ENVIRONMENTAL CHANGE AND ARCTIC PALEOINDIANS

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Abstract. Intensive Paleoindian occupation of the Mesa site occurred between 10,300 and 9700 ¹⁴C 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 ¹⁴C 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 ¹⁴C 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-
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-km² 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 (Sphagnno-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-integifoliate-Caricetum bigelowi), which is dominated by non-tussock sedges (Carex bigelowii, C. membranacea, and Eriophorum...
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 auferis 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 14C 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 14C 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 14C 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 14C 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 14C 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 11,220 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 14C 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-
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 oblongolate projectile points (R. Gal, personal communication, 1998; Rasic 2000). In addition, three AMS dates on wood charcoal at the Tulaq 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 chronzone. 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 14C 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 ± 70 14C yr B.P. and Beta-55236, 11,660 ± 80 14C 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 14C 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 ± 60 14C 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 14C 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 14C 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, was also documented in stratigraphic sections exposed in stream cuts.

Rising water levels in the LOP around 12,500 14C yr B.P. marked the beginning of a period of rapid alluviation by braided streams which lasted until ~11,000 14C 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 12,500 14C 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 14C 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 14C 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 14C yr B.P. Glaciers in the Brooks Range underwent a minor re-advance between ~13,000 and 11,500 14C years B.P., possibly in response to increasing winter snowfall (Hamilton, 1986). On the Arctic Coastal Plain, the Ipkikpuk dunes became inactive between ~12,500 and 11,000 14C 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 14C 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
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 early Holocene (Anderson 1988; Nelson and Carter 1987; Ritchie et al. 1983).

The LOP sections suggest that water levels rose further after $\sim$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 $\sim$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 peatification (Walker and Everett 1991).

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 1σ 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).
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. Bathymetric data for depths <150 m 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.
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-
stances 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 14C 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 14C yr B.P. in response to rising sea level (Fig. 11). After 9000 14C 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 14C yr B.P. and achieves maximum rates 11,000–8500 14C yr B.P., with a total of 1–3°C of cooling predicted between 12,000 and 6000 14C 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.
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...
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 14C yr B.P., then increased very rapidly 10,000–8000 14C 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 14C 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 14C yr B.P., probably had a great impact on Alaskan climate. Vegetation changes repeatedly swept through northern Alaska between ca. 14,000 and 6000 14C 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
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; Dumont 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 14C yr B.P. at the Engbigsticik 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 14C 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 heterogeneous 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 "^14C yr B.P." Dates that are calibrated to calendar ages are expressed as "cal yr B.P."

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