Warmings in the far northwestern Pacific promoted pre-Clovis immigration to America during Heinrich event 1

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ABSTRACT

Well-dated multidecadal- to centennial-scale sediment records from the subarctic northwest Pacific show that the early deglacial 18.5–15.0 ka was marked by 3 pronounced short-term warmings of ~5 °C. They lasted 500–1500 yr each and were coeval with early to late stages of cold Heinrich event 1 in the North Atlantic. These regional climate windows may have promoted a pre-Clovis emigration of people from the cold-arid monsoon climate in East Asia to the climatically more favorable, then-emerged Beringian and Aleutian shelf regions and the Americas, as suggested by archeological findings.

Keywords: subarctic North Pacific, sea-surface warming, paleoceanography, Heinrich I stadial, pre-Clovis immigration.

INTRODUCTION

The deglacial evolution of sea-surface temperature (SST) and climate in the subarctic North Pacific is poorly known on centennial to millennial time scales. We investigate SST changes in the northwest Pacific over glacial termination I and define their phase relation with temperature changes in the North Atlantic region, including Greenland. Here the early deglacial is marked by the extremely cold and long-lasting stadial of Heinrich event 1 (H1), 18.0–14.7 ka (Sarnthein et al., 2001), followed by the warm Bølling-Allerød interstadial, the cold spell of the Younger Dryas, and an abrupt Preboreal warming (Grootes et al., 1993). In the subarctic northwest Pacific, first results for marine isotope stage 3 (Kiefer et al., 2001) suggest that SST changes were generally antiphase with North Atlantic Dansgaard-Oeschger oscillations, whereas temperature changes coeval with the North Atlantic were suggested for the northeast Pacific margin (Kienast and McKay, 2001). The paleoclimate record presented here provides the first marine evidence for a prominent phase shift between deglacial climate changes in the subarctic North Pacific and the North Atlantic. We discuss the potential impact of subarctic SST changes on the supposed late glacial paleoindian immigration from northeastern Asia to America.

Archeological findings, although debated (Marshall, 2001; Dixon, 2001), indicate earliest immigration pulses to Beringia and North America as early as ca. 18.3–14.5 ka (15–12.5 ^{14}C ka) (Table 1). The most likely immigration route of these pre-Clovis people led along the southern coast of the then dry Bering shelf, the Aleutian island arc, and the shoreline of British Columbia (Fig. 1; Meltzer, 2004; Dixon, 2001). The alternative inland route for migration via Alaska and western Canada was still blocked by the continental Laurentide ice sheet until ca. 13.5 ka (Mandryk et al., 2001).

Early deglacial immigration pulses from eastern Siberia to the Americas (Meltzer, 1997) form an apparent paradox in view of the coeval major cold spell H1: to resolve this, new evidence that documents a coeval noteworthy climatic amelioration along the northern subarctic Pacific coastal region is required. In particular, perennial sea ice near the Aleutian Islands and in the Bering Sea can now be excluded as possible scenarios that may have formed a major barrier to nearshore navigation.

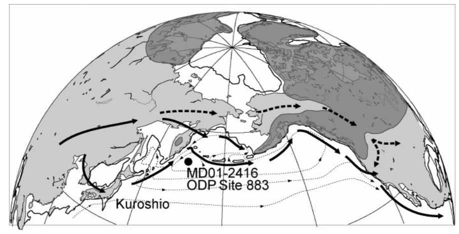

Figure 1. Possible Clovis (dashed arrows) and pre-Clovis (solid arrows) paleoindian immigration routes from northeast Asia to America on and along emerged continental shelves (bold contour line; 100 m water depth) and locations of RV *Marion Dufresne* (MD) Site 01-2416 and Ocean Drilling Program (ODP) Site 883 in northwest Pacific subarctic gyre. Dark areas outline glacial ice sheets, dotted lines with arrows mark surface water currents (Dodimead et al., 1963).

MATERIALS AND METHODS

New multidecadal- to centennial-scale records of SST were obtained at International Marine Global Changes Program Site MD01–2416 (51°16′N, 167°44′E, 2317 m water depth, w.d.) and Ocean Drilling Program (ODP) Site 883D (51°12′N, 167°46′E, 2385 m w.d.) on the northern Emperor Seamounts

TABLE 1. KEY ARCHEOLOGICAL EVIDENCE OF AMERICAN EARLY HUMAN SITES, SELECTED AFTER DIXON (2001) AND MELTZER (2004)

Site	Region	Age of earliest occupation: ^{14}C years BP	Age of earliest occupation: Cal. years BP	Refs. (Data Repository)
Clovis and Coeval Cultures				
Folsom Sites	North and South America	Cluster from 10,900–10,200	12,950–11,800	(11)
Clovis Sites	North and South America	Cluster from 11,200–10,900	13,150–12,950	(6)
Pre-Clovis Sites				
Monte Verde	Southern Chile	12,500	14,500–15,200	(4)
S.E. Wisconsin Mammoth sites	Wisconsin	12,200–13,510	14,150–16,650	(10)
Big Eddy	Missouri	12,950	15,700	(7)
Topper	South Carolina		~15,000–16,000	(5)
Taima-Taima	Venezuela	12,980–14,200	15,900–17,500	(2)
Little Salt Spring	Florida	13,450	16,500	(3)
Saltville	Virginia	14,510	17,750	(9)
Meadowcroft Rockshelter	Pennsylvania	14,555/19,600	17,800/23,500	(1)
Cactus Hill	Virginia	15,070	18,300	(8)

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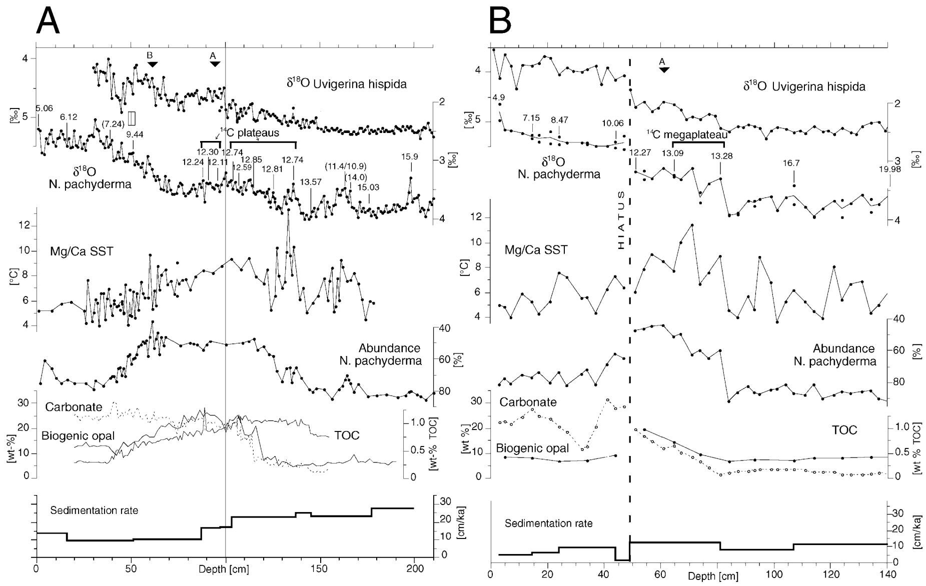

Figure 2. Paleoceanographic records and sedimentation rates for core MD01–2416 (A) and Ocean Drilling Program (ODP) Hole 883D (B). Age control is based on reservoir age-corrected ^{14}C ages (Table DR1; see footnote 1) measured on *Neogloboquadrina pachyderma* sinistral (Nps) and on ^{14}C plateaus at 12.2, 12.8–13.3, and 20 ^{14}C ka (Hughen et al., 2004). Rejected ages (Table DR1) are in parentheses. Gray bar at 50 cm indicates geomagnetic intensity minimum at 10 calendar (cal.) ka (Stoner et al., 2002). Lines labeled A and B refer to sudden climate ameliorations ca. 14.7 cal. ka (Dansgaard-Oeschger [DO] event 1) and 11.6 cal. ka in Greenland Ice Sheet Project 2 (GISP2) record (see Fig. 4). Hiatus shown at 49 cm in ODP Hole 883D is derived from ^{14}C dates and sediment discontinuity. SST—sea-surface temperature; TOC—total organic carbon.

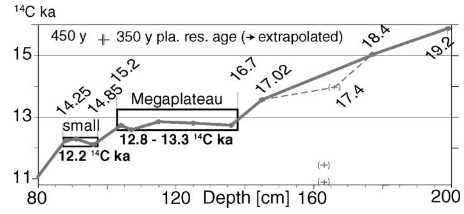

Figure 3. Reservoir-corrected ^{14}C ages in core MD01–2416 reveal two major ^{14}C plateaus and derived planktic (pla.) ^{14}C reservoir (res.) ages (numbers at top). Rejected ^{14}C ages are in parentheses. Oblique numbers are resultant age control points (in cal. ka).

(Fig. 1). At these locations carbonate dissolution is modest, and planktic and benthic foraminifera tests are abundant throughout the sediment sections.

Variations in SST were estimated by means of three different proxies: percentages of the polar planktic foraminifer species *Neogloboquadrina pachyderma* sinistral (Nps) >150 μm (Kiefer et al., 2001) and the Mg/Ca ratio and δ^{18}O values measured on 30 tests of Nps (150–250 μm). Mg/Ca samples were cleaned (after the method in Barker et al., 2003) and analyzed with a Varian Vista inductively coupled plasma-atomic emission spectrometer (de Villiers et al., 2002). Mg/Ca ratios were converted into temperatures (±0.6 °C) using the species-specific calibration of Elderfield and Ganssen (2000). Oxygen isotopes were measured on Nps and hispid forms of (benthic) *Uvigerina* spp. (8–12 specimens >250 μm) as described in Kiefer et al. (2001). To estimate an SST trend from δ^{18}O values of Nps (~0.22‰/°C; Shackleton, 1974), the δ^{18}O record was corrected for the global volume effect through the deglacial, using sea-level records of Hanebuth et al. (2000) (20–11 ka) and Geyh et al. (1979) (11–2 ka) for 0.11‰ δ^{18}O per 10 m sea-level change.

Low percentages of benthic foraminifera and foraminifera fragments at sites MD01–2416 and ODP 883 (not shown) suggest that changes in carbonate dissolution were modest and have little affected our SST records. Biogenic opal concentrations in core MD01–2416 were measured following the automated leaching method of Müller and Schneider (1993). All data are available at the PANGAEA databank (http://www.pangaea.de/PangaVista).

AGE CONTROL

Independent chronostratigraphies were established for cores MD01–2416 and ODP Site 883 (Figs. 2A, 2B) on the basis of more than 30 accelerator mass spectrometry ^{14}C ages. As listed in Data Repository Table DR1[1], planktic ^{14}C dates from different intervals were corrected for differential North Pacific ^{14}C reservoir ages, which were deduced by means of diverse techniques.

Southon and Fedje (2003) showed that northeast Pacific reservoir ages decrease from 700 to 500 yr from 0 to 10 ^{14}C ka. For the early deglacial we obtained independent global time markers with centennial precision and thus a close estimate of local paleoreservoir ages from ages that define the top and base of two ^{14}C plateaus recently found in the age-calibrated ^{14}C record of Termination Ia from the Cariaco Basin, which has been tied to the incremental time scale of Greenland Ice Sheet Project 2 (GISP2) (Hughen et al., 2000, 2004; Stuiver and Grootes, 2000). After correction for additional 200 yr ^{14}C reservoir effect (Kromer et al., 2004), a smaller plateau ca.12.2 ^{14}C ka extends from 14.25 to 14.85 cal. ka, subsequent to a ^{14}C megaplateau at 12.8–13.3 ^{14}C ka, lasting from 15.2 to 16.7 calendar (cal.) ka. In the densely sampled ^{14}C record of core MD01–2416 we identified both plateaus (Table DR1 [see footnote 1]; Fig. 3). Site 883 documents the older megaplateau and a minor plateau ca. 20 ^{14}C ka.

In core MD01–2416, the Preboreal ^{14}C age of 9.44 ka (10.65 cal. ka) is supported by a geomagnetic intensity minimum at 50 cm with an age of ca. 10 ka (Stoner et al., 2002; Fig. 2). The age of 7.24 ^{14}C ka from 39 cm was ignored as too young because it is on top of an ash layer that barred upward mixing of old Nps tests (Sarnthein et al., 2004). Three aberrant dates at 163 cm and 166 cm depth (Fig. 3) were rejected because they are probably linked to a deep burrow. In contrast, a benthic ^{14}C age at 163 cm appears little biased by downward mixing (Table DR1). The MD01-2416 age model and regional significance of results based on this age control are supported by the near synchroneity and close match of paleoceanographic events at neighbor Site 883 within a few hundred years (Fig. 4).

Sedimentation rates over Termination 1A are fairly uniform, varying from 8 to 12 cm/k.y. at Site 883 and 17 to 27 cm/k.y. at Site MD01-2416 (Figs. 2A, 2B), a record extended by piston coring (Skinner and McCave, 2003).

RESULTS

The three independent SST records (Fig. 4) are consistent in showing several warm-cold oscillations during the early deglacial, with three major warm phases during H1. Mg/Ca values suggest that SST increased by as much as 4–6 °C during both early H1, 18.2–17.2 and 16.8–16.3 ka, and late H1, 16.2–14.7 ka (Fig. 4), 1500 yr prior to Dansgaard-Oeschger (DO) event 1 in Greenland and the North Atlantic (14.67 ka in GISP2; Grootes et al., 1993). During these intervals SSTs of 8–11 °C clearly excluded sea ice formation in the far northwestern Pacific (51°N), at least for late

[1]Data Repository item 2006029, Table DR1, is available online at www.geosociety.or/pubs/ft2006.htm, or on request from editing@geosociety.org, or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

spring and early fall (Kuroyanagi et al., 2002). Each increase in SST precisely matches a decrease in (ice volume–corrected) planktic $\delta^{18}O$. However, this decrease has been only modest (0.6‰ equivalent to <2.5–3 °C), implying a relative enrichment of $^{18}O_{water}$ by 1‰–1.5‰. The warmings thus accompanied a local sea-surface salinity increase of 1–3 units, presumably reflecting a short-term dominance of warm and saline Kuroshio water. The late H1 warmings also concurred with strongly reduced planktic ^{14}C reservoir ages (Fig. 3). They amounted to 350 yr during the ^{14}C megaplateau (and older?) and 450 yr during the smaller Bølling-age plateau, compared to 800–900 yr today (Southon et al., 1990; Southon and Fedje, 2003).

Starting from late H1 ca.15.8 ka, both Mg/Ca and $\delta^{18}O$ based estimates reveal a gradual SST decrease of 2–3 °C toward a broad SST plateau of 9 °C that extended over the Allerød interstadial and early Younger Dryas (Fig. 4). The gentle cooling may reflect an enhanced advection of cold and nutrient-rich water from below and a shallowed pycnocline; this is supported by a prominent biogenic opal maximum (Figs. 2 and 4) and much reduced benthic-planktic ^{14}C age differences (Table DR1; see footnote 1): 705 yr at Site 883 (51 cm) and 965 yr at MD01–2416 (88 cm) compare with a Preboreal value of 1335 yr at Site 883 (44 cm) and >1400 yr today (Schlosser et al., 2001). Prior to 15.8 ka, low concentrations of biogenic opal suggest low nutrient budgets and a deep nutricline. Thus the striking SST maxima during H1 (Fig. 4) appear unrelated to pycnocline depth.

All three SST records suggest a gentle sawtooth-style North Pacific warming curing the upper Younger Dryas that preceded the abrupt Preboreal warming of the Greenland–North Atlantic temperature record by ~800 yr (Fig. 4). In contrast to the marked abrupt warming in Greenland (Grootes et al., 1993), the 11.5 ka Preboreal onset led to a renewed, initially abrupt, later gentler, temperature drop of ~2–3 °C in the subarctic North Pacific. Middle to late Holocene Mg/Ca based SST at Site MD01–2416 remained near 4–7 °C, far below the mild temperatures during deglacial time (Sarnthein et al., 2004).

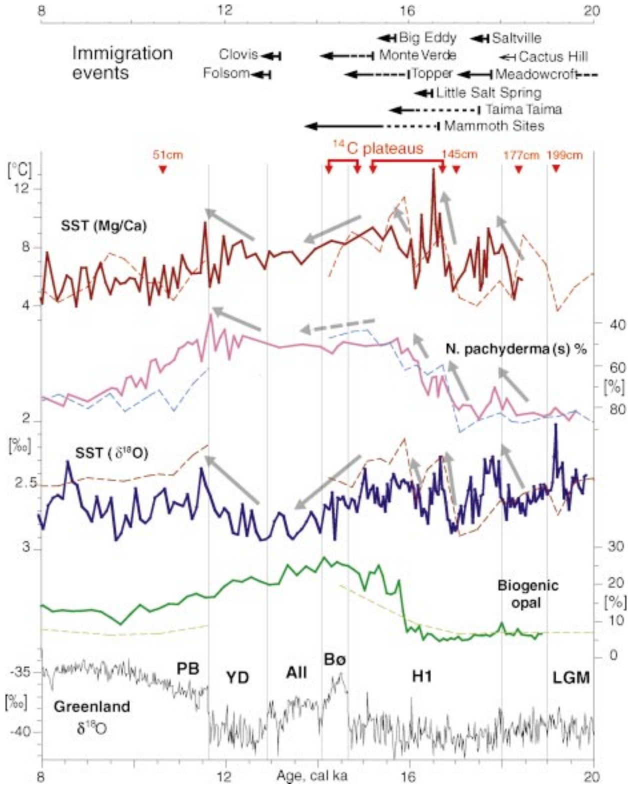

Figure 4. Possible immigration events of Folsom, Clovis, and pre-Clovis people (see Table 1), sea-surface temperature (SST) records from far northwestern Pacific from 8 to 20 ka (solid lines: MD01-2416, dotted lines: Ocean Drilling Program [ODP] Hole 883D), and Greenland Ice Sheet Project (GISP2) $\delta^{18}O$ temperature record from Greenland (Stuiver and Grootes, 2000). SST estimates are deduced from Mg/Ca ratios, inverse abundance, and planktic $\delta^{18}O$ (corrected for global ice effect) of *Neogloboquadrina pachyderma* sinistral, representing high (late) spring and early fall at 30–100 m water depth. PB—Preboreal, YD—Younger Dryas, All—Allerød, Bø—Bølling, H1—Heinrich event 1, LGM—Last Glacial Maximum. Bold arrows outline major SST trends. Small arrowheads mark age control points.

DISCUSSION

Patterns of both atmospheric and oceanic circulation control teleconnections between North Atlantic and North Pacific climate on centennial to millennial time scales. The coupled general circulation model (GCM) of Mikolajewicz et al. (1997) revealed a dominant atmospheric signal transfer that implies centennial-scale variations of North Pacific SST in phase with the North Atlantic. In contrast, the (University of Victoria) GCM runs of Schmittner et al. (2003) as well as a model of Weijer and Dijkstra (2003) depict an antiphase trend between SST in the subarctic North Pacific and the North Atlantic, which entails a dominant control of global ocean circulation on North Pacific temperatures. However, all models suggest an H1 climate deterioration for the East Asia monsoon region, which was in phase with that in the North Atlantic.

Our three independent proxy records (Fig. 4) clearly support the antiphase models for the northern North Pacific. The SST culminations (and coeval maxima in salinity) were characteristic of high (late) spring and early fall, and imply a much increased, or less diluted, predominance of warm and salt-enriched subtropical Kuroshio water in the Pacific subarctic gyre. H1 dinocyst assemblages record warm and saline surface water prevailing in the Gulf of Alaska (de Vernal and Pedersen, 1997). Thus the H1 North Pacific shows good analogies to the modern North Atlantic, which means that warm subtropical water was advected into the subarctic gyres at much higher rates than during interstadial time.

The final stadial H1, the subsequent Bølling-Allerød, and early Younger Dryas were periods of gentle surface-water cooling, by 2–3 °C, and a maximum in percent biogenic opal (Fig. 4). It documents a regional-scale culmination of plankton production in the subarctic northwestern Pacific (Keigwin et al., 1992; Gorbarenko, 1996; Crusius et al., 2004) that may be linked to strong vertical mixing of the surface ocean and upwelling of nutrient-rich (but cold) subsurface water, although the concomitant SST reduction could be stronger to support this scenario. There is a major drop in the $\delta^{18}O$ difference between Nps and the surface dweller *Globigerina bulloides*, from 0.5‰–1.0‰ to 0.2‰–0.3‰, recording minimum stratification of surface water after 15.2 ka (unpublished data). The period of thermocline shallowing in the northernmost Pacific was largely coeval with a culmination in North Atlantic Deepwater formation and thus suggests a link to the great intensification of North Atlantic MOC (meridional overturning circulation) during the Bølling-Allerød (Sarnthein et al., 2001).

The timing of the favorable climate windows during H1 is consistent with ages reported for the best-accepted pre-Clovis sites of early human occupation in North America and southern Chile (Table 1). We cannot properly assess the evidence and quality of the records of these archeological sites (Hoffecker et al., 1993; Dixon, 2001; Hoffecker and Elias, 2003; Meltzer, 2004). However, if accepted, their ages correlate with distinct periods of mild regional climate in the northernmost subarctic Pacific, where SSTs of 8–11 °C document sea-ice–free conditions at least for late spring to fall.

In contrast to those warm spells, the H1 stadial at least temporarily induced severe climate deterioration in East Asia. A dominant cold-arid winter monsoon (Wang et al., 2001) was highly unfavorable for humans, driving them to the shorelines. In harmony with all models, the culminations in Asian winter monsoon appear in phase with North Atlantic stadial events via a dominating influence of westerly winds.

Once at the shoreline, the pronounced warmings in the subarctic North Pacific provided most favorable conditions for further northeastward emigration of people alongshore to Beringia (with favorable steppe conditions; Zazula et al., 2003) and the Americas as early as 18–17 ka, near 16.5 ka, and 16–14.5 ka, during pre-Clovis time (Figs. 1 and 4). Southward migration waves along the northwestern American coast may have become possible as soon as the Cordilleran ice sheet had retreated from the then-exposed shelf ca. 17 ka (Mandryk et al., 2001).

Focused studies of potential human settlement locations along this route to the North American west coast and shelf may provide further insights into the migration of pre-Clovis people, a migration possibly promoted by a unique scenario of coeval climate deterioration in eastern Asia and amelioration near the Aleutian Islands.

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