blunier and Brook, 2001), but this is not a matter of discussion here. Isotopic data from caves in China as well as Greenland paleotemperatures for MIS 3 (Alley, 2004) confirmed the regional impact of the MIS 3 climatic changes, both in temperature and precipitation in such areas which are geographically related to Beringia.

Table 1
List of Dansgaard-Oeschger events during MIS 3, with the relative position of sea level corresponding to each event. Chronology and sea level data from the literature cited in the text.

Dansgaard-Oeschger (D-O) events	Age (cal. ka B.P.)	Sea level position (m below present sea level)
2	23.5	−140
3	27	−135
4	29	−128
5	31	−80
6	33.5	−87
7	34	−85
8	38	−78
9	40	−88
10	41	−85
11	43	−80
12	45	−65
13	47	−72
14	52	−55

The palynological record for MIS 3 in NE Siberia shows that in the northern lowlands tundra predominated, under moderately warm environmental conditions (Lozhkin and Anderson, 2007), probably together with isolated larch-birch tree communities. Based on pollen records, MIS 3 is represented in Siberia by the

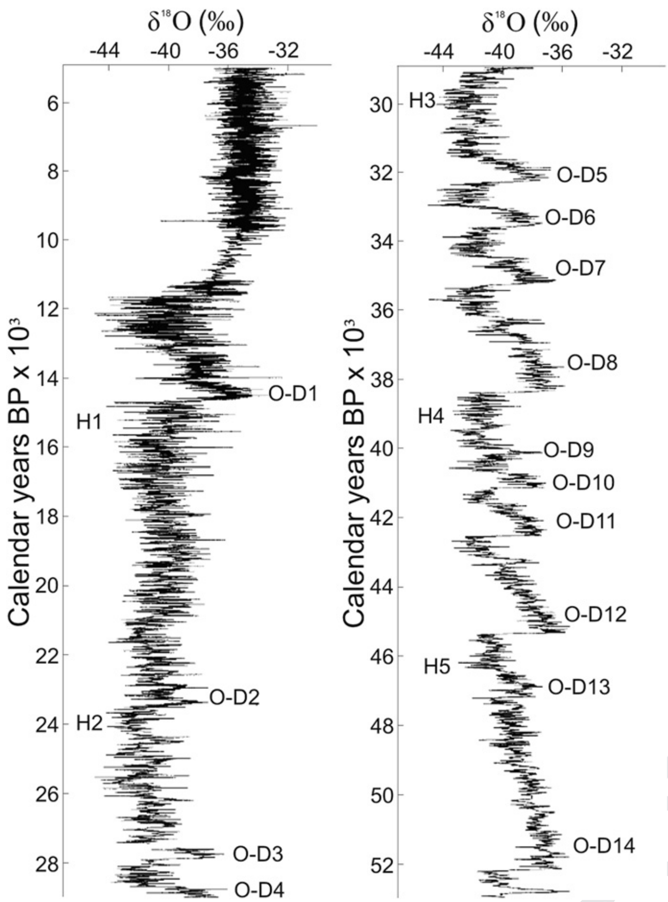

Fig. 4. Abrupt climatic oscillations during the last 90,000 years in GIPS II core from Greenland (after Denton, 2000). H 1 to H 5 represents the cold Heinrich events. O-D 1 to O-D 14 corresponds to the Dansgaard-Oeschger warm events.

Karginski interstadial, which is separated into five environmental phases, as follows: ca. 50–45 ka B.P., warmer; ca. 45–43 ka B.P., cooler; ca. 43–33 ka B.P., maximum warmth, the so-called Malokhetski sub-horizon; ca. 33–30 ka B.P., cooler, the Konotzelski sub-horizon; and ca. 30–22 ka B.P., warmer, the Lipovskoy-Novoselovski sub-horizon (Lozhkin and Anderson, 2007). Likewise, in northwestern North America, pollen records dating to MIS 3, between ca. 60–30 ka B.P., indicate widespread tundra across Alaska, perhaps with minor amounts of spruce in interior Alaska and Yukon (Bigelow, 2007). In western Alaska, MIS 3 was characterized by grass, sedge, and *Artemisia*, with minor amounts of willow and birch. In the Yukon, spruce pollen frequencies of less than 20% suggest the existence of scattered trees within widely extended birch/graminoid tundra (Bigelow, 2007).

Similarly, paleoentomological studies in NW North America and NE Siberia have shown that climate was much milder during MIS 3 than during the LGM. Elias (2007) identified a “long MIS 3 interstadial complex in eastern Beringia”, with warming intervals at 46.4, 36, and 33.6 ka B.P. The latter one is known from the Totaluk River beetle fauna, with an association indicating that the maximum temperature during this event was between 0.5 and 2.0 C° warmer than present. Other sites have indicated maximum temperatures only between 0.5 and 2.0 C° cooler than today. However, there are also faunas suggesting much cooler conditions, up to 7.0–8.0 C° cooler than present, proving the existence of dramatic temperature oscillations in this period. The identified beetle faunas are characterized by species which correspond to open-ground habitats, not necessarily occupied by trees. The open-ground or steppe tundra environments were maintained throughout MIS 3. Elias (2007) stated that, for this area, MIS 3 “oscillations coincide with climatic patterns inferred from oxygen isotope records in Greenland ice cores”.

Elias and Brigham-Grette (2007) have identified substantial differences between western and eastern Beringia during MIS 3, dated between 48 and 28 ka B.P. In western Beringia, temperatures reached near present-day levels and the forest migrated northwards near its present position. Contrarily, in eastern Beringia there is little evidence of coniferous forest expansion during MIS 3. The Arctic regions reached temperatures perhaps up to 1.5 C° above present times at ca. 35 ka B.P., whereas in Sub-arctic environments, temperature was ~2 C° below today’s conditions at the same time (Elias and Brigham-Grette, 2007). In any case, the environmental conditions were not too different from those found today, and the region would have been fully accessible for humans during MIS 3. Finally, the transition between MIS 3 to MIS 2 in eastern Beringia, from interstadial to full glacial conditions, has been dated in ca. 32–31 ka B.P.

Likewise, Sher and Kuzmina (2007) found, for the 35–40 ka B.P. period in northeastern Asia, beetle associations with a high percentage of arboreal, mostly shrub, pollen, in contrast to the completely grass-herb dominated spectra of the LGM. Though they acknowledged the possibility of radiocarbon dating problems, they identified xerophilic beetle species for the 48–34 ^{14}C ka B.P. period; then, an increase of Arctic species by 34 ^{14}C ka B.P., almost equating the LGM levels; and again xerophilic beetles with mesic tundra insects between 34 and 24 ^{14}C ka B.P. After this age, the beetle species indicated a gradual decrease in temperature towards the LGM. They also stated that the regional climate was much more continental during MIS 3 times than it is today, a condition which they assigned to a lower sea level (Table 1).

The vertebrate record of the Late Pleistocene in northern Asia shows evidence of faunas of a warm interval called the Briansk or Dunaevo interstadial, dated between 33 and 24 ka B.P., the last of a series of warm episodes along MIS 3 (Markova and Puzachenko, 2007). The faunas characteristic of Beringia for this period are included in the Arctic sub-assemblage of the Mammoth I assemblage, with woolly mammoth, woolly rhinoceros, reindeer, Pleistocene bison, horse, rare saiga, arctic fox, cave hyena, cave bear, steppe pika, arctic hare, several lemming species, and voles. No forest animals are found in this assemblage (Markova and Puzachenko, 2007). The distribution and composition of this assemblage shows differences with present faunas, indicating a climate cooler than today; but this faunal association became later severely restricted in surficial terms during the LGM epoch. The abundance of large Pleistocene herbivores and cave carnivores during MIS 3 also depicts the large variations from today’s faunas (Markova and Puzachenko, 2007).

Relevant to the topics developed in the present paper, careful analysis of recently published glacial geological evidence in northern and northeastern Asia and northwestern North America is also pointing towards very warm conditions during MIS 3. Andrews and Dyke (2007) established that very soon after the MIS 4/MIS 3 transition rising insolation forced the retreat of the Laurentide Ice Sheet from the western Canadian lowlands, a condition that probably lasted for more than ca. 30–40 years, until the end of MIS 3, allowing the availability of the Yukon corridor for human displacements. Velichko et al. (2011) have identified a warm period during the Late Pleistocene in NE Europe which they named as the Middle Valdai. During this period, the ice had receded as far north as at least 68° N, with milder climates and temperate environments such as mixed forest of conifers and broad-leaved trees and southern taiga along the Arctic coasts around 38–40 ka B.P. They have called this period as a “megainterstadial” or the “Leningrad or

Bryansk megainterval", with alternating warm and cool phases, rhythmic climate changes, and a main warm phase between 40 and 34 ka B.P., with environmental conditions quite close to that of Mulikino, the last interglacial or MIS 5e. They consider this period as "a short interglacial", extending over D-O 10 and 12 events, with a new warm pulse in the Dunaevo warming episode, dated at 31–25 ka B.P., the terminal phase of MIS 3.

Likewise, Vorren et al. (2011) have shown that the ice sheet of Northern Siberia was restricted only to the Kara Sea and Novaja Zemlya islands between 55 and 45 ka B.P., and that the Barents Sea was mostly ice free between 48 and 26 ka B.P. Moller et al. (2011) determined that there was no ice on the Taymir Peninsula and the Severnaya Zemlya island between 50 and 25 ka B.P. In NE Asia, sedimentology studies have shown that no major changes in the environment had occurred between 60 and 12 ka B.P., with a mosaic of arctic tundra and tundra-steppe communities dominating during the Karginsky interstadial (MIS 3) and the Sartan ice age (MIS 2) (Glushkova, 2011). According to this author, climate was continental, with summer not colder than today but with colder winters. Glaciation was restricted to the mountain cirques during MIS 3, and much more reduced than during previous glaciations as well as in MIS 2. In contrast to the viewpoint of previous researchers, glaciers during the LGM were located then only in a few regions of the highest mountains. Therefore, it may be deduced that there were no physical restrictions to human displacement towards Beringia and Alaska during both cited isotope stages.

In the Verkhoyansk Mountains, an important orographic barrier across easternmost Siberia, the youngest proven glaciations dated back to ca. 50 ka B.P., and no LGM glaciations have been identified. East of this mountain range, restricted MIS 2 glaciation has been found, this being explained as a result of atmospheric paleo-circulation and differential moisture availability (Stauch and Lehmkuhl, 2011). It should then be noted that there were no ice barriers here for human displacement during MIS 3 and 2. It is also interesting to note that, similarly, there were no glaciers in the Central Alaska lowlands throughout the entire Late Pleistocene (Kaufman et al., 2011). Glaciation in the high mountains of easternmost Siberia, including the Chukchi Uplands of Beringia (Sheinkman, 2011), was characterized by expansion of the glaciers between late MIS 5 and MIS 4, and significant retreat during MIS 3, with a short ice advance ca. 45–40 ka B.P. and a major readvance of the ice in MIS 2.

In northwestern North America, Clague and Ward (2011) presented a model of glaciation of British Columbia with glaciers limited to the summits and uppermost valleys for the 35–30 ka B.P. period, and full glacial conditions and closing of the Yukon corridor only ca. 25 ka B.P. A "non-glacial Olympia interval" is described for the 50–25 ka B.P. period, correlated with MIS 3. Thus, this information confirms that the Yukon corridor would have been available for humans entering from Beringia during a very long period before 25 ka B.P. In western Alberta, Jackson et al. (2011) have described non-glacial, fossil bearing sediments dated between 39 and 24 ka B.P., and correlated them to MIS 3, of clearly interglacial nature. In eastern Alberta, Barendregt (2011) mentioned "mid-Wisconsin interglacial sediments", well dated between 65 and 23 ka B.P., also corresponding to MIS 3. Much farther south, the paleoclimate pattern is similar. Gillespie and Clark (2011) have identified very intense D-O events as far south as the Sierra Nevada of California, from D-O 8 (ca. 41–40 ka B.P.) to D-O 4 (31 ka B.P.), with intermediate warm episodes as D-O 7, 6 and 5, at ca. 36, 35 and 34 ka B.P., respectively.

3. Paleogeography of Beringia during MIS 3

For our analyses, we used GLOBAL MAPPER 10 software (http://www.globalmapper.com) for the elaboration of a digital model of sea level variations, taking into consideration the curve of global sea level rise since 140,000 yr B.P. as proposed by Lambeck and Chappell (2001). Following Elias and Brigham-Grette (2007), by mapping the −120 m contour line it is possible to reconstruct the land distribution in Beringia for full glacial times. The digital land elevation models of the Shuttle Radar Topography Mission (SRTM), W180N90.BATHYMETRY.SRTM, W140N90.BATHYMETRY.SRTM, and E140N90.BATHYMETRY.SRTM, with a 1 × 1 km resolution pixel, were analyzed. With these tools, several successive palaeogeographical maps were drawn, showing the position of sea level at different times. The approximate timing for each of these sea level positions was obtained by means of the Lambeck and Chappell (2001) and Lambeck et al. (2002) curves, and the indicated calibrated ages follow their data. The model was then superimposed to the maps of the North American deglaciation, presented by Dyke (2004). These maps were then geo-referred manually so as to allow the analysis using GLOBAL MAPPER 10. The radiocarbon ages were converted to calendar years BP using the program CALIB 6.0 (Stuiver et al., 2005) (see Table 2).

Table 2
List of radiocarbon and calibrated ages of some the oldest archaeological sites of South America.

Localities/sities	^{14}C ka B.P.	cal. ka B.P.	Reference	Location
Arroyo Seco (Argentina)	12–10	14–11.5	Politis et al. (2009)	
Monte Verde (Chile)	12.8–11.9	15.3–13.8	Dillehay (1997)	
Piedra Museo (Argentina)	12.9–11	15.6–12.9	Miotti et al. (1999, 2003)	

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Table 2 (*continued*)

Localities/sities	^{14}C ka B.P.	cal. ka B.P.	Reference	Location
Cueva Fell (Chile)	11	12.9	Borrero (1999)	
Tres Arroyos, Tierra del Fuego (Chile)	11.8	13.9	Massone (1987, 2003)	
Cerro Tres Tetas (Argentina)	11.5	13.4	Paunero (2003)	
Cueva Casa del Minero (Argentina)	11	12.9	Paunero (2003)	
Cueva Tixi; Abrigo Los Pinos; Amalia Sitio 2 (Argentina)	10.3; 10.4; 10.4	12.2; 12.4; 12.4	Mazzanti et al. (2011)	
La China 1; La China 2; La China 3; El Sombrero (Argentina)	10.8; 11.5; 10.6, 10.7;	12.7; 13; 12.4; 12.7	Flegenheimer and Mazzia (2011)	
El Trébol (Argentina)	10	11.5	Hajduk (1998)	
Santa Elina (Brazil)	27–10.1	31.7–11.6	Vialou (2003)	
Paiján (Perú)	10.8–8.5	12.7–9.4	Dillehay et al. (2003)	
San Isidro (Colombia)	9.5–10	10.8–11.6	Gnecco (2003)	

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Table 2 (*continued*)

Localities/sities	^{14}C ka B.P.	cal. ka B.P.	Reference	Location
Pedra Pintada (Brazil)	11.1–10.8	13–12.7	Roosevelt et al. (2002)	
Taima-taima (Venezuela)	ca. 13.0 (several dates)	ca. 15.6	Gruhn and Bryan (1984); Bryan et al. (1978); Gruhn (2005)	

Sea level during the Late Pleistocene is one of the key questions concerning human population of the Americas, since the availability of a terrestrial path across Beringia allowed the eastwards displacement of Siberian humans into the new continent. The position of sea level during MIS 3 is crucial to understand that the Beringia land-bridge was available for humans not only during the LGM but during many thousands of years before as well. The sea level curves by Lambeck and Chappell (2001) and Lambeck et al. (2002) are clearly indicating which would have been the position of the coastline during different times of MIS 3. Lambeck et al. (2002) estimated that, using data from Papua-New Guinea and Australia, sea level was never below −50 m between 50 and 30 cal. ka B.P., thus fully supporting the paleogeographic reconstructions presented in this paper.

The last closure of the Bering Straits started at around 82 cal. ka B.P., when sea level lowered 45 m below its present position. The straits remained closed continuously until 11.5 cal. ka B.P. González (2007), when describing what she called the "Pre-Clovis-Early Entry Model", mentioned that "it is known that this land bridge existed from 25 to 10 ka ago". In fact, the figures presented here show that the closure period was much more long lived: perhaps up to 70 ky. During the closure period, a very large plain emerged along the western Alaskan coast (Fig. 3A). The surface of this plain between the Newenham Cape in the S (N 58° 44′ 12.46″ and W 162° 17′ 0.02″) and Hope Point at the N (N 68° 22′ 14.52″ and W 166° 40′ 13.18″) was of at least 268,000 km^2. This ancient, emerged plain included the present Kotzebue Sound and Norton Sound (Fig. 2) and extended westwards comprising the present St. Lawrence Island (Figs. 2 and 3A). Along the E coast of Siberia, a smaller plain emerged during this period, with about 13,000 km^2. Following this paleogeographical model, a large number of small islands would have evolved during these times along the present Bering Straits. None of these islands would have exceeded 200 km^2 in surface. At an approximate distance of 100 km NW from the present Alaskan coast, a very large island would have developed. This paleo-island, of at least 19,800 km^2 in surface, was located around 72 km eastwards from the then more extensive Wrangell island, which at that time had a surface around 14,000 km^2, that is, twice its present area.

During most of MIS 3 (between 55 and 30 cal ka B.P.), sea level oscillated between a maximum elevation of −55 m (between 48,000 and 52,000 cal. B.P., which would roughly correspond to the D-O 14 event) and a minimum stand at −90 m (at around 32,000 and 40,000 cal. B.P., approximately, in coincidence with the H3 and H4 events).

During its lowermost position, an enormous plain connected both continents (Fig. 3B). Southwards, this plain would include the present Pribilof Islands and, towards the north, the present Wrangell Island (Fig. 2). Towards the NE, the plain would follow the northern coast of Alaska and parts of Canada, with a mean width of at least 80 km; it extended continuously until approximately longitude 128° W. Towards the NW, the plain formed a narrow wedge at the latitude of Wrangell Island (Fig. 2), to later on become in contact with another huge plain developed in northern Russia. This plain presented an enormous surface of approximately 1,200,000 km^2 between longitude W 180° and W 156°. It presented an extension as large as 1,800 km in N–S direction at the longitude of the Bering Straits. Its relief was mostly flat, and the general slope was smaller than 0.2°, with a maximum local relief in the order of 60 m between its northern and southern extremes. According to the Lambeck and Chappell (2001) sea level curve, which relates sea level with ice volume on the continents, a sea level position at −90 m would be equivalent to the ice volume that existed around 13,000 cal. B.P.

Dyke (2004) identified the existence of two main ice-sheets in northern North America by 13 cal. ka B.P., the Cordilleran mountain ice sheet, developed on top of the Rocky Mountains and the Pacific Ranges, and the Laurentide Ice Sheet, of much larger size, extended over most of Canada and the whole of Greenland (Figs. 3B and 5a). This latter ice sheet had an approximate surface of 11 million km^2. In between them, there was an ice-free corridor which communicated Alaska with the rest of the continent (Fig. 3B). It had an approximate length of 1400 km in a NW–SE direction and a width which varied between 400 and 700 km (Fig. 5a). Immediately to the west of this corridor, another smaller ice sheet had developed over the Mackenzie Mountains. This situation would have represented the maximum ice extension during MIS 3, which would have been coincident with a sea level position of −90 m.

The highest sea level position during MIS 3 was perhaps at −55 m. This condition took place in two periods, towards 52 and 48 ka B.P. and it is coincident with one of the warmest D-O oscillations (D-O event 14; Table 1) and with the smallest ice expansion during MIS 3. During these events, the emerged surface along the present Bering Straits between longitude W 180° and W 156° was about 845,000 km^2 (Fig. 3C). This plain, at the present position of the Bering Straits, had a minimum length of about 1500 km in N–S direction. The present Wrangell Island was separated from the rest of the continent by a rather narrow strait with a varying width between 32 and 112 km (Fig. 3C). This island presented at that time an emerged surface of around 26,000 km^2. According to Lambeck and Chappell (2001), a sea level position of about −55 m would be equivalent to a continental ice cover similar to that developed around 11 cal. ka B.P. According to the deglaciation model for North America developed by Dyke (2004), there was already only one ice sheet remaining towards 11 cal. ka B.P. which was located in Eastern Canada (Figs. 3C and 5b), covering an area close to 7,800,000 km^2 (almost 80% of the present total Canadian surface).

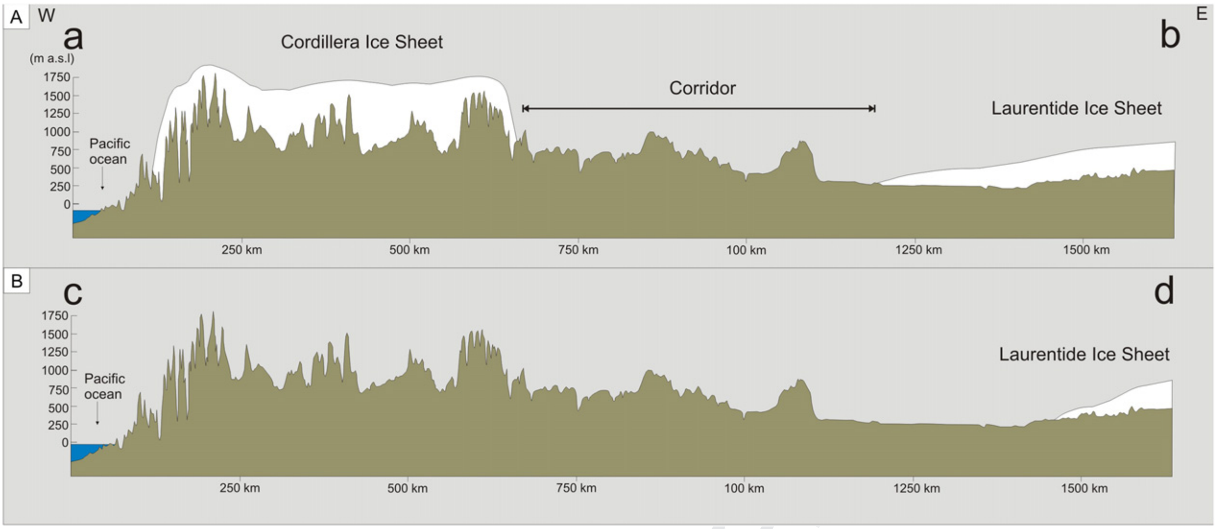

Fig. 5. Topographic profiles from SRTM images using GLOBAL MAPPER 10 program, as indicated in Fig. 3.

The geographical conditions of Beringia determined that the area lowlands were permanently devoid of ice during the Late Pleistocene; in spite of being cold enough, the land bridge was too dry to arid polar conditions to develop glaciers at low elevations (Elias and Brigham-Grette, 2007). The absence of lowland glaciers allowed the availability of the land bridge for human displacement throughout MIS 3 and 2.

4. Discussion: the "Clovis First" model and alternative hypothèses

The "Clovis First" model assumes that the culture to which such name was given was brought to the American continent by those humans who were forming the first migratory wave coming from Siberia. Other possible routes of human colonization of the Americas (from Africa and/or Europe; see Politis et al., 2009), even if they actually existed, are not discussed in this paper.

All human groups of the American continent would be descendant from those peoples, occupying all environments and all geographical conditions. The Clovis culture has been closely studied in North America, and its chronology has been clearly established at 11.5/10.9 ^{14}C ka B.P. (12.9/12.55 cal. ka B.P.), though Waters and Stafford (2007) calculated it between 11.2 and 10.8 ^{14}C ka B.P. See an excellent summary in Politis et al. (2009).

The penetration of these groups from Beringia would have been along the Yukon Corridor, in between the two major ice-sheets, the Laurentide Ice Sheet and the Cordilleran Ice Sheet (Figs. 3B and 5a), once they separated after having been coalescent during the LGM. Alternatively, it has been suggested that the colonization took place following the Pacific coastal route, or even both of them (Gruhn, 1994; Bryan and Gruhn, 2000, among other papers).

There are many important sites in North America in which human occupation has been claimed to be of pre-Clovis age: Meadowcroft, Pennsylvania (Adovasio et al., 1999); Cactus Hill, Virginia (McAvoy and McAvoy, 1997), Topper Site, South Carolina (Goodyear, 1999), among many others. Human coprolites have been dated at >1000 yr before the accepted Clovis age in Oregon, U.S.A. (Gilbert et al., 2008). While this manuscript was being prepared, Waters et al. (2011) presented new information about Buttermilk Creek, an outstanding archaeological site in Texas, where over 15,000 pre-Clovis artifacts have been excavated from layers dating in between ca. 13,200 and 15,500 years old, making this site the best evidence today for pre-Clovis groups in North America. Besides, both a news article and a popular, comprehensive review about this site and its implications for the peopling of the Americas should be taken into consideration (Pringle, 2011a,b).

The radiocarbon chronology for South American oldest human groups shows that many archaeological sites have been radiocarbon dated between 10 and 11 ^{14}C ka B.P., but several sites are even older (Table 2). Leaving aside those very controversial sites such as Pedra Furada (Guidon and Delibrias, 1986), some of the archaeological localities have well established radiocarbon chronologies clearly beyond 11 ^{14}C ka B.P. When these ages are calibrated, whatsoever method chosen for it, the South American ages are, at least, comparable or even older than true Clovis ages (Table 2).

The "Clovis First" model has not taken into consideration the early South American peopling chronology and particularly that of Patagonia and Tierra del Fuego, which is the farthest region from Beringia and therefore the last one in being occupied assuming that no coastal sailing took place during colonization. The academic attitude of those scientists sustaining the "Clovis First" model has not taken into consideration and systematically ignored the existing information about the peopling of the South American continent (see, particularly, Gruhn, 2005) and, especially concerning the academic interest of one of the present authors (J.R.), that of Patagonia and Tierra del Fuego (Miotti et al., 2003; Rabassa, 2008). The peopling of Patagonia took place at the same time or, most likely, even before the occurrence of the Clovis people. However, the defendants of the model have not modified their basic concepts, and they have maintained that humans reached from the Yukon to southern Patagonia in only 1000 years or even less (Haynes, 1987; Fiedel and Haynes, 2004; Fiedel, 2000; among others; see discussion in; Miotti et al., 2003; Miotti, 2006; Salemme and Miotti, 2008).

The first American peoples were hunter-gatherer groups which were coming from extreme climate and ecosystem conditions in Siberia. Following their displacement, they would have encountered very different environments until reaching Patagonia, from the sub-polar Canadian steppes through prairies, deserts, tropical rain forests, pampas, to again the sub-polar Patagonian and Fuegian steppes. Obviously, their adaptation to these new environments would have not been instantaneous.

Petraglia and Dennell (2007) have suggested that the process of colonization of Beringia accelerated immediately after 40 ka B.P. Goebel (1999) also recognized that humans began to colonize

Beringia and areas >55° N already not long after 26 ka B.P. Bryan (1999) presented his ideas that human settlement in the Americas began perhaps between 20 and 50 ka ago. Clague et al. (2004) have already discussed the paleoenvironments of northwestern North America before the Last Glacial Maximum, and the possibility of humans entering America before such times.

It is possible that in the early phase of the displacement southwards, things would have been quite fast and easy in North America, since there was an obvious natural pressure in search of more benign climates, particularly milder winters, which were to be found towards the Equator. Contrarily, it is highly improbable that the same displacement speed would have been sustained when reaching the subtropical and tropical latitudes, even less when advancing southwards in South America, reaching the Pampas and Patagonia, walking away from milder and wetter climates. In this case, the ecological pressure might have been negative, and the permanent southwards movement would only be explained by cultural pressure under population growth or the arrival of new human groups.

Therefore, the estimated rates for the hypothetical human displacement throughout the Americas based on the "Clovis First" model would have been extremely high, even in comparison with those of invading terrestrial mammals in recent times. In their journey, and at those very high movement rates, these humans would have found very different climates, ecosystems, food and water resources, and raw materials, which would have to be modified for a certain human group even during the life of a single generation. These circumstances are highly improbable both in biological and cultural terms, and the displacement rates should then be re-estimated, suggesting that there would have been other human waves preceding the Clovis people. Besides, the "Clovis First" model does not explain whether the Clovis people spent the full LGM in Siberia or Beringia, and how they managed to do so; but in any case, it argues that they were there, as if they were waiting for the Yukon Corridor to open. This is quite unlikely, since all species (including humans) moved away from the ice during glacial stadials and certainly not towards more frigid environments.

These unlikely circumstances suggest alternative hypotheses are necessary. Note that *Homo sapiens* needed at least 40,000 years (that is ca. 2000 generations) to reach Australia from Africa, which is a comparable distance, but in this case voyaging always along subtropical and tropical latitudes, following a general E–W direction, and not a N to S route instead, traversing the climate belts, as it was the case in the Americas.

Assuming instead much slower movement rates than those estimated by the "Clovis First" model, it is possible to estimate a probable age for the incoming Siberian humans. This age would lie clearly sometimes before the LGM, when the Yukon corridor was closed and the glaciers were calving into the Pacific Ocean. The first human penetration through Beringia would have happened then, not during the Late Glacial (i.e., the period between 15 and 10 ^{14}C ka B.P.), but much before. In our vision, the first humans would have crossed Beringia during any of the warmer and wetter D-O events of MIS 3, most likely sometime between 52 and 29 cal. ka B.P., during any of D-O 4 to D-O 14, although D-O 5 (32 ka B.P.), D-O 8 (38 ka B.P.), D-O 10 (42 ka B.P.) and D-O 12 (44 ka B.P.) may be favored due to their relative warmer/wetter conditions. During this period, sea level was still low enough so as to keep the Beringia route opened, with a climate much milder than that of the LGM, and extensive temperate ecosystems in the area, closer to those present today. Since the LGM (MIS 2) did not start until 26 cal. ka B.P., this dating may suggest that the penetration of the first human groups would have taken place when the Laurentide and Cordilleran ice sheets were still not coalescent, the terrestrial southward pass was clearly opened and the Pacific coast was probably ice free during the entire MIS 3 (Fig. 3C). Different archaeological findings both in Canada and the U.S.A., radiocarbon dated in times clearly older than Clovis (see Politis et al., 2009), would be then fully coherent with the penetration and dispersal chronology of Siberians in North America (and afterwards, their journey towards Cape Horn), in the periods and paleoclimatic conditions proposed in this paper. Although the present authors are aware of mtDNA genetic studies and linguistic investigations which would eventually support the viewpoints presented in this paper, these lines of evidence are not discussed here.

5. Final remarks

The "Clovis First" model does not explain the early peopling of Pampa and Patagonia. The initial human penetration in the American continent might have taken place, perhaps in several population waves, during one or more of the warmer and wetter Dansgaard-Oeschger paleoclimatic events during MIS 3, dated between ca. 28 and 52 ka B.P, sometime between the Heinrich cold events 2 and 5. In those times, the Laurentide and the Cordilleran ice caps had not merged yet, the Yukon corridor was open, the coastal route was ice free, sea level was still low enough to provide a large, wide land bridge between Siberia and Alaska, and the climate was milder and wetter than during the LGM.

However, no widely accepted archaeological evidence is still available for such period south of the LGM glacial boundary. Consequently, if the ideas presented in this paper are found acceptable, it would be reasonable to encourage the revision of the available chronologies throughout the entire American continent, give more attention to those archaeological sites in North and South America with older radiocarbon dates, and intensify the search of human evidence in North America in sediments deposited during the MIS 3, before the LGM.

Uncited reference

Eshleman et al., 2003; Nichols, 1990; Schurr, 2004; Stariskovskaya et al., 1998; Torroni et al., 1994; Blunier and Brook, 2003; Fiedel, 2006; Hajduk et al., 2004; Mazzia and Felgenheimer, 2011; Roosevelt et al., 1996.

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