ENVIRONMENTAL CHANGE AND ARCTIC PALEOINDIANS

DANIEL H. MANN, RICHARD E. REANIER, DOROTHY M. PETEET, MICHAEL L. KUNZ, and MARK JOHNSON

Abstract. Intensive Paleoindian occupation of the Mesa site occurred between 10,300 and 9700 ^{14}C yr B.P. Was the timing of this occupation controlled by environmental changes? We investigated stratigraphic records of geomorphology and vegetation to describe how landscapes in the Arctic Foothills changed between 13,000 and 8000 ^{14}C yr B.P. Paleoindians were present during a time of rapid and sweeping changes in vegetation, slope erosion, floodplain dynamics, permafrost stability, and soil type. We speculate that Paleoindians moved into arctic Alaska to exploit population highs in large ungulates that in turn were triggered by landscape-scale, geomorphic disturbances caused by climate changes. Environmental changes slowed and rising sea levels flooded Alaska's continental shelves during the Early Holocene, causing summer temperatures to fall and precipitation to increase. A more stable climate and the prevalence of maritime air masses allowed the spread of tussock-tundra vegetation, which probably drove both the Paleoindians and their prey species out of the region.

Introduction

Paleoindians occupied arctic Alaska during a time of sweeping environmental changes at the Pleistocene-Holocene boundary. Did some of these environmental changes determine the timing of their occupation of Alaska? For events occurring 10,000 years ago, we can only infer cause and effect from temporal coincidences between environmental and human history. Elsewhere (Mann et al. 2002), we describe in detail how ecosystems responded to the rapid shifts in climate that occurred between 13,000 and 8000 ^{14}C yr B.P.[1] in the Arctic Foothills. Here we infer the possible effects that these environmental changes had on the timing of Paleoindian occupations. Rising sea level was one of the most important factors driving paleoenvironmental change in Beringia during post-glacial times was rising sea level. Preliminary analyses, presented here, describe how the flooding of Alaska's continental shelves by rising sea levels may have altered the regional climate.

Our conclusions are speculative. We think that the Paleoindian occupations of Alaska, north of the Brooks Range, represent intermittent forays into an otherwise inhospitable territory by an opportunistic and mobile cultural group during brief intervals when its prey species reached high population den-

Daniel H. Mann, Institute of Arctic Biology and Alaska Quaternary Center, University of Alaska, Fairbanks, AK 99775
Richard E. Reanier, Reanier and Associates, 1807 Thirty Second Avenue, Seattle, Washington 98122
Dorothy M. Peteet, NASA Goddard Institute for Space Studies and Lamont Doherty Earth Observatory, Palisades, New York 10964
Michael L. Kunz, Bureau of Land Management, 1150 University Avenue, Fairbanks, AK 99708
Mark Johnson, Institute of Marine Sciences, University of Alaska, Fairbanks, AK 99775

ARCTIC ANTHROPOLOGY Vol. 38, No. 2, pp. 119–138, 2001 ISSN 0066-6939

sities. Similarities in timing and lithic technology between the Mesa and Agate Basin complexes of the High Plains (Bever, this volume) suggest these sites were occupied by a related, if not single people, who consequently must have been mobile across continental distances. Whether Paleoindians moved north into Alaska from the Great Plains or first developed their cultural traits in the Arctic, their subsistence strategy probably was tied closely to bison. Bison may have flourished in northern Alaska during the Pleistocene-Holocene transition because of rapid climatic shifts that maintained immature, relatively dry soils dominated by early successional vegetation containing significant amounts of grass. Both bison and Paleoindians probably departed Alaska because of the spread of tussock-tundra vegetation that was caused by an increasingly moist summer climate, a change driven in part by the flooding of the Bering Land Bridge. The Paleoindian's intermittent and probably prey-specialized occupation of northern Alaska may have been typical of the opportunistic way humans utilized northern landscapes during the periods of climatic instability that characterized much of the Late Pleistocene.

Study Area

Many of the processes that organize the modern landscapes of arctic Alaska are peculiar to this region, and understanding them is necessary to interpret events in prehistory. Alaska's North Slope has two major physiographic divisions, the Arctic Foothills flanking the north side of the Brooks Range and the Arctic Coastal Plain lying between the Arctic Foothills and the Chukchi and Beaufort Seas (Fig. 1). Our 100 × 200 km study area is in the Arctic Foothills and crosses from the Brooks Range to the southern edge of the Arctic Coastal Plain. Both physiographic divisions of the North Slope are described here because their environmental histories are closely interrelated.

The Arctic Foothills are east-west trending ridges of carbonate bedrock that protrude from tundra-covered plains (Grantz et al. 1994). Permafrost is continuous north of the Brooks Range and reaches a thickness of several hundred meters (Ferrians 1994). Much of the Arctic Foothills region has never been glaciated. Areas near the Brooks Range and including the Mesa archaeological site (Kunz and Reanier 1994) were last glaciated in the Tertiary and Early Pleistocene. At the last glacial maximum (LGM), glaciers in the Brooks Range terminated at the northern range front (Hamilton 1986).

The Arctic Coastal Plain is underlain by a broad, low relief bedrock surface that dips seaward from the Arctic Foothills. Over the last 3 m.y., the sea has repeatedly transgressed and receded across this surface, leaving a veneer of unconsolidated and interfingering marine and non-marine deposits (Dinter et al. 1990). Among the non-marine deposits are those of sandy river channels and deltas. During dry intervals in the Late Pleistocene, these sandy sediments formed extensive dune fields and loess belts (Carter et al. 1987). Immediately north of the study area, the Arctic Coastal Plain is underlain by the now-stable Ikpikpuk Dunes, which formed a 12,000-km^2 sand sea during the LGM and was partly reactivated during post-glacial times (Carter, 1981, 1993; Dinter et al. 1990; Galloway and Carter 1993).

Marked north-south gradients in climate occur across the North Slope (Walker 1987, 2000). July mean temperature increases from 4°C at Barrow to 12°C at Toolik Lake near the Brooks Range front (Zhang et al. 1996). Mean annual precipitation increases inland from 200 mm at Barrow to 320 mm at Toolik Lake. About half of the precipitation is snow, which persists on the ground for more than eight months of the year. Rainfall increases over the course of the summer with maxima during cyclonic storms in July, August, and September (Kane et al. 1992). Most of these storms cross the Brooks Range from the Bering Sea (Moritz 1979).

During summer, much of the North Slope exists in a state of waterlogged aridity. Potential evapotranspiration equals or exceeds total annual precipitation (Rovansek et al. 1996), actual evapotranspiration exceeds annual runoff (Hinzman et al. 1996), and the region is classified as semi-arid by the Thornthwaite method (Patric and Black 1968; Newman and Branton 1972). Nonetheless, soils at many sites remain saturated throughout the summer because water tables are perched on the frozen, ice-rich substrate, and water is concentrated at the ground surface. This situation can persist because evapotranspiration is greatest in early summer before active layers fully thaw, and precipitation in late summer recharges soil moisture at a time when evapotranspiration is low (Hinzman et al. 1996; Zhang et al. 1997).

Tundra covers the entire North Slope; however, a major vegetation boundary lies along the northern edge of the Arctic Foothills (Walker et al. 1998). In the Arctic Foothills, most vegetation is moist acidic tundra (*Sphagno-Eriophoretum*) dominated by dwarf shrubs (*Betula nana, Ledum palustre, Salix planifolia pulchra*), tussock sedges (*Eriophorum vaginatum*), and acidophilous mosses, among which *Sphagnum* species are prominent. An important point for paleoecology is that ericaceous shrubs, *Sphagnum* moss, and *Rubus chamaemorus* (cloudberry) are characteristic of moist acidic tundra vegetation today, which is everywhere underlain by peaty organic horizons (Bockheim et al. 1998). On the Coastal Plain, most vegetation is moist, non-acidic tundra (*Dryado-integrifoliae-Caricetum bigelowii*), which is dominated by non-tussock sedges (*Carex bigelowii, C. membranacea,* and *Eriophorum*

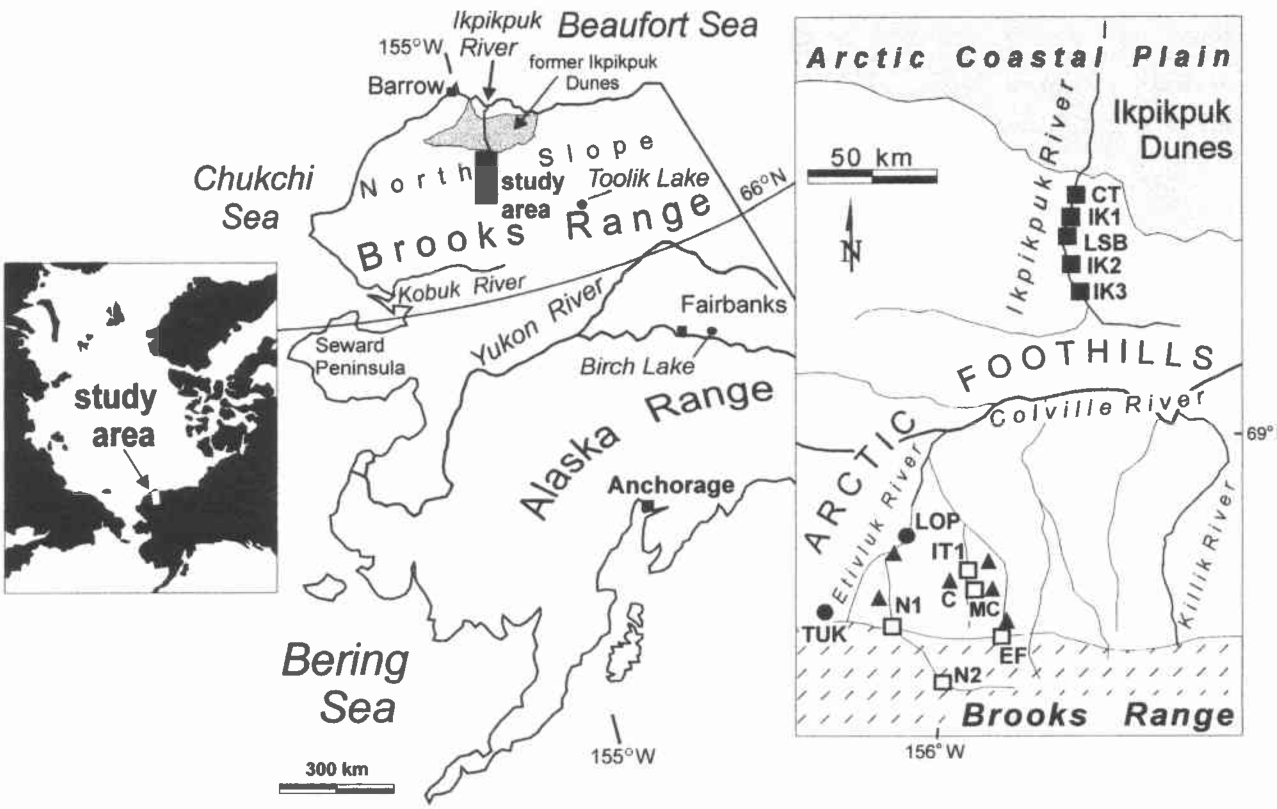

Figure 1. The Arctic Foothills lie between the Brooks Range and the Arctic Coastal Plain on Alaska's North Slope. The right panel shows the locations of stratigraphic sections described in Mann et al. (2002) and reviewed here. The squares mark fluvial sections. *N1* is Nigu 1, *N2* is Nigu 2; *EF* is on the East Fork of the Etivluk River; *MC* is Mesa Creek section; and *IT1* is on Iteriak Creek just downstream of the Mesa archaeological site. Along the Ikpikpuk River, *CT* is Cottonwood Bend; *IK1* is Ikpikpuk 1; *LSB* is Little Supreme Bluff; *IK2* is Ikpikpuk 2; and *IK3* is Ikpikpuk 3. *LOP* is the "Lake of the Pleistocene." Triangles indicate solifluction sections; C is Cobra Gulch. TUK is Tukuto Lake. The portion of the Arctic Coastal Plain shown here includes part of the stabilized Ikpikpuk dunes.

triste), prostrate shrubs (*Dryas integrifolia, Salix arctica, S. reticulata,* and *Arctuous rubra*), and minerotrophic moss taxa (Walker et al. 1998). Trees are absent from the North Slope except for several widely separated stands of *Populus balsamifera* (balsam poplar) growing on floodplains in the Arctic Foothills (Murray 1980; Edwards and Dunwiddie 1985). With a mean July temperature of 10–12°C, the Arctic Foothills lie near the latitudinal treeline today (Hopkins 1959; MacDonald et al. 2000).

The general trend of soil development on the North Slope is towards paludification, the accumulation of waterlogged organic material on previously well-drained terrain (Bockheim et al. 1998). In the Arctic Foothills today, much of the landscape is blanketed by 5–40 cm of peat (Everett and Brown 1982; Ping et al. 1998), which is soil material containing >30% organic matter (Heathwaite et al. 1993). The water logging that accompanies peat accumulation influences vegetation distribution throughout the region (Walker and Walker 1996; Walker et al. 1998). *Sphagnum* mosses play a key role in paludification on the North Slope by acidifying soils, lowering soil-nutrient levels, and retaining water. As the result of insulation by organic surface horizons and their high water content, active layers are typically only 25 cm thick in poorly drained areas (Everett and Brown 1982; Kane 1996). In contrast, summer thaw on well-drained slopes with thin or disturbed organic surface horizons can penetrate to depths of 1 m (Kane 1996). Organic soil horizons affect floodplain dynamics by retarding slope erosion and limiting the input of sediments to streams (Hinzman et al. 1996).

Floodplains play key roles in North Slope ecosystems. In contrast with much of the surrounding terrain, floodplain soils have deep active layers, lack thick organic horizons, and are often well drained (Ping et al. 1998). They are sites of high primary productivity and plant-species diversity (Shaver et al. 1996). Unvegetated parts of floodplains are sources of loess, which has pervasive effects on soils and vegetation located downwind and beyond floodplain margins (Walker and Everett 1991). Loess and sand input retards soil acidification, which limits organic-matter accumulation and maintains relatively deep and well-drained active layers.

The major runoff event of the year on the North Slope is the snowmelt flood (Arnborg et al. 1966; Carter et al. 1987; Kane 1996); however, frozen soils restrict erosion during snowmelt, and summer rainstorms probably cause most erosion on slopes. This also is true for the beds of smaller streams where bottom-fast ice and frozen sediments armor channels during snowmelt (Scott 1978). Where channels impinge on higher terrain, a large part of lateral channel migration is due to thermal erosion of ice-rich permafrost (Carter et al. 1987). Most streams have wandering, gravel- and cobble-bedded channels today, though braided reaches exist in areas of *aufeis* accumulation, and low-order streams often are beaded or straight-channeled between banks of peat.

Results and Discussion

Chronology of Human Occupation at the Mesa Site

When did Paleoindians live in the Arctic Foothills? The answer to this question defines the time period of interest. Fifty-one radiocarbon dates have been obtained from the Mesa site (see Bever, this volume), providing a degree of age control that is unique for a Paleoindian archaeological site. Seven of these ages come from standard, radiometric dates on multiple grams of wood charcoal, while the other 44 are accelerator mass spectrometry (AMS) dates on milligrams of wood charcoal. Paired radiometric and AMS samples reveal that the radiometric ages from the Mesa site are anomalous and usually too young. Only the ages of the 44 AMS samples are considered further.

The 1-sigma errors of 42 of the Mesa AMS dates fall between 12,400 and 10,400 cal yr B.P. Unfortunately for chronological precision, the C-14 time scale is distorted by global fluctuations in the concentration of radiocarbon that occurred during the Younger Dryas (YD) chronozone (ca. 11,000–10,000 ^{14}C yr B.P.) (Goslar et al. 1995; Goslar et al. 2000; Björck et al. 1996; Hajdas et al. 1998; Kitagawa and van der Plicht 1998). As a result, radiocarbon ages in this time range correspond to an unusually wide range of calendar ages (Stuiver et al. 2000).

Forty-one of the Mesa AMS dates lie between 10,300 and 9700 ^{14}C yr B.P. The combined, 1-sigma errors of these dates span the interval from 12,350 to 11,100 cal yr B.P. An outlier date of 9330 ^{14}C yr B.P. has a 1-sigma error range between 10,640 and 10,430 cal yr B.P. Unlike the other 41 dates, the 2-sigma error of this young outlier does not overlap with the 2-sigma error of the next older date.

The age distribution of thirteen AMS dates from Gordon's Hearth provides insights into the precision of age control at the Mesa site. The radiocarbon ages from Gordon's Hearth encompass the age ranges of the remaining 28, post-11,000 ^{14}C yr B.P. dates from the Mesa, with the exception of the young outlier just described (Fig. 3). Gordon's Hearth probably was used only briefly, probably for several hours to several days. How could the ages of charcoal fragments in this one hearth span most of the history of the entire site? As noted earlier, large and rapid fluctuations occurred in atmospheric ^{14}C levels during the YD and earliest Holocene causing radiocarbon ages in this time range to correspond to an unusually wide range of calendar ages. Perhaps contributing to this imprecision is the fact that Paleoindians were burning wood of varying ages. The oldest willow bushes growing along Iteriak Creek today are <50 years old; however, dead wood could conceivably be preserved on gravel bars for several additional decades. In light of the wide range of ages from Gordon's Hearth, we cannot eliminate the possibility that the Paleoindian occupation of northern Alaska was very brief. At one extreme, their occupation of the Mesa site might have lasted only the hours or days that a fire burned in Gordon's Hearth. The large number of Paleoindian hearths at the Mesa (n > 30) indicates this is unlikely and suggests multi-year occupation of this site (Kunz and Reanier, 1994). The Mesa site probably was occupied seasonally over an interval ranging from decades to centuries.

Most radiocarbon dates from other sites where northern Paleoindian artifacts occur fall within the range of ages from Gordon's Hearth at the Mesa site. Charcoal fragments associated with edge-ground, lanceolate projectile points at two other Brooks Range sites, Hilltop and the nearby Bedwell site (Reanier, 1995), produced dates whose 1-sigma errors range from 12,810 to 11,960 cal yr B.P. (Fig. 2), making them slightly older than the 42 Mesa dates just described, though their 2-sigma age ranges still overlap with ages from Gordon's Hearth. At the Engigstciak site on the Beaufort Sea coast in northwestern Canada, three bones of extinct *Bison priscus* yielded radiometric dates of 9400 ± 230, 9770 ± 180, and 9870 ± 180 ^{14}C yr B.P. (Cinq-Mars et al. 1991; MacNeish, 2000). The calibrated ages of these samples overlap with ages from Gordon's Hearth (Figs. 2, 3), and collections from the Engigstciak site seem to include Mesa-type projectile points. In southwestern Alaska at Spein Mountain (Ackerman, 1996), an AMS date on charcoal associated with Mesa-type projectile points has a 1-sigma error ranging between 11,900 and 11,500 cal yr B.P., which overlaps with ages from Gordon's Hearth (Fig. 2). An outlier whose age does not match the ages from Gordon's Hearth comes from the Putu site in the northern Brooks Range (Reanier, 1995). Char-

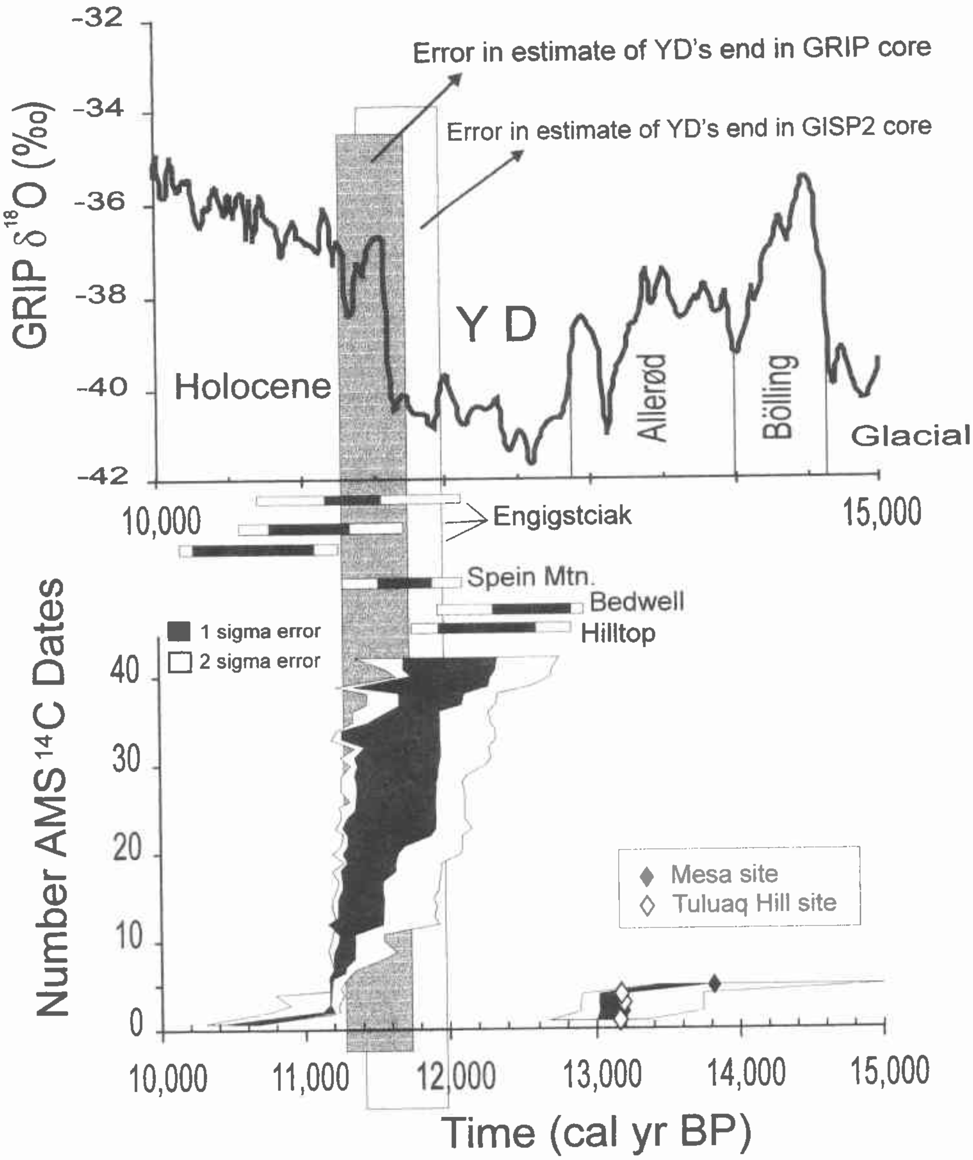

Figure 2. AMS ^{14}C dates relating to the Mesa complex in Alaska and the Yukon. Hilltop and Bedwell sites are described by Reanier (1995), Spein Mountain by Ackerman (1996), and the Engigstciak site by MacNeish (2000). The delta ^{18}O curve from the GRIP ice core (ftp://medias. meteo.fr/paleo/icecore/greenland/summit/grip/isotopes/gripd18o.txt; Johnsen et al. 1999) shows the timing of the Younger Dryas (YD) cold interval in Greenland. Estimates of the timing of the end of the YD in the GISP2 core are from Alley et al. (1993, 1997). Although known to have been abrupt, the timing of the end of the YD has an error of ±250 years, and estimates of its timing differ between the two ice cores. Most AMS ages from the Mesa site are either contemporaneous with or younger than the 11,640 ± 250 cal yr B.P. age for the end of the YD that was suggested by Alley et al. (1993, 1997). Pre-13,000 cal yr B.P. ages from the Mesa site and the Tuluaq Hill site form a distinct group of outliers. The present discussion focuses on the large group of younger dates, but it is interesting that the older ages coincide with the Allerod chronozone, which was a time of warm climate in northern Europe and Greenland.

coal fragments associated with edge-ground, lanceolate projectile points at Putu yielded an AMS date of 8810 ± 60 ^{14}C yr B.P. (Reanier, 1995), which when calibrated yields a 2-sigma age range between 10,150 and 9560 cal yr B.P.

In the Noatak River drainage southwest of the Mesa site, reconnaissance work has yielded AMS dates ranging from 10,100 to 9500 ^{14}C yr B.P. on wood charcoal associated with oblanceolate projectile points (R. Gal, personal communication, 1998; Rasic 2000). In addition, three AMS dates on wood charcoal at the Tuluaq Hill site range in age from

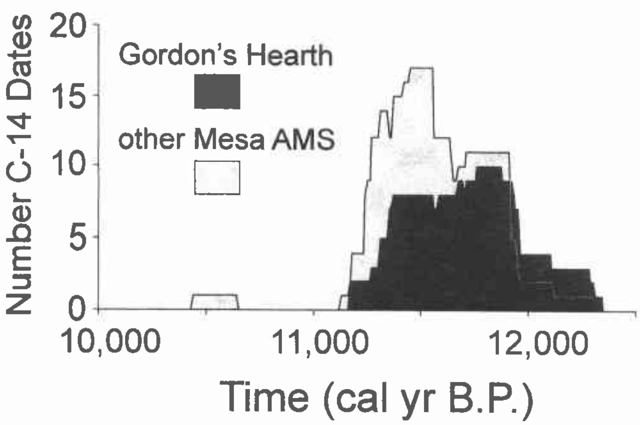

Figure 3. Radiocarbon ages of charcoal fragments from Gordon's Hearth superimposed over other post-13,000 cal yr B.P. ages from the Mesa site. The histograms depict the number of AMS ages whose calibrated 1-sigma ranges (Stuiver et al. 1998, 2000) fall within a given decade. The 13 radiocarbon ages from this single hearth encompass the same 1300-year interval spanned by most of the other radiocarbon ages from the site. It is known that rapid fluctuations in C-14 concentrations occurred in the atmosphere during the YD chronozone. These fluctuations cause numerous reversals and plateaus when the radiocarbon ages of wood that was alive during the YD are plotted against the calibrated ages of the same samples. Radiocarbon ages from Gordon's Hearth indicate that the main occupation of the Mesa site could have been much shorter than 1300 years.

11,110 to 11,200 ^{14}C yr B.P. (Rasic 2000). The artifacts from Tuluaq Hill and other sites in the Noatak valley probably belong to a Mesa-type assemblage, though further work is required to confirm this relationship.

Two AMS dates on charcoal from the Mesa site are distinctly older than the other 42 dates (Beta-57430, 11,190 $\pm$ 70 ^{14}C yr B.P. and Beta-55286, 11,660 $\pm$ 80 ^{14}C yr B.P.). The charcoal producing these two dates came from a single hearth in a locality that also contained other nearby hearths dating to ca. 10,000 ^{14}C yrs. B.P. (Kunz and Reanier 1995:20). No distinctly different artifact types were associated with these older two radiocarbon dates. The technological uniformity of the site's artifacts (Kunz and Reanier 1994, 1995) suggests occupation by a single cultural group. Several possible explanations exist for the presence of these two older dates. They could represent "old wood," wood interred in frozen, fluvial deposits for many centuries before it was gathered by the Mesa people for firewood (Hamilton and Goebel 1999). Indeed, in geological studies along the Ikpikpuk River, we encountered burnable wood >10,000 years old that was preserved in fluvial sections (Mann et al. 2002). A second explanation is that the two older dates record occupation by an earlier cultural group whose diagnostic artifacts have not yet been found. Finally, the older dates could represent a pre-13,000 cal yr B.P. occupation of the Mesa site by people using the same tool assemblage that they did almost 1500 calendar years later. At present, we are unable to eliminate any of these hypotheses.

In summary, the available radiocarbon chronology suggests that Paleoindians occupied northern Alaska and the Yukon intermittently between 13,800 and 9700 cal yr B.P. Evidence for the pre-13,000 cal yr B.P. occupation of the region is fragmentary in comparison with the period of occupation between 12,400 and 11,100 cal yr B.P. that is so well-documented at the Mesa site. Except for the two pre-13,000 cal yr B.P. dates and the lone, younger outlier, the 1-sigma errors of AMS dates from the Mesa site fall within this 1300-year interval, as do the dates from Spein Mountain (Ackerman 1996), Enigstciak (MacNeish 2000), and the Bedwell and Hilltop sites (Reanier 1995). The date series from Gordon's Hearth suggests that AMS ages whose 1-sigma errors fall between 12,400 and 11,100 cal yr B.P. could represent Paleoindian occupation during a much shorter period of real time. In this paper, we ignore the hints of a pre-13,000 cal yr B.P. occupation of northern Alaska by Paleoindian people and concentrate on their well-dated use of the Arctic Foothills between 12,400 and 11,100 cal yr B.P. (Fig. 2). We suggest that Paleoindians disappeared from northern Alaska before 9560 cal yr B.P., which is the lower limit of the 2-sigma, calibrated age range of the 8800 $\pm$ 60 ^{14}C yr B.P. date from the Putu site (Reanier 1995). The time interval of interest here for paleoenvironmental reconstructions is roughly 15,000 to 8000 cal yr B.P.

Comparisons between Archaeology and Ice-Core Records of Paleoclimate

Isotope, dust, snow-accumulation, and acidity records from the Greenland ice cores provide paleoenvironmental type sections against which climatic events in other parts of the world can be compared. The most intensive Paleoindian occupation of the Mesa site occurred around the close of the YD, a 1200–1300-year-long climatic reversal with a strikingly rapid initiation and end (Alley, 2000). The exact relationship between the Paleoindian occupation of the Arctic and the cold, dry climatic conditions typically ascribed to the YD is obscured by the previously described difficulties in the radiocarbon time scale during this period and by inaccuracies in the dating of the Greenland ice cores (Fig. 2). Dating uncertainties in the ice cores are around 2% at levels corresponding to the Pleistocene to Holocene transition (Alley et al. 1995; Meese et al. 1997; Johnsen et al. 1997). Hence, even though the end of the YD is known to have been abrupt (Alley, 2000), age estimates for its end have errors of about ±250 calendar years. Perhaps the best estimate for the end of the YD is 11,640 ± 250 cal yr B.P. (Alley et al. 1993; Alley et al. 1997). In Figure 2, the shaded bars show the range of age estimates for the end of the YD in the GISP2 and GRIP ice cores. Intensive Paleoindian use of the Mesa site may have occurred immediately after the YD as recorded in the GISP2 core. The 1-sigma errors of all but the two youngest of the <11,000 ^{14}C yr B.P. dates from the Mesa site are compatible with this interpretation (Fig. 2). However, given the imprecision of radiocarbon ages during the YD chronozone, it is also possible that Paleoindians were using the Mesa site during the latter half of the YD as well. Whether they were there before, during, or after the YD's termination, the important point remains that Paleoindian occupation of the Arctic occurred during a period of rapid changes in global climate.

Synthesis of Arctic Foothills Paleoenvironmental History

What environmental changes were occurring in northern Alaska when Paleoindians occupied the Arctic Foothills? To answer this question, we used the stratigraphic records contained in fluvial, lacustrine, hillslope, and peat deposits to infer how surficial geology, soils, permafrost, and vegetation responded to rapid climatic changes occurring between 13,000 and 8000 ^{14}C yr B.P. during the Pleistocene to Holocene (P-H) transition in the Arctic Foothills. Results of these studies are reported in detail elsewhere (Mann et al. 2002) and are only summarized here. They show that a series of sweeping changes occurred in land-surface processes and vegetation characteristics in parallel with the general trends in northern hemisphere climate described by the Greenland ice cores.

Central to our reconstructions of paleoenvironmental changes in the Arctic Foothills are the deposits of the Lake of the Pleistocene (LOP), an informally named drained lake 20 km west of the Mesa site in the Arctic Foothills (Fig. 1). The sediments of the LOP are exposed in a cutbank of the Etivluk River and contain lengthy records of lake-level and vegetation changes (Mann et al. 2002). We used sedimentary structures to infer lake-level fluctuations, and pollen and spores to reconstruct vegetation history. The history of lake-level fluctuations indicated by the LOP sections coincides with changes in vegetation, paludification, floodplain dynamics, and solifluction in the surrounding region (Fig. 4). The history of paludification was reconstructed by radiocarbon dating basal peats recovered by augering through permafrost and by examining stratigraphic sections in stream cuts. Floodplain dynamics were described by studying the chronology of terrace aggradation and erosion as revealed in stratigraphic sections along streams draining the Arctic Foothills. The history of solifluction, the slow downslope movement of water-saturated sediments resulting from the thaw of frozen ground, also was documented in stratigraphic sections exposed in stream cuts.

Rising water levels in the LOP around 12,500 ^{14}C yr B.P. marked the beginning of a period of rapid alluviation by braided streams which lasted until ~11,000 ^{14}C yr B.P. Increased alluviation probably was caused by a combination of increased permafrost melting and heightened hillslope erosion, which perhaps was triggered by increased summer rainfall on a landscape with discontinuous vegetation cover (cf. Cogley and McCann 1986; Edlund et al. 1989).

Rising water levels in LOP around 12,5000 ^{14}C yr B.P. also coincide with the spread of shrub tundra in the Arctic Foothills as indicated by pollen records from the LOP and Tukuto Lake (Oswald et al. 1999). At the same time, peat deposition began all across the North Slope (Fig. 4), probably also in response to increasing effective moisture, a well-known trigger for paludification (Gorham 1991; Ovenden 1990). Effective moisture equals annual precipitation minus annual evapotranspiration. Prior to 10,000 ^{14}C yr B.P., peat deposition was limited to topographic low points in the Arctic Foothills, suggesting that effective moisture was lower than during the Holocene. *Populus* trees expanded their range between 12,000 and 11,000 ^{14}C yr B.P. in response to warmer summers and the wider availability of recently deposited alluvium.

Elsewhere in northern and interior Alaska, there also is evidence for a major increase in effective moisture ~12,500 ^{14}C yr B.P. Glaciers in the Brooks Range underwent a minor re-advance between ~13,000 and 11,500 ^{14}C years B.P., possibly in response to increasing winter snowfall (Hamilton, 1986). On the Arctic Coastal Plain, the Ikpikpuk dunes became inactive between ~12,500 and 11,000 ^{14}C yr B.P., most likely in response to increased soil moisture (Carter, 1993). During this same interval in interior Alaska, wetter conditions led to the erosion of extensive gully systems on loess slopes (Hamilton et al. 1988), and water levels at Birch Lake rose >18 m between 12,700 and 12,200 ^{14}C yr B.P. (Abbott et al. 2000).

During the YD, water levels fell in LOP and paludification slowed in the Arctic Foothills (Fig. 4). Streams incised their floodplains, probably because a decline in effective precipitation reduced the input of slope sediments. Sediment input may have declined because of reduced solifluction activity and fewer landslides caused by permafrost melting. The distribution of *Populus* in the Arctic Foothills seems to have retracted, perhaps in response to

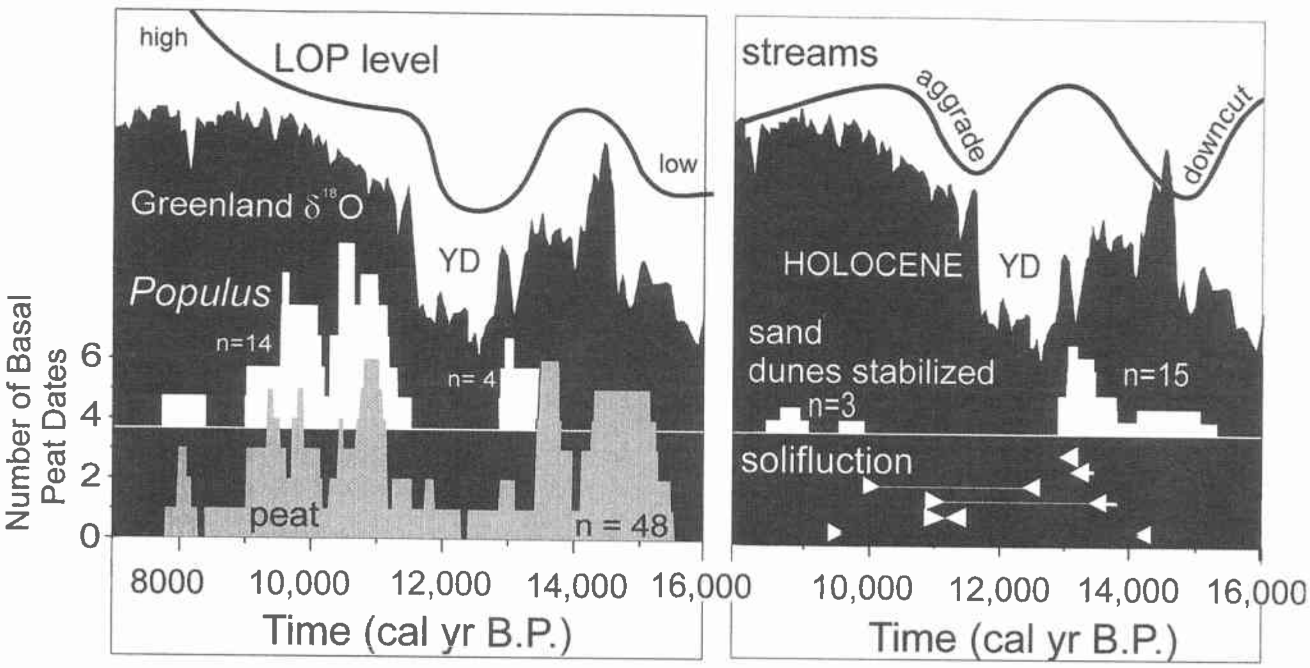

Figure 4. Synthesis of environmental changes in the Arctic Foothills during the Pleistocene-Holocene transition (Mann et al. 2002). Time scale in calendar years to allow comparison with the GISP2, Greenland $\delta^{18}O$ record from Grootes and Stuiver (1997). Histograms depict numbers of ^{14}C dates whose calibrated 1δ age range falls within a given decade. Dates on stabilization of the Ikpikpuk dunes from Carter (1993). Data on stream geomorphology, solifluction, basal peat ages, lake level in Lake of the Pleistocene (LOP), and ages of *Populus* wood come from Mann et al. (2002).

cooler summers and to the shrinkage of its floodplain habitat as streams became entrenched. On the Arctic Coastal Plain, dunes were reactivated after 11,000 ^{14}C yr B.P. in response to decreased soil moisture (Carter 1993).

Around 10,000 ^{14}C yr B.P. water levels in LOP again rose, and *Populus* again expanded its distribution in the Arctic Foothills. A brief episode of widespread solifluction occurred, probably in response to the melting of ground ice that had accumulated during the YD. Rapid alluviation resumed in valleys, and this time, at least in the Ikpikpuk valley, channels assumed meandering planforms. This second aggradation episode perhaps was triggered by intense slope erosion caused by increased summer rains, deeper thawing of soils, and widespread solifluction. In northwestern Canada, numerous thaw lakes developed between 10,000 and 9000 ^{14}C yr B.P. in response to an increase in active-layer thickness (Burn et al. 1986; Burn 1997). Temporary northward extensions of thermophilic plant taxa on the North Slope and in northwestern Canada suggest that summer temperatures were higher than today during the earliest Holocene (Anderson 1988; Nelson and Carter 1987; Ritchie et al. 1983).

The LOP sections suggest that water levels rose further after ~8600 ^{14}C yr B.P. This observation is consistent with paleoclimatic findings elsewhere in the region. On the Arctic Coastal Plain, increasing soil moisture again stabilized the Ikpikpuk dunes ~8500 ^{14}C yr B.P. (Carter 1993). In interior Alaska, water levels at Birch Lake rose markedly between 8800 and 8000 ^{14}C yr B.P. (Abbott et al. 2000; Edwards et al. 2001).

The LOP pollen record suggests that the modern vegetation of the Arctic Foothills, along with its poorly drained, peaty soils, probably was established between 9000 and 8500 ^{14}C yr B.P. Other pollen records from the North Slope (Eisner and Peterson 1998; Oswald et al. 1999) are consistent with this interpretation. The widespread establishment of organic soil horizons was a major turning point for ecosystem history in the Arctic Foothills. Soil temperatures must have fallen and soil moisture risen because of the insulating and water-holding properties of the organic horizons (Bockheim et al. 1998). These same organic surface horizons restricted the frost heaving of mineral material to the ground surface and reduced soil erosion, thus depriving streams of sediment inputs and forcing them into a long-term trend of floodplain incision. As floodplains narrowed and became vegetated, the rate of loess deposition in downwind areas slowed, probably enhancing soil acidification and promoting further plaudification (Walker and Everett 1991).

Changes in Continentality Caused by Flooding of Alaska's Continental Shelves

Shifts in regional and global climate drove many of the landscape changes just described from the Arctic Foothills. One of the most important of these background changes was the flooding of Alaska's continental shelves by post-glacial, sea level rise. Today, Alaska is a peninsula surrounded by seas, and maritime air masses exert strong influences on temperature and precipitation throughout the state. During the LGM, the present Alaska was embedded in a much larger land mass created by the exposure of continental shelves by lower sea level. Increased distance from the ocean affected climate by changing the continentality of many sites. The post-glacial flooding of the Bering Strait has long been identified as a probable cause for major climatic changes in Beringia (Anderson and Brubaker 1994; Cwynar 1982; Elias et al. 1996; Guthrie 1990, 2001; Hopkins 1967, 1982; Lozhkin et al. 1993). To date, no attempt has been made to quantify the effects of changing continentality on Alaska's climate during the flooding of its continental shelves.

Here we present a preliminary analysis of the effects of post-glacial sea level rise on climate near the Mesa site. This analysis consists of six steps starting with the construction of depth/area curves derived from modern bathymetric data (Fig. 5). First, bathymetric data from the National Geophysical Data Center's global bathymetry files were interpolated within 5 × 5 minute areas in the Bering, Chukchi, East Siberian, and Beaufort Seas. Areas were calculated using spherical coordinates. Bathymetric data for depths <150 m then were sorted into 5-m elevation bins for the entire Bering and Chukchi Seas, the East Siberian Sea east of longitude 170° E, and the Beaufort Sea west of longitude 140° W. We excluded from consideration the Pacific continental shelf of Alaska because of extensive Late Wisconsin glaciation of the Aleutian Islands and Alaska Peninsula (Mann and Peteet 1994).

Second, we applied well-dated, eustatic, sea level curves from tectonically stable and ice-sheet distant parts of the globe to infer how post-glacial sea level changed on Alaska's continental shelves. There is no widely applicable, eustatic curve for Alaska (Mann and Hamilton 1995). In lieu of locally derived sea-level histories, post-glacial sea level histories from tropical regions (Bard et al. 1990, 1996; Fairbanks 1989) are the next best thing, especially if they can be constrained locally by limiting dates. Fortunately, work in western Alaska and northwestern Canada (Elias et al. 1992, 1996; Faas 1966; Pelletier 1987; Jordan and Mason 1999) provide limiting dates that check the general applicability of tropical sea level curves to the Bering Strait region. The local dating control, though sparse, verifies that the tropical sea-level curves are indeed applicable to the coastline of northern Alaska (Fig. 6).

The third step involved combining the eustatic sea-level curve with the bathymetric data from Alaska's marginal seas to reconstruct the history of flooding of the continental shelves. Similar results are presented in PALE (2000) at different time and depth intervals. Fourth, we estimated the changing

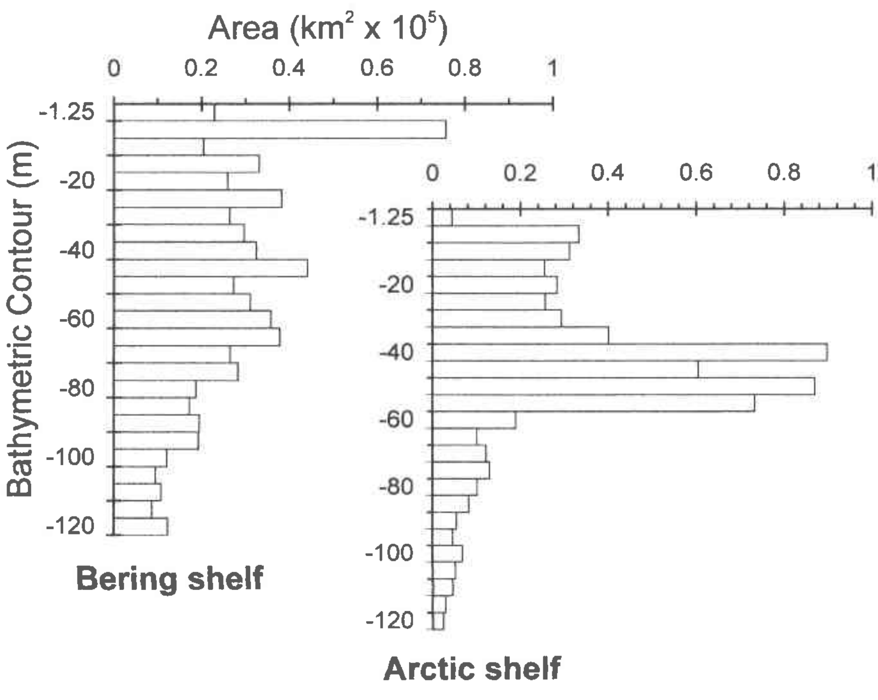

Figure 5. Hypsometry of the Alaskan continental shelves today. The Arctic shelf includes the Chukchi Sea, the Beaufort Sea west of 140° W, and the East Siberian Sea east of longitude 170° E.

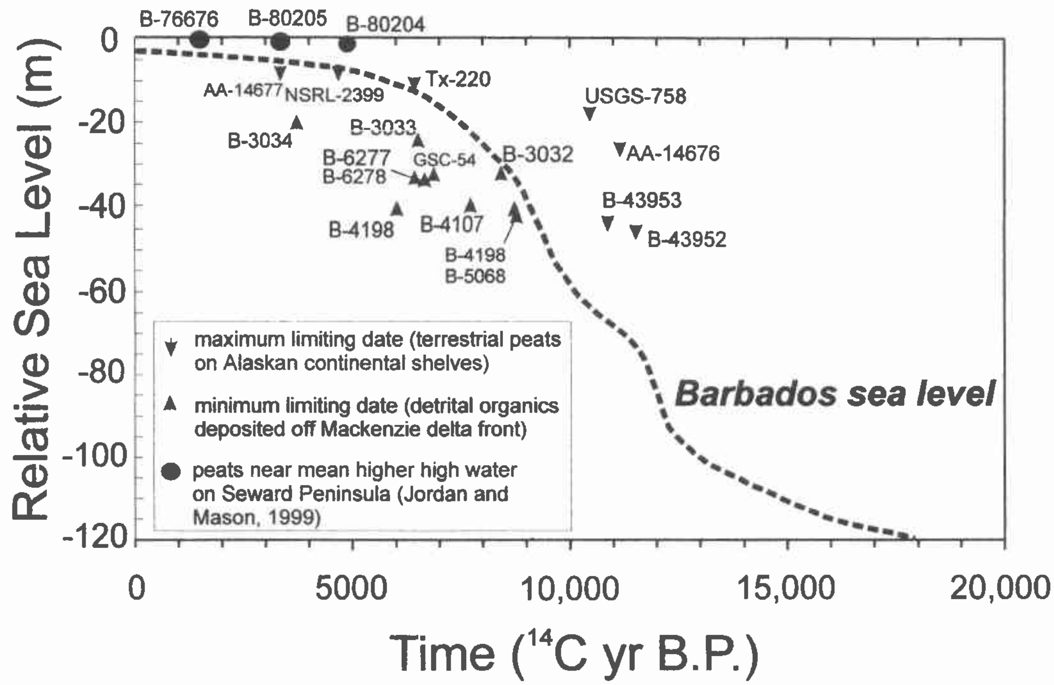

Figure 6. The Barbados sea level curve of Fairbanks (1989) and Bard et al. (1996) compared with maximum-limiting radiocarbon ages on sea level changes on the continental shelves off northern and western Alaska (Faas 1966; Elias et al. 1996; Jordan and Mason 1999). Data from the Mackenzie River delta from Pelletier (1987). Dates produced by Beta-Analytic Incorporated are abbreviated as "B-."

distances between the Mesa site and the Chukchi and Beaufort Sea coasts as sea level rose (Fig. 7).

The fifth step was to establish modern relationships between climatic factors and distance from the sea. Regressions between July mean temperature and distance to the ocean show that interior sites (high continentality) are warmer in summer than coastal ones (Figs. 8, 9). July temperatures increase rapidly in the first 50 km from the coastline then more slowly for 100s of km inland. Transects inland from the southwestern Bering Sea, the Chukchi Sea, and the Beaufort Sea reveal similar relationships between distance inland and July temperature.

The relationship between distance from the sea and mean annual precipitation is more complicated. At weather stations located along a broad transect from Sand Point in the western Gulf of Alaska to Fort Yukon in the eastern interior (Fig. 10), precipitation declines rapidly over the first several hundred km from the coastline, then decreases more slowly for 1800 km inland. In contrast, on the North Slope, precipitation increases markedly inland from the Beaufort Sea over a distance of 250 km to the northern front of the Brooks Range (Zhang et al. 1996). Most of the precipitation on the North Slope, however, falls in July, August, and September and comes from maritime air masses arriving from the Bering Sea region (Moritz 1979). Hence the Beaufort Sea is not acting as the primary moisture source; rather sites on the North Slope are at the extreme interior end of a moisture-transport system originating in the Bering Sea and North Pacific.

The final step in our analysis was to apply these modern relationships to the changing dis-

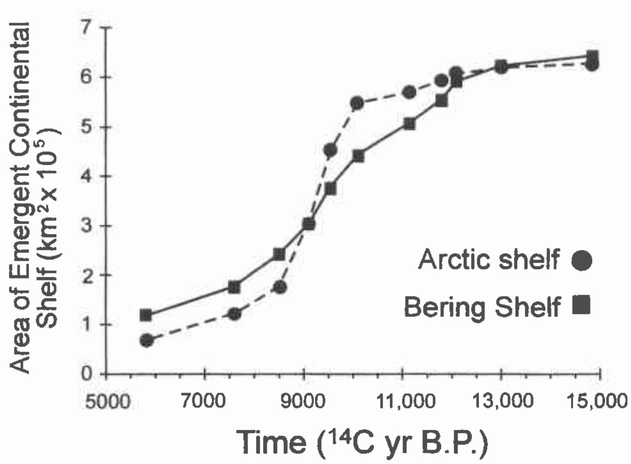

Figure 7. Changes in the area of the emergent continental shelves bordering northern Alaska during the late Pleistocene and early Holocene.

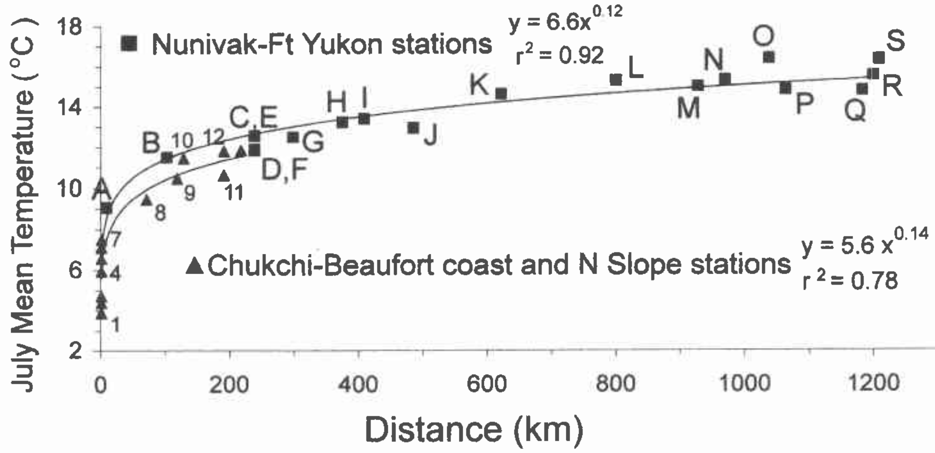

Figure 8. The upper curve shows the gradient in July mean temperature at Alaskan stations along a coast to interior transect stretching northeastwards from Nunivak Island. *A*, Nunivak Island; *B*, Hooper Bay; *C*, Emmonak; *D*, Bethel; *E*, Mountain Village; *F*, St. Mary's; *G*, Russian Mission; *H*, Aniak; *I*, Holy Cross; *J*, Sleetmute; *K*, McGrath; *L*, Lake Minchumina; *M*, Manley Hot Springs; *N*, Nenana, *O*, Fairbanks; *P*, Central; *Q*, Venetie; *R*, Circle; *S*, Fort Yukon. Climate records from Leslie (1989). Bottom line (*triangles*) shows stations at different distances inland from Beaufort and Chukchi Seas. *1*, Barrow; *2*, Point Hope; *3*, Point Lay; *4*, Barter Island; *5*, Wainwright; *6*, Kuparuk; *7*, Lonely; *8*, Franklin Bluffs; *9*, Umiat, *10*, Happy Valley; *11*, Imnavait Creek; *12*, Toolik Lake; *13*, Galbraith Lake. Climate records from Leslie (1989).

tances to the coastline after 18,000 years ago, and to estimate the contribution that the flooding of Alaska's continental shelves had on climatic change near the Mesa site. In this very preliminary analysis, we calculate changing distance to the sea along straight lines drawn northwestward and southwestward from the Mesa site. The bathymetric and sea level history data indicate that flooding of the continental shelves was most rapid between 10,000 and 8500 ^{14}C yr B.P. (Fig. 7). Flooding was especially rapid during this interval in the Chukchi, Beaufort, and East Siberian basins due to the occurrence of extensive shelf areas there that lie between −60 and −40 m (Fig. 5). Regression equations relating modern July temperature to distance from the sea along a line stretching northwest from the Mesa site into the Chukchi Sea suggest July temperatures at the Mesa site fell 1–1.5°C between 10,000 and 9000 ^{14}C yr B.P. in response to rising sea level (Fig. 11). After 9000 ^{14}C yr B.P., cooling rates decreased as the approach of the ocean slowed. When distance to the sea is calculated along a line stretching southwest from the Mesa site into the Bering Sea, cooling starts earlier, ca. 12,000 ^{14}C yr B.P. and achieves maximum rates 11,000–8500 ^{14}C yr B.P., with a total of 1–3° C of cooling predicted between 12,000 and 6000 ^{14}C yr B.P. In contrast, the decline in summer temperature caused by marine transgression along the Beaufort Sea coast was probably minor because of the narrowness of this continental shelf.

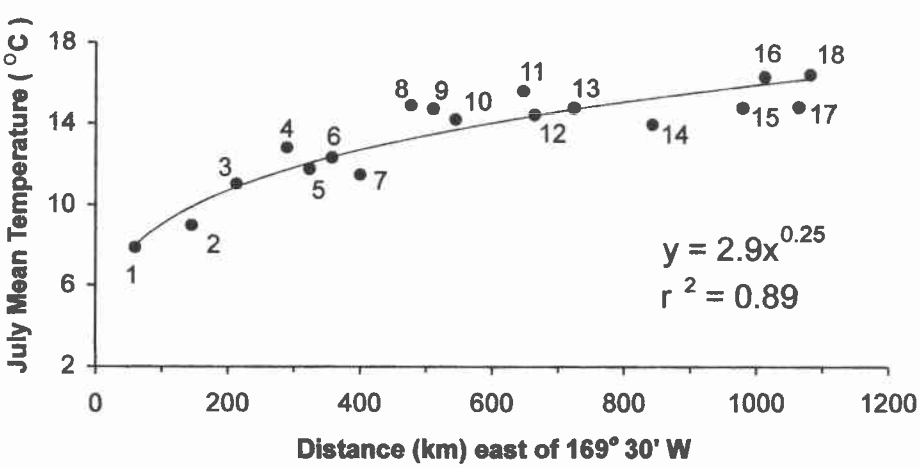

Figure 9. The modern gradient in July mean temperature from coastal Alaska inland along a west to east transect of stations. *1*, Wales; *2*, Shishmaref; *3*, Kivalina; *4*, Kotzebue; *5*, Candle; *6*, Noorvik; *7*, Selawik; *8*, Ambler; *9*, Shungnak; *10*, Kobuk; *11*, Hughes; *12*, Allakaket; *13*, Bettles; *14*, Rampart; *15*, Venetie; *16*, Fort Yukon; *17*, Central; *18*, Circle. Climate records from Leslie (1989).

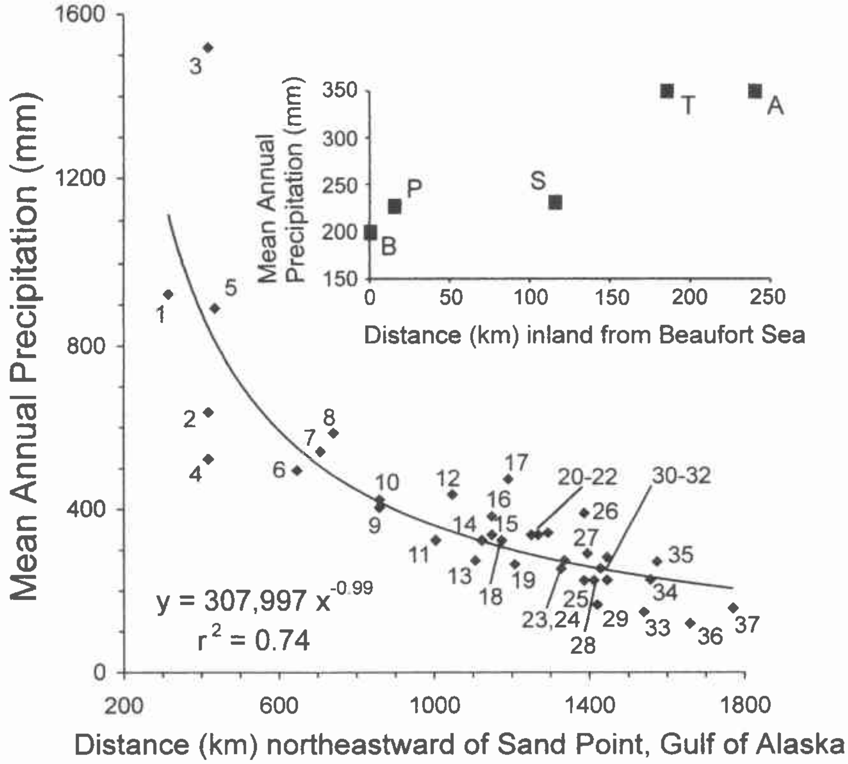

Figure 10. The modern precipitation gradient between Bristol Bay in southwest Alaska and the Beaufort Sea. *1*, Cape Newenham; *2*, Dillingham; *3*, Dillingham 17 NW; *4*, Naknek; *5*, Aleknagik; *6*, Aniak; *7*, Sleetmute; *8*, Stony River; *9*, McGrath; *10*, Farewell; *11*, Galena, *12*, Ruby, *13*, Rampart 2; *14*, Clear; *15*, Tanana; *16*, Manley Hot Springs; *17*, Hughes; *18*, Indian Mountain; *19*, Fairbanks; *20*, Allakaket; *21*, Livengood; *22*, Bettles; *23*, Central; *24*, Circle Hot Springs; *25*, Circle; *26*, Cold Foot; *27*, Wiseman, *28*, Venetie, *29*, Fort Yukon; *30*, Anaktuvuk; *31*, Dietrich; *32*, Chandalar Lake; *33*, Umiat; *34*, Arctic Village; *35*, Coleen River; *36*, Barrow; *37*, Barter Island. Data from Leslie (1989). Inset shows precipitation on North Slope redrawn from Zhang et al. (1996). *B*, Barrow; *P*, Prudhoe Bay; *S*, Sagwon; *T*, Toolik; *A*, Atigun Camp. Climate records from Leslie (1989).

Some of the greatest impacts of lowered sea level on the climate of Beringia probably came through its effects on storm tracks, and this preliminary analysis describes these effects only indirectly. Today, most precipitation in Alaska north of the Alaska Range comes in summer and autumn from cyclonic storms originating in the northwest Pacific Ocean (Hare and Hay 1974; Kane 1996; Moritz 1979). The penetration of Pacific storms into Alaska is markedly seasonal today and probably was also in the past (Bryson and Hare 1974). In winter and spring when sea ice covers much of the Chukchi and Bering Seas, strongly zonal circulation steers Pacific storms south of mainland Alaska across the Gulf of Alaska (NASA/GISS, 1999). During these seasons, high pressure over the Arctic Basin causes northeasterly flow across Alaska's North Slope. Circulation tends to reverse in summer and autumn when ice-free conditions permit meridional circulation to develop over the Bering Sea. Pacific cyclones move northeastward along this trough to penetrate the interior of the state (Hare and Hay 1974; Mock et al. 1998; Moritz 1979). North of the Brooks Range, additional summer precipitation originates from rather weak cyclones generated along the Arctic front over Russian sectors of the Arctic Ocean.

Exposure of the continental shelves during the ice age probably affected storm tracks in several ways. Dry land, like sea ice, deprives cyclonic storms of the thermal energy otherwise available from the underlying water (Lamb 1972). The East Asian Trough was probably less developed when the continental shelves were exposed, and cyclogenesis in Russian sectors of the Arctic basin would have been lessened. It is likely that the Arctic front (Krebs and Barry 1970) was shifted south of the Bering Strait in summer to lie along the southern edge of the exposed Bering Sea shelf where the temperature gradient between sea and land was steepest. The Arctic front would have steered Pacific storms eastwards and away from higher latitudes.

By ignoring the effects of changing storm tracks, our results undoubtedly miss some of the

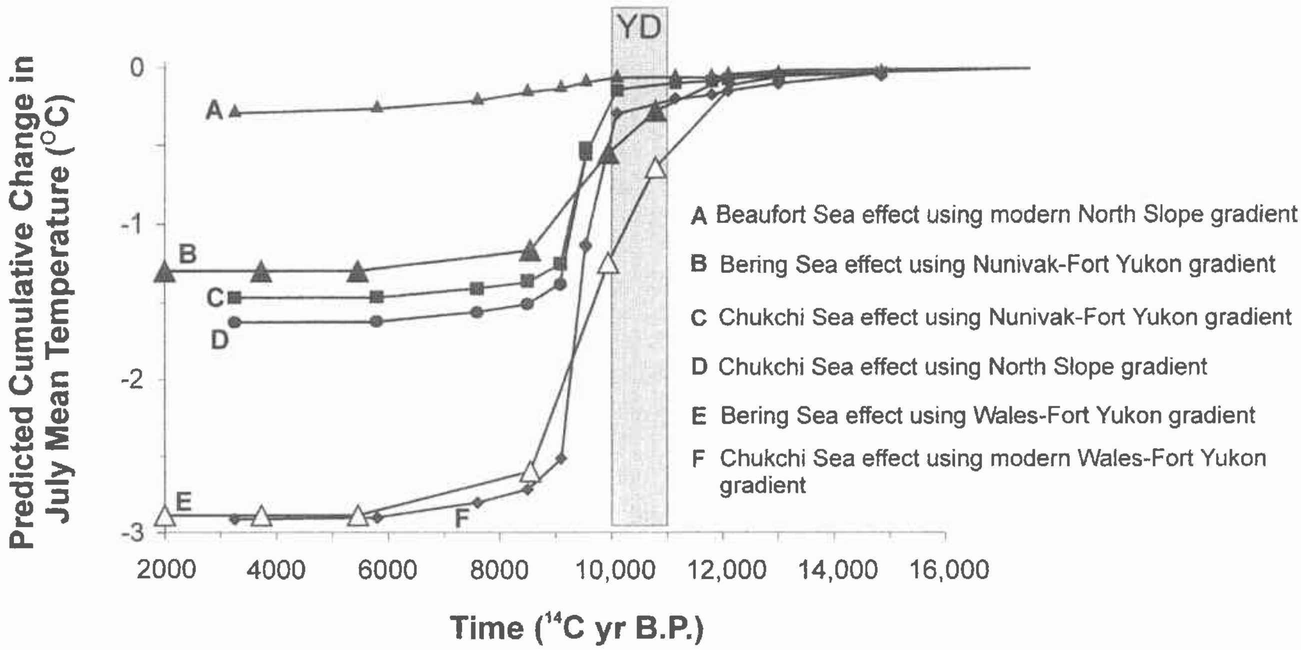

Figure 11. Cumulative changes in July temperature near the Mesa site that could have occurred in response to flooding of the continental shelves. Predictions are based on regressions between modern temperature and distance-to-coast shown in Figures 8 and 9.

most dramatic changes in climate caused by changing continentality. Though similar in sign, the precipitation changes we predict here for the North Slope probably underestimate the total impacts of changing continentality on precipitation.

This said, we use the modern relationship between distance to coast and mean annual precipitation to predict changes in precipitation at the Mesa site caused by the approach of the Bering Sea. The changing distance to the sea is measured along a line drawn southwest across the central Seward Peninsula to St. Matthew Island in the central Bering Sea. Precipitation first increased ca. 12,500 ^{14}C yr B.P., then increased very rapidly 10,000–8000 ^{14}C yr B.P. (Fig. 12). The total predicted increase in mean annual precipitation is 300 mm between the LGM and the mid-Holocene. This figure is a crude estimate. Nonetheless, remembering that mean annual precipitation is only 200–300 mm over much of the North Slope today, it suggests that changing continentality had a major impact on the moisture regime of the North Slope during the Pleistocene to Holocene transition.

Speculations and Discussion

Were Arctic Paleoindians Dependent on Environmental Disturbance?

It would be difficult to find a time period containing more radical shifts in climate and biota than the several millennia years spanning the Pleistocene to Holocene transition; the remainder of the Holocene was uneventful by comparison. Global climate jumped from interglacial conditions to glacial conditions during the YD (Johnsen et al. 1997; Alley 2000; Elias 2000), then back to interglacial conditions within less than a decade around 10,000 ^{14}C yr B.P. (Alley et al. 1993; Alley 2000; Isarin and Bohncke 1999; Mayewski et al. 1993). Widespread extinctions affected the world's megafauna during this interval (Martin and Klein 1984; Guthrie 1990). As described earlier, the flooding of Alaska's continental shelves, especially after 10,000 ^{14}C yr B.P., probably had a great impact on Alaskan climate. Vegetation changes repeatedly swept through northern Alaska between ca. 14,000 and 6000 ^{14}C yr B.P. (Anderson and Brubaker 1994). Shifts in climate and vegetation disturbed soils by altering water erosion, solifluction rates, floodplain extent, and loess deposition.

Why did the Paleoindians utilize arctic Alaska during an interval of repeated, widespread, and rapid environmental disturbances? The answer may be that their prey species flourished intermittently during alternations in ecological disturbance regimes that occurred within this period of rapid climatic change. Any discussion about the ways in which environmental factors controlled human history in northern Alaska 10,000 years ago devolves to a discussion about the effects of the environment on the large-mammal prey species. The climate of

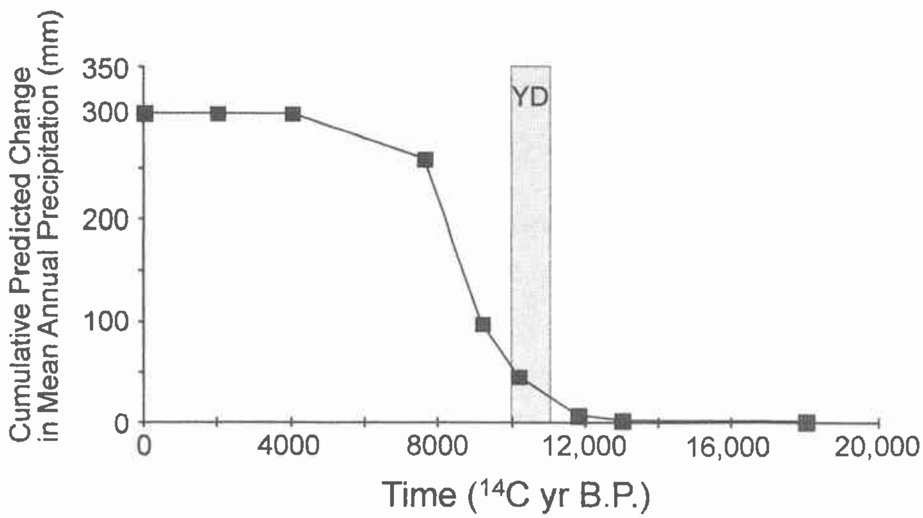

Figure 12. Cumulative changes in precipitation near the Mesa site that could have occurred in response to flooding of the continental shelves. These predictions are based on the modern relationship between distance-to-coast and precipitation shown in Figure 10.

northern Alaska is harsh, and potential food sources are geographically and seasonally limited, especially for people not using marine resources. Ethnographic and archaeological records show unequivocally that in interior (non-coastal) arctic landscapes of North America, aboriginal people relied on the hunting of large ungulate prey species to survive (Meltzer and Smith 1986; Dumond and Bland 1995). In northern Alaska and northern Canada, caribou were the mainstay of interior Inuit populations (Spencer, 1959; McGhee, 1996), and musk oxen were vital to the episodic occupations of the world's northernmost point, Peary Land in northern Greenland, during the Middle and Late Holocene (Knuth 1966/67).

During the transition from Pleistocene to Holocene, bison was the most likely primary prey species of Paleoindians ranging north of the Brooks Range. *Bison priscus* were butchered 9800–9400 ^{14}C yr B.P. at the Engigstciak site 500 km east of the Mesa site (Cinq-Mars et al. 1991) by people using a tool assemblage similar to that used at the Mesa site. The radiocarbon ages of a large series of bones from the Ikpikpuk River indicate that bison were present on the North Slope during the interval 13,000–10,000 ^{14}C yr B.P., but that caribou were rare during this time (P. Matheus, personal communication). On the Great Plains, the people of the Agate Basin Paleoindian complex hunted bison (Frison and Stanford 1982), utilizing a stone tool assemblage very similar to that employed at the Mesa site (Kunz and Reanier 1994; Bever, this volume). The apparent chronological synchrony between Agate Basin and Mesa complexes (Holliday 2000; Kunz and Reanier 1994, 1995) suggests these people dispersed very rapidly across continental distances, which also argues for a hunting economy specialized on a single widespread species (Kelly and Todd 1988). Bison, with their far-ranging migratory behavior and subsequent intercontinental distribution (Guthrie 1990), seems the most likely candidate for this prey species. Natural populations of bison are absent from Alaska today, though several small, introduced populations survive on the geomorphologically disturbed floodplains of the Delta, Kuskokwim, and Chitina Rivers in the interior, the most climatically continental region of Alaska.

The very climatic instability that characterized the Pleistocene-Holocene transition may have allowed bison populations to flourish in northern Alaska during this period. Steppe bison ate mainly graminoids, especially grasses (Guthrie 1990, 2001). In boreal regions where forests are the climax vegetation today, graminoid species capable of supporting bison often are abundant in early successional plant communities. Tree arrival into northern regions lagged behind deglaciation by anywhere from centuries to millennia (MacDonald and Cwynar 1985), and grasses and sedges would have been abundant components of the interim vegetation. Today in the Arctic Foothills, grasses are abundant where soils are disturbed frequently by animal digging, solifluction, stream erosion, or loess deposition (Walker et al. 2001). The species diversity and primary productivity of grasses are highest where soil disturbance prevents organic accumulation and maintains thick active layers. Today in the Arctic Foothills, grasses are important components of vegetation on streamside bluffs, active sand dunes, and recently stabilized floodplains (Walker and Everett 1991). By repeatedly destabilizing soils and interrupting ecological succession, climatic changes may have favored bison habitat in northern Alaska, especially under the continental climate regimes that preceded flooding of the continental shelves.

It also is possible that musk oxen were an important prey species for the Mesa people. Musk ox bones are abundant in Pleistocene- and Holocene-aged deposits along the Ikpikpuk River; though these bones are currently undated. Like bison, musk oxen undergo explosive population growth during brief periods of favorable climate (Jingfors and Klein 1982). Also like bison, the optimal forage of musk oxen is provided by early successional plants growing in geomorphically disturbed sites (Forchhammer and Boomsma 1995; Klein and Bay 1984).

Why did Paleoindians abandon northern Alaska? The answer probably lies with the increasing climatic stability that accompanied the onset of the present interglacial, decreasing continentality, and the resultant spread of tussock-tundra (moist acidic tundra) vegetation. The spread of tussock tundra probably drove bison off the North Slope by greatly reducing the amount of grass-dominated vegetation, by lowering the energetic efficiency of bison locomotion (see Guthrie 1990, 2001), and by fostering dense populations of mosquitoes. In a seasonally and spatially heterogenous landscape, high mobility is important both for large ungulates (Klein 1999) and for hunter-gatherer groups (Mandryk 1993). Human foot travel across tussock tundra is very difficult in summer. Bison are small-footed, dry-ground grazers who cope with seasonal changes in grazing conditions by making long migrations. The location of the Mesa, Putu, Bedwell, and Hilltop sites on lookout points along the northern flank of the Brooks Range may be related to seasonal bison migration routes through these mountains. Besides requiring ease of movement during migration, ungulates, such as bison and caribou, require high mobility on their summer grounds if forage is widely scattered, as typically it is today in the Arctic. Caribou are well adapted to tussock tundra by virtue of their large feet and energetically efficient gait (Klein 1996, 1999); bison are not.

Another attribute of tussock tundra that is hostile to both bison and humans is the huge populations of mosquitoes that breed there in numerous small ponds. Today it is well-known that mosquitoes have deleterious effects on caribou health by robbing them of blood and by harassing them during critical feeding periods (Klein 1999). Mosquitoes probably had similar effects on bison in the Arctic, as they certainly do on humans today. The swarms of mosquitoes that plague the Arctic Foothills in summer today probably accompanied the establishment of the tussock tundra.

Acknowledgments. We thank Charles and Connie Adkins, L. Plug, K. Tae, P. Heiser, E. Dillingham, J. Chase, J. Dubét, T. Reanier, S. Durand, and H. Macdonald for their help in the field. A. Krumhardt and D. Hood provided invaluable laboratory support. We thank D. Murray, C. Parker, and A. Batten for help with macrofossil identifications; O. Mason for references; and D. Meltzer, M. Bever, P. Groves, D. Hopkins, and S. Walker for valuable discussions. The Bureau of Land Management provided funding for support of paleoenvironmental research at the Mesa archaeological site.

End Note

1. Radiocarbon and calendar years diverge widely in the early Holocene and Late Glacial. To describe the interrelationships between the chronologies that are the subject of this study, it is necessary to cite both C-14 and calendar years. We express uncalibrated C-14 ages as "^{14}C yr B.P." Dates that are calibrated to calendar ages are expressed as "cal yr B.P."

References

Abbott, M. B., B. P. Finney, M. E. Edwards, and K. R. Kelts
2000 Lake-level Reconstructions and Paleohydrology of Birch Lake, Central Alaska, Based on Seismic Reflection Profiles and Core Transects. *Quaternary Research* 53:154–166.

Ackerman, R. E.
1996 Spein Mountain. In *American Beginnings,* edited by F. H. West, pp. 456–460. University of Chicago Press, Chicago.

Alley, R. B., A. J. Gow, S. J. Johnsen, J. Kipfstuhl, D. A. Meese, and T. Thorsteinsson
1995 Comparison of Deep Ice Cores. *Nature* 373:393–394.

Alley, R. B., D. A. Meese, C. A. Shuman, A. J. Gow, K. C. Taylor, P. M. Grootes, J. W. C. White, M. Ram, E. D. Waddington, P. A. Mayewski, and G. A. Zielinski
1993 Abrupt Increase in Greenland Snow Accumulation at the End of the Younger Dryas Event. *Nature* 362:527–529.

Alley, R. B., C. A. Shuman, D. A. Meese, A. J. Gow, K. C. Taylor, K. M. Cuffey, J. J. Fitzpatrick, P. M. Grootes, G. A. Zielinski, M. Ram, G. Spinelli, and B. C. Elder
1997 Visual-Stratigraphic Dating of the GISP2 Ice Core: Basis, Reproducibility, and Application. *Journal of Geophysical Research* 102:26,367–26,381.

Alley, R. B.
2000 The Younger Dryas Cold Interval as Viewed from Central Greenland. *Quaternary Science Reviews* 19:213–226.

Anderson, P. M.
1988 Late Quaternary Pollen Records from the Kobuk and Noatak River Drainages, Northwestern Alaska. *Quaternary Research* 29:263–276.

Anderson, P. M. and L. B. Brubaker
1994 Vegetation History of Northcentral Alaska: A Mapped Summary of Late-Quaternary Pollen Data. *Quaternary Science Reviews* 13:71–92.

Arnborg, L., H. J. Walker, and J. Peippo
1966 Water Discharge in the Colville River, 1962. *Geografiska Annaler* 48A:195–210.

Bard, E., B. Hamelin, and R. G. Fairbanks
1990 U-Th Ages Obtained by Mass Spectrometry in Corals from Barbados: Sea Level during the Past 130,000 Years. *Nature* 346:456–458.

Bard, E., B. Hamelin, M. Arnold, L. Montaggioni, G. Cabioch, G. Faure, and F. Rougerie
1996 Deglacial Sea-level Record from Tahiti Corals and the Timing of Global Meltwater Discharge. *Nature* 382:241–244.

Björck, S., B. Kromer, S. Johnsen, O. Bennike, D. Hammarlund, G. Lendahl, G. Possnert, T. L. Rasmussen, B. Wohlfarth, C. U. Hammer, and M. Spurk
1996 Synchronized Terrestrial-Atmospheric Deglacial Records Around the North Atlantic. *Science* 274: 1155–1160.

Bockheim, J. G., D. A. Walker, L. R. Everett, F. E. Nelson, and N. I. Shiklomanov
1998 Soils and Cryoturbation in Moist Nonacidic and Acidic Tundra in the Kuparuk River Basin, Arctic Alaska, USA. *Arctic and Alpine Research* 30: 166–174.

Bryson, R. A. and F. K. Hare
1974 The Climates of North America. In *World Survey of Climatology,* edited by R. A. Bryson and F. K. Hare, pp. 1–48. Climates of North America, Vol. 11. Elsevier Scientific, New York.

Burn, C. R.
1997 Cryostratigraphy, Paleogeography, and Climate Change during the Early Holocene Warm Interval, Western Arctic Coast, Canada. *Canadian Journal of Earth Sciences* 34:912–925.

Burn, C. R., F. A. Michel, and M. W. Smith
1986 Stratigraphic, Isotopic, and Mineralogical Evidence for an Early Holocene Thaw Unconformity at Mayo, Yukon Territory. *Canadian Journal of Earth Sciences* 23:794–803.

Carter, L. D.
1981 A Pleistocene Sand Sea on the Alaskan Arctic Coastal Plain. *Science* 211:381–383.

1993 Late Pleistocene Stabilization and Reactivation of Eolian Sand in Northern Alaska: Implications for the Effects of Future Climatic Warming on an Aeolian Landscape in Continuous Permafrost. In *Proceedings, Sixth International Conference on Permafrost, Beijing, China,* Vol. 1, pp. 78–83. South China University Technology Press, Wushan.

Carter, L. D., L. A. Heginbottom, and M-K. Woo
1987 Arctic Lowlands. In *Geomorphic Systems of North America,* edited by W. L. Graf, pp. 583–628. Geology of North America, Vol. 2, Geological Society of America, Boulder.

Cinq-Mars, J., C. R. Harington, D. E. Nelson, and R. S. MacNeish
1991 *Engigstciak Revisited: A Note on Early Holocene AMS Dates from the "Buffalo Pit."* Occasional Paper No. 1, Canadian Archaeological Association.

Cogley, J. G. and S. B. McCann
1976 An Exceptional Storm and Its Effects in the Canadian High Arctic. *Arctic and Alpine Research* 8: 105–110.

Cwynar, L. C.
1982 A Late-Quaternary Vegetation History from Hanging Lake, Northern Yukon. *Ecological Monographs* 52:1–24.

Dinter, D. A., L. D. Carter, and J. Brigham-Grette
1990 Late Cenozoic Geologic Evolution of the Alaskan North Slope and Adjacent Continental Shelves. In *The Arctic Ocean Region,* edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 459–490. Geological Society of America, Boulder.

Dumond, D. E. and R. L. Bland
1995 Holocene Prehistory of the Northernmost North Pacific. *Journal of World Prehistory* 9:401–450.

Edlund, S. A., B. T. Alt, and K. Young
1989 Interaction of Climate, Vegetation, and Soil Hydrology at Hot Weather Creek, Fosheim Peninsula, Ellesmere Island, Northwest Territories. *Geological Survey of Canada, Paper* 89-1D, pp. 125–133.

Edwards, M. E. and P. W. Dunwiddie
1985 Dendrochronological and Palynological Observations on *Populus balsamifera* in Northern Alaska. *Arctic and Alpine Research* 17:271–278.

Edwards, M. E., C. J. Mock, B. P. Finney, V. A. Barber, and P. J. Bartlein
2001 Potential Analogues for Paleoclimatic Variations in Eastern Interior Alaska During the Past 14,000 Years. *Quaternary Science Reviews* 20:189–202.

Eisner, W. R. and K. M. Peterson
1998 High-resolution Pollen Analysis of Tundra Polygons from the North Slope of Alaska. *Journal of Geophysical Research* 103:28,929–28,937.

Elias, S. A.
2000 Late Pleistocene Climates of Beringia, Based on Analysis of Fossil Beetles. *Quaternary Research* 53:229–235.

Elias, S. A., S. K. Short, and R. L. Phillips
1992 Paleoecology of Late-Glacial Peats from the Bering Land Bridge, Chukchi Sea Shelf Region, Northwestern Alaska. *Quaternary Research* 38: 371–378.

Elias, S. A., S. K. Short, C. H. Nelson, and H. H. Birks
1996 Life and Times of the Bering Land Bridge. *Nature* 382:60–63.

Everett, K. R. and J. Brown
1982 Some Recent Trends in the Physical and Chemi-

cal Characterization and Mapping of Tundra Soils, Arctic Slope of Alaska. *Soil Science* 133: 264–280.

Faas, R. W.
1966 Paleoecology of an Arctic Estuary. *Arctic* 19:343–348.

Fairbanks, R. G.
1989 A 17,000-year Glacio-eustatic Sea Level Record: Influence of Glacial Melting Rates on Younger Dryas Event and Deep-ocean Circulation. *Nature* 342:637–642.

Ferrians, O. J.
1994 Permafrost in Alaska. In *The Geology of Alaska,* edited by G. Plafker and H. C. Berg, pp. 845–854. Geological Society of America, Boulder.

Forchhammer, M. C. and J. J. Boomsma
1995 Foraging Strategies and Seasonal Diet Optimization of Muskoxen in West Greenland. *Oecologia* 104:169–180.

Frison, G. C. and D. J. Stanford
1982 *The Agate Basin Site, A Record of the Paleoindian Occupation of the Northwestern High Plains.* Academic Press, New York.

Galloway, J. P. and L. D. Carter
1993 Late Holocene Longitudinal and Parabolic Dunes in Northern Alaska: Preliminary Interpretations of Age and Paleoclimatic Significance. *United States Geological Survey Bulletin* 2068:3–11.

Gorham, E.
1991 Northern Peatlands: Role in the Carbon Cycle and Probable Responses to Climatic Warming. *Ecological Applications* 1:82–195.

Goslar, T., M. Arnold, E. Bard, T. Kuc, M. F. Pazdur, M. Ralska-Jasiewiczowa, K. Rozanski, N. Tisnerat, A. Walanus, B. Wicik, and K. Wieckowski
1995 High Concentrations of Atmospheric ^{14}C during the Younger Dryas Cold Episode. *Nature* 377: 414–417.

Goslar, T., M. Arnold, N. Tisnerat-Laborde, J. Czernik, and K. Wieckowski
2000 Variations of Younger Dryas Atmospheric Radiocarbon without Ocean Circulation Changes. *Nature* 403:877–880.

Grantz, A., S. D. May, and P. E. Hart
1994 Geology of the Arctic Continental Margin of Alaska. In *The Geology of Alaska,* edited by G. Plafker and H. C. Berg, pp. 17–48. Geological Society of America, Boulder.

Grootes, P. M. and M. Stuiver
1997 Oxygen 18/16 Variability in Greenland Snow and Ice with 10^3 to 10^5-Year Time Resolution. *Journal of Geophysical Research* 102:26,455–26,470.

Guthrie, R. D.
1990 *Frozen Fauna of the Mammoth Steppe.* University of Chicago Press, Chicago, Illinois.

2001 Origin and Causes of the Mammoth Steppe: A Story of Cloud Cover, Wooly Mammoth Tooth Pits, Buckles, and Inside-out Beringia. *Quaternary Science Reviews* 20:549–574.

Hajdas, I., G. Bonani, P. Bodén, D. M. Peteet, and D. H. Mann
1998 Cold Reversal on Kodiak Island, Alaska, Correlated with the European Younger Dryas Using Variations of Atmospheric ^{14}C Content. *Geology* 26:1047–1050.

Hamilton, T. D.
1986 Late Cenozoic Glaciation of the Central Brooks Range. In *Glaciation in Alaska,* edited by T. D. Hamilton, K. M. Reed, and R. M. Thorson, pp. 9–50. Alaska Geological Society, Anchorage.

Hamilton, T. D. and T. Goebel
1999 Late Pleistocene Peoplings of Alaska. In *Ice Age People of North America,* edited by R. Bonnichsen and K. L. Turnmire, pp. 156–199. Oregon State University Press, Corvallis.

Hamilton, T. D., J. L. Craig, and P. V. Sellman
1988 The Fox Permafrost Tunnel: A Late Quaternary Geologic Record in Central Alaska. *Geological Society of America Bulletin* 100:948–969.

Hare, F. K. and J. E. Hay
1974 The Climate of Canada and Alaska. In *Climates of North America,* Vol 11, *World Survey of Climatology,* edited by R. A. Bryson and F. K. Hare, pp. 49–192. Elsevier Scientific, New York.

Heathwaite, A. L., E. G. Göttlich, E. G. Burmeister, G. Kaule, and T. Grospietsch
1993 Mires: Definitions and Forms. In *Mires: Process, Exploitation, and Conservation,* edited by A. L. Heathwaite, pp. 1–76. John Wiley, New York.

Hinzman, L. D., D. L. Kane, C. S. Benson, and K. R. Everett
1996 Energy Balance and Hydrological Processes in an Arctic Watershed. In *Landscape Function and Disturbance in Arctic Tundra,* edited by J. F. Reynolds and J. D. Tenhunen, pp. 131–152. Springer Verlag, New York.

Holliday, V. T.
2000 The Evolution of Paleoindian Geochronology and Typology on the Great Plains. *Geoarchaeology* 15: 227–290.

Hopkins, D. M.
1959 Some Characteristics of the Climate in Forest and Tundra Regions of Alaska. *Arctic* 12:214–220.

1967 The Cenozoic History of Beringia—A Synthesis. In *The Bering Land Bridge,* edited by D. M. Hopkins, pp. 451–484. Stanford University Press, Stanford.

1982 Aspects of the Paleogeography of Beringia during the Late Pleistocene. In *Paleoecology of Beringia,* edited by D. M. Hopkins, J. V. Mathews, C. E.

Schweger, and S. B. Young, pp. 3–28. Academic Press, New York.

Isarin, R. F. B. and S. J. P. Bohncke
1999 Mean July Temperatures during the Younger Dryas in Northwestern and Central Europe as Inferred from Climate Indicator Plant Species. *Quaternary Research* 51:158–173.

Jingfors, K. and D. Klein
1982 Productivity in Recently Established Muskox Populations in Alaska. *Journal of Wildlife Management* 46:1092–1096.

Johnsen, S. J., H. B. Clausen, W. Dansgaard, N. S. Gundestrup, C. U. Hammer, U. Andersen, K. K. Andersen, C. S. Hvidberg, D. Dahl-Jensen, J. P. Steffensen, H. Shoji, A. E. Sveinbjornsdottir, J. White, J. Jouzel, and D. Fisher
1997 The Delta O-18 Record along the Greenland Ice Core Project Deep Ice Core and the Problem of Possible Eemian Climatic Instability. *Journal of Geophysical Research* 102:26,397–426,410.

Jordan, J. W. and O. K. Mason
1999 A 5000-Year Record of Intertidal Peat Stratigraphy and Sea Level Change from Northwest Alaska. *Quaternary International* 60:37–47.

Kane, D.L.
1996 The Impact of Hydrologic Perturbations on Arctic Ecosystems Induced by Climate Change. In *Global Change and Arctic Terrestrial Ecosystems,* edited by W. C. Oechel, T. Callaghan, T. Gilmanov, J. I. Holten, B. Maxwell, U. Molau, and B. Sveinbjornsson, pp. 63–81. Springer Verlag, New York.

Kane, D. L., L. D. Hinzman, M-K. Woo, and K. R. Everett
1992 Arctic Hydrology and Climate Change. In *Arctic Ecosystems in a Changing Climate, an Ecophysiological Perspective,* edited by F. S. Chapin, R. L. Jeffries, J. F. Reynolds, G. R. Shaver, and J. Svoboda, pp. 35–57. Academic Press, New York.

Kelly, R. L. and L. C. Todd
1988 Coming into the Country: Early Paleoindian Mobility and Hunting. *American Antiquity* 53:231–244.

Kitigawa, H. and J. van der Plicht
1998 Atmospheric Radiocarbon Calibrations to 45,000 Years B.P.: Late Glacial Fluctuations and Cosmogenic Isotope Production. *Science* 279:1187–1190.

Klein, D. R.
1996 Arctic Ungulates at the Northern Edge of Terrestrial Life. *Rangifer* 16:51–56.

1999 The Roles of Climate and Insularity in Establishment and Persistence of *Rangifer tarandus* Populations in the High Arctic. *Ecological Bulletins* 47:96–104.

Klein, D. R. and C. Bay
1994 Resource Partitioning by Mammalian Herbivores in the High Arctic. *Oecologia* 97:439–450.

Knuth, E.
1966/7 The Ruins of Musk-ox Way. *Folk* 8–9:191–219.

Krebs, J. S. and R. G. Barry
1970 The Arctic Front and the Tundra-Taiga Boundary in Eurasia. *Geographical Review* 60:548–554.

Kunz, M. L. and R. E. Reanier
1994 Paleoindians in Beringia: Evidence from Arctic Alaska: *Science* 263:660–662.

1995 The Mesa Site: A Paleoindian Hunting Lookout in Arctic Alaska. *Arctic Anthropology* 32:5–30.

Lamb, H. H.
1972 *Fundamentals of Climate Now.* Methuen, London.

Leslie, L. D.
1989 Alaska Climate Summaries: A Compilation of Long-Term Means and Extremes at 478 Alaskan Stations. Alaska Climate Technical Note Number 3. Arctic Environmental Information and Data Center, University of Alaska, Fairbanks.

Lozhkin, A. V., P. M. Anderson, W. R. Eisner, L. G. Ravako, D. M. Hopkins, L. B. Brubaker, P. A. Colinvaux, and M. C. Miller
1993 Late Quaternary Lacustrine Pollen Records from Southwestern Beringia. *Quaternary Research* 39: 314–324.

MacDonald, G. M., A. A. Velichko, C. V. Kremenetski, O. K. Borisova, A. A. Goleva, A. A. Andreev, L. C. Cwynar, R. T. Riding, S. L. Forman, T. W. D. Edwards, R. Aravena, D. Hammarlund, J. M. Szeicz, and V. N. Gattaulin
2000 Holocene Treeline History and Climate Change Across Northern Eurasia. *Quaternary Research* 53(3):302–311.

MacDonald, G. M. and L. C. Cwynar
1985 A Fossil-Based Reconstruction of the Late Quaternary History of Lodgepole Pine (*Pinus contorta* ssp. *latifolia*) in the Western Interior of Canada. *Canadian Journal of Forest Research* 15:1039–1044.

MacNeish, R. S.
2001 The Significance of Early Radiocarbon Dates on Extinct Bison Priscus Bones from Engigstciak, Yukon Arctic Coast. In *Mounds, Modoc, and Mesoamerica: Papers in Honor of Melvin L. Fowler,* edited by S. R. Ahler, pp. 1–24. Illinois State Museum Scientific Papers, Vol. 28. Springfield.

Mandryk, C. A. S.
1993 Hunter-Gatherer Social Costs and the Nonviability of Submarginal Environments. *Journal of Anthropological Research* 49:39–71.

Mann, D. H. and D. M. Peteet
1994 Extent and Timing of the Last Glacial Maximum in Southwest Alaska. *Quaternary Research* 42: 136–148.

Mann, D. H. and T. D. Hamilton
1995 Late Pleistocene and Holocene Paleoenvironments of the North Pacific Coast. *Quaternary Science Reviews* 14:449–471.

Mann, D. H., D. M. Peteet, R. E. Reanier, and M. L. Kunz
2002 Responses of an Arctic Landscape to Late Glacial and Early Holocene Climatic Changes: The Importance of Moisture. *Quaternary Science Reviews* 21:997–1021.

Martin, P. S. and R. G. Klein
1984 *Quaternary Extinctions, A Prehistoric Revolution.* University of Arizona Press, Tucson.

Mayewski, P. A., L. D. Meeker, S. Whitlow, M. S. Twickler, M. C. Morrison, R. B. Alley, and K. Taylor
1993 The Atmosphere during the Younger Dryas. *Science* 261:195–197.

McGhee, R.
1996 *Ancient People of the Arctic.* University of British Columbia Press, Vancouver.

Meese, D. A., A. J. Gow, R. B. Alley, G. A. Zielinski, P. M. Grootes, M. Ram, K. C. Taylor, P. A. Mayewski, and J. F. Bolzan
1997 The Greenland Ice Sheet Project 2 Depth-Age Scale: Methods and Results. *Journal of Geophysical Research* 102:26,411–26,423.

Meltzer, D. J. and B. D. Smith
1986 Paleoindian and Early Archaic Subsistence Strategies in Eastern North America. In *Foraging, Collecting, and Harvesting: Archaic Period Subsistence and Settlement in the Eastern Woodlands,* edited by S. Neusis, pp 3031. Center for Archaeological Investigations Occasional Paper Number 6, Southern Illinois University, Carbondale.

Mock, C. J., P. J. Bartlein, and P. M. Anderson
1998 Atmospheric Circulation Patterns and Spatial Climatic Variability in Beringia. *International Journal of Climatology* 18:1085–1104.

Moritz, R. E.
1979 *Synoptic Climatology of the Beaufort Sea Coast of Alaska.* Institute of Arctic and Alpine Research Occasional Paper Number 30, 176 pp.

Murray, D. F.
1980 Balsam Poplar in Alaska. *Canadian Journal of Anthropology* 1:29–32.

Nelson, R. E. and L. D. Carter
1987 Paleoenvironmental Analysis of Insects and Extralimital *Populus* from an Early Holocene Site on the Arctic Slope of Alaska, USA. *Arctic and Alpine Research* 19:230–241.

NASA/GISS
1999 Storm Track Atlas. URL: http://icp.giss.nasa.gov/cgi-bin/storms1.cgi. NASA/Goddard Institute for Space Studies, New York.

Newman, J. E. and C. I. Branton
1972 Annual Water Balance and Agricultural Development in Alaska. *Ecology* 53:513–519.

Oswald, W. W., L. B. Brubaker, P. M. Anderson
1999 Late Quaternary History of the Howard Pass Area, Northwestern Alaska. *Canadian Journal of Botany* 77:570–581.

Ovenden, L.
1990 Peat Accumulation in Northern Wetlands. *Quaternary Research* 33:377–386.

PALE
2000 Paleoenvironmental Atlas of Beringia, National Geophysical Data Center URL: http://ngdc.noaa.gov/paleo/pale/atlas/beringia/index.html.

Patric, J. H. and P. E. Black
1968 Potential Evaporation and Climate in Alaska by Thornthwaite's Classification. *United States Department of Agriculture Forest Service Research Paper* PNW-71. Pacific Northwest Forest and Range Experimental Station, Institute of Northern Forestry, Juneau.

Pelletier, B. R.
1987 *Marine Science Atlas of the Beaufort Sea: Geology and Geophysics.* Geological Survey of Canada Miscellaneous Report 40, Energy, Mines, and Resources, Ottawa.

Ping, C. L., J. G. Bockheim, J. M. Kimble, G. J. Michaelson, and D. A. Walker
1998 Characteristics of Cryogenic Soils along a Latitudinal Transect in Arctic Alaska. *Journal of Geophysical Research* 103:28,917–28,928.

Rasic, J. T.
2000 Prehistoric Lithic Technology at the Tuluaq Hill Site, Northwest Alaska. M.A. thesis, Department of Anthropology, Washington State University, Pullman.

Reanier, R. E.
1995 The Antiquity of Paleoindian Materials in Northern Alaska. *Arctic Anthropology* 32:31–50.

Ritchie, J. C., L. C. Cwynar, and R. W. Spear
1983 Evidence from North-west Canada for an Early Holocene Milankovitch Thermal Maximum. *Nature* 305:126–128.

Rovansek, R. J., L. D. Hinzman, and D. L. Kane
1996 Hydrology of a Tundra Wetland Complex on the Alaska Arctic Coastal Plain, USA. *Arctic and Alpine Research* 28:311–317.

Scott, K. M.
1978 Effects of Permafrost on Stream Channel Behavior in Arctic Alaska. *United States Geological Survey Professional Paper* 1068:18 pp.

Shaver, G. R., J. A. Laundre, A. E. Giblin, and K. J. Nadelhoffer
1996 Changes in Live Plant Biomass, Primary Production, and Species Composition along a Riverside

Toposequence in Arctic Alaska, USA. *Arctic and Alpine Research* 28:363–379.

Spencer, R. F.
1959 *The North Alaskan Eskimo: A Study in Ecology and Society.* Bureau of American Ethology, Bulletin 171, United States Government Printing Office, Washington, D.C.

Stuiver, M., P. J. Reimer, and R. Reimer
2000 CALIB 4.3 Radiocarbon Calibration. http://depts.washington.edu/qil/calib/calib.html

Stuiver, M., P. J. Reimer, E. Bard, J. W. Beck, G. S. Burr, K. A. Hughen, B. Kromer, G. McCormac, J. Van der Plicht, and M. Spurk
1998 INTCAL98 Radiocarbon Age Calibration, 24,000–0 cal B.P. *Radiocarbon* 40:1041–1084.

Walker, D. A.
1987 Height and Growth-Ring Response of *Salix lanata* ssp. *Richardsonii* along the Coastal Temperature Gradient of Northern Alaska. *Canadian Journal of Botany* 65:988–993.

2000 Hierarchical Subdivision of Arctic Tundra Based on Vegetation Response to Climate, Parent Material, and Topography. *Global Change Biology* 6: 19–34.

Walker, D. A. and K. R. Everett
1991 Loess Ecosysyems of Northern Alaska: Regional Gradient and Toposequence at Prudhoe Bay. *Ecological Monographs* 6:437–464.

Walker, D. A. and M. D. Walker
1996 Terrain and Vegetation of the Imnavait Creek Watershed. In *Landscape Function and Disturbance in Arctic Tundra,* edited by J. F. Reynolds and J. D. Tenhunen, pp. 73–108. Springer Verlag, New York.

Walker, D. A., J. G. Bockheim, F. S. Chapin, W. Eugster, J. Y. King, J. McFadden, G. J. Michaelson, F. E. Nelson, W. C. Oechel, C. L. Ping, W. S. Reeburgh, S. Regli, N. I. Shiklomanov, and G. I. Vourlitis
1998 Energy and Trace-Gas Fluxes across a Soil pH Boundary in the Arctic. *Nature* 394:469–472.

Walker, D. A., J. G. Bockheim, F. S. Chapin, W. Eugster, F. E. Nelson, and C. L. Ping
2001 Calcium-Rich Tundra, Wildlife, and the "Mammoth Steppe." *Quaternary Science Reviews* 20: 149–163.

Zhang, T., T. E. Osterkamp, and K. Stamnes
1996 Some Characteristics of the Climate in Northern Alaska, USA. *Arctic and Alpine Research* 28: 509–518.

1997 Effects of Climate on the Active Layer and Permafrost on the North Slope of Alaska, U.S.A. *Permafrost and Periglacial Processes* 8:45–67.