# Holocene timberline and palaeoclimate of the northern Uinta Mountains, northeastern Utah, USA

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Received 1 July 2001; revised manuscript accepted 7 March 2002

A HOLOCENE RESEARCH PAPER

**Abstract:** Clastic and organic sediments exposed in two stream cutbanks above modern timberline in the headwaters of the Henrys Fork drainage record multiple episodes of fluvial, lacustrine and wetland deposition. The location of the upper Henrys Fork at the boundary between modern summer-wet/winter-dry and summer-dry/winter-wet precipitation regimes suggests that changes in vegetation during the Holocene were due primarily to variations in growing-season temperature. A radiocarbon date of 9310 ± 70 BP on a *Salix* fragment from the base of one exposure indicates that the upper reaches of the Henrys Fork were vegetated by riparian willows by the early Holocene. Four other dates on wood and bulk organics ranging up to 4070 ± 70 BP indicate that deposition continued through the middle Holocene. High *Picea/Pinus* ratios and high percentages of *Artemisia* pollen suggest that an open *Picea* parkland was established at timberline by 9.5 ka cal. BP, in response to mean annual and July temperatures ~1.0°C greater than at present. Continued warmth through the middle Holocene allowed *Pinus* to expand upwards into the spruce parkland by 7.5 ka cal. BP. A period of maximum warmth was reached between 6.5 and 5.4 ka cal. BP, and near-modern conditions prevailed over the final ~1000 years of the record (until 3.8 ka cal. BP).

**Key words:** Vegetation history, alpine treeline, *Picea*, *Pinus*, palaeoenvironment, palaeoclimate, pollen, Uinta Mountains, Utah, Holocene.

## Background

Recent studies of postglacial palaeoclimate in the western USA have emphasized the role of local factors, such as topography, in amplifying or suppressing broader climatic changes, including the early-Holocene warming that was driven by increased summer insolation (Whitlock and Bartlein, 1993; Feiler *et al.*, 1997). In the central and northern Rocky Mountains, postglacial palaeoclimate records have been studied from the Wind River Range (e.g., Fall *et al.*, 1995), the Colorado Rockies (e.g., Maher, 1972; Short, 1985; Fall, 1992), the Snake River Plain (e.g., Davis *et al.*, 1986) and the Yellowstone/Grand Teton area (e.g., Whitlock, 1993). In contrast, the Uinta Mountains of northeastern Utah have received little attention. Yet, because of their location at the border between two contrasting modern climate regimes and their unique east–west orientation, study of the postglacial history of the Uintas is crucial for developing a broader understanding of the spatial variability of Holocene palaeoclimate in the Rocky Mountains.

Whitlock and Bartlein (1993) completed an analysis of annual precipitation patterns across the western USA, and distinguished two strongly contrasting climatic regimes: summer-wet/winter-dry and summer-dry/winter-wet. During the summer months, high pressure builds in the eastern Pacific Ocean. Widespread atmospheric subsidence associated with the development of this anticyclone suppresses precipitation across much of eastern Washington and Oregon, Idaho, western Montana and Wyoming, resulting in summer drought. During the winter months, the anticyclone decays, and abundant orographic precipitation is produced on upwind slopes of mountain ranges as storm systems sweeping off the Pacific Ocean are carried eastward along the jet stream.

In contrast, areas of the southwestern USA and parts of the western high plains are relatively dry in the winter, due primarily to shielding by upwind mountain ranges. During the summer, however, these areas receive abundant precipitation as monsoonal moisture moves northward from the Gulf of California and Gulf of Mexico. This summer-wet/winter-dry climate is best developed in the southwestern USA, but monsoonal moisture penetrates as far north as Yellowstone National Park (Whitlock and Bartlein, 1993) and northwestern Colorado (Feiler *et al.*, 1997).

Because subregional or local precipitation is primarily controlled by topography, the boundary between the summer-dry/winter-wet and summer-wet/winter-dry regimes has remained

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fixed through the Holocene (Whitlock *et al.*, 1995). Moreover, areas currently experiencing a summer-dry/winter-wet regime became drier as increased summer insolation augmented the eastern Pacific High in the early Holocene (Thompson *et al.*, 1993). Simultaneously, areas currently affected by monsoonal moisture became moister as increased sea-surface temperatures (driven by amplified summer insolation) strengthened the monsoon (Thompson *et al.*, 1993; Whitlock and Bartlein, 1993).

Regions located along the modern boundary between these climatic regimes experience a relatively even distribution of precipitation throughout the year. They are located far enough from the eastern Pacific high-pressure system, and near enough to the monsoonal circulation, to receive moderate amounts of summer moisture. Likewise, while they may be partially shielded by upwind mountain ranges, considerable moisture is still delivered during winter months by storms tracking eastward along the jet stream. Given the apparent stability of this climatic boundary over time (Whitlock *et al.*, 1995; Feiler *et al.*, 1997), the modern balanced distribution of annual precipitation in these areas should have persisted throughout the postglacial period. Palaeoclimate records from these areas should, therefore, primarily record insolation-driven changes in temperature; effects of seasonal redistribution of precipitation should have been minimal.

This theory has relevance to study of palaeoclimate records from the Uinta Mountains because the modern boundary between the summer-dry/winter-wet and summer-wet/winter-dry regimes is located in the vicinity of the Uintas in northeastern Utah (Mitchell, 1976). Palaeoclimate archives from the Uintas should therefore primarily record temperature changes free from the complicating effects of precipitation variations.

Accordingly, this study involved construction of a Holocene palaeoclimate record for the northern Uintas based on pollen preserved in clastic and organic sediments exposed in two stream cutbanks in the headwaters of the Henrys Fork, a tributary of the Green River draining the north-central Uinta Mountains (Figure 1). The sediments in the lower cutbank (Exposure HF98–1), located ~1 km southwest of Dollar Lake at 3300 m a.s.l., accumulated behind a moraine dam that persisted until the later Holocene. Exposure HF98–2, located ~4 km south of Dollar Lake in the upper basin at 3500 m, was impounded by debris flow deposits (Figure 1).

## Previous work

Two previous studies of Holocene vegetation and climate in the Uintas focused on sites located below modern timberline at the eastern end of the range. Carrara *et al.* (1985) analysed pollen data from a subalpine lake (at 3135 m a.s.l.) and suggested that the climate was cooler than present from 6500 to 4600 $^{14}$C yr BP, and warmer than present from 4600 to 600 $^{14}$C yr BP. A period of maximum warmth spanned from 4600 to 2100 $^{14}$C yr BP, and the past 600 years were the coolest of the record. The authors concluded that upper timberline lay above the lake for the entire record, and that the local climatic changes were minor (Carrara *et al.*, 1985).

More recently, Elias and Short (1995) investigated fossil insects and pollen from two meadows on the south slope of the Uintas. Conclusions were hampered by a paucity of insect fossils and reversals in radiocarbon ages. Nevertheless, the pollen data suggest that cooler and moister conditions prevailed between 5300 and 5100 $^{14}$C yr BP, followed by conditions similar to the present for the past 5100 $^{14}$C years (Elias and Short, 1995).

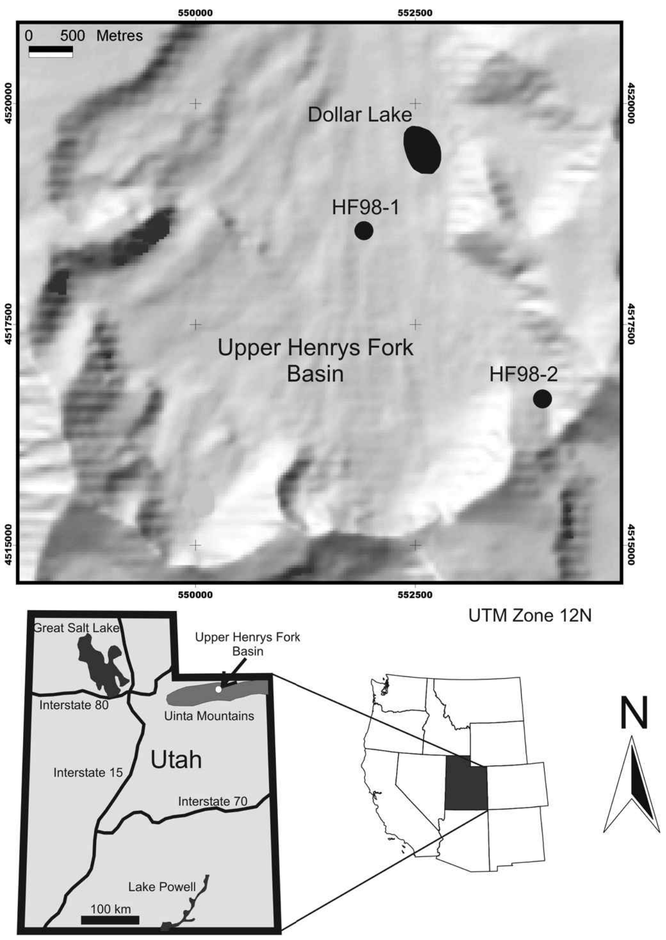



**Figure 1** Location of the Uinta Mountains in northeastern Utah, the upper Henrys Fork basin, and the two exposures (HF98–1 and HF98–2).

## Setting

The Uinta Mountains extend approximately 150 km across northeastern Utah (Figure 1). Structurally, the Uintas are a Laramide-age uplift of Precambrian sedimentary rocks comprising the highest summits in Utah. Alpine glaciation was extensive in the Uintas during the Pleistocene, but no glaciers are extant in the range today. Instead, the compound cirque basins are filled with a mosaic of lakes, wet meadows and relatively dry uplands interspersed with outcrops of striated and polished bedrock.

Timberline, the upper elevation of continuous forest (Wardle, 1965), averages 3300 m a.s.l. in the upper Henrys Fork, although isolated patches of spruce/fir krummholz are present to 3450 m a.s.l. The primary tree species at timberline are *Picea engelmannii* (Engelmann spruce) and *Abies lasiocarpa* (subalpine fir). *Pinus contorta* (lodgepole pine) is locally present and increases in abundance at lower elevations, dominating the forest below 2900 m. *Salix* (willow) species are ubiquitous along the stream courses, and Cyperaceae (sedge) species are present in poorly drained areas. *Polygonum bistortoides* (alpine bistort), *Artemisia* (sagebrush) and members of the Rosaceae (rose family), Caryophyllaceae (pink family), Saxifragaceae (saxifrage family) and Poaceae (i.e., Gramineae, grasses) are present on well-drained sites near timberline and upward into the alpine tundra.

On the basis of modern climate data from Snowpack Telemetry (SNOTEL) stations in the northern Uintas, the adiabatic lapse rate for July is 6.6°C/km, and the rate for mean annual temperature is 5.3°C/km (J.S. Munroe, unpublished analysis of SNOTEL data). Given these rates and the site elevations, July temperatures at the study sites average 9 to 10.5°C, while mean annual temperatures are below 0°C (–1.6 to –0.6°C). Extrapolation from lower elevation SNOTEL stations (*c*. 3000 m) across the north slope of the range reveals that precipitation averages ~900 mm per year, with 60% falling as snow in the upper Henrys Fork (J.S. Munroe, unpublished analysis of SNOTEL data).

## Methods

Both exposures were surveyed with an eye-level and stadia rod, with elevations determined relative to the water level in the streams running along their bases. Samples were taken of each major clastic unit for grain-size analysis, while organic-rich layers were sampled for radiocarbon dating and pollen analysis. Grain-size distribution was determined through a combination of wet-sieving and hydrometer analysis, and analysed statistically with the moment method (Krumbein and Pettijohn, 1938; Boggs, 1987). The grain-size data, stratigraphy and sedimentary features were used to distinguish sedimentary facies from which depositional environments were interpreted. Six of the organic samples were dated by a combination of conventional and AMS techniques. Radiocarbon dates (designated as '$^{14}$C') were calibrated using the online program CALIB 4.3 (Stuiver *et al.*, 1998; 2000); calibrated dates are noted as 'cal. BP' in the text. Interpolation of ages for other strata was performed assuming a linear sedimentation rate using DEP-AGE v.3.9 (Maher, 1992; 1998). Fossil pollen was extracted from 10 organic layers and three organic-rich clastic layers with a treatment of acetolysis and HF (Faegri and Iversen, 1989). Pollen concentrates were mounted in silicone, and a total of ~400 grains, including aquatics, palynomorphs and unknown or indeterminate pollen types, was counted for each level; Cyperaceae grains were tallied but not included in the pollen sum due to their extreme abundance in several of the samples. Vegetation reconstructions were based on a comparison of fossil pollen spectra with three samples of modern pollen obtained from wet and dry surfaces within 10 m of each of the two exposures (six samples total). Ratios were calculated between percentages of specific taxa in fossil and modern pollen sums, allowing data from both exposures, which are located at different elevations, to be considered simultaneously.

Finally, period-of-record averages for annual precipitation at 16 SNOTEL stations in the Uinta Mountains were analysed to determine the position of the upper Henrys Fork basin relative to the modern summer-wet/winter-dry and summer-dry/winter-wet climatic boundary. Average summer (June/July/August) and winter (December/January/February) precipitation was calculated at each station and normalized as a percentage of total annual precipitation. The difference between summer and winter precipitation percents was then linked to the locations of the SNOTEL stations in a GIS allowing interpolation of a surface representing the balance between modern summer and winter precipitation across the range.

## Results and interpretations

### Sedimentology and stratigraphy

Figures 2 and 3 present a summary of the stratigraphy and sedimentology of Exposures 98HF-1 and 98HF-2; details of the sedimentology, stratigraphy and facies interpretations will be presented elsewhere. Both exposures contain numerous layers of clastic sediment, which range in mean grain size from fine silt (0.006 mm) to medium sand (0.177 mm). The mean grain size of the 20 samples from Exposure HF98–1 and the eight samples from Exposure HF98–2 is identical (.024 mm, medium silt), but layers in Exposure HF98–2 are less well sorted. Peat layers containing fragments of *Salix* wood are present at the base of both exposures, directly above glacial till. Multiple peat layers are present at higher levels within the sections (four in HF98–1 and six in HF98–2). These are conformable over lower clastic layers, but bounded above by unconformities. The uppermost peat layer in HF98–1 and the layer between 125 and 150 cm in HF98–2 exhibit loading structures suggesting rapid deposition of the overlying sediment.

The stratigraphy in Exposure HF98–1 represents lateral migration of the Henrys Fork channel as the basin impounded behind the end-moraine downstream gradually filled in. The coarsest layers were deposited when the sandy channel of the Henrys Fork was at the site of the exposure. Conversely, the finest layers were deposited when the channel had migrated away from the site, and low-energy slackwater deposits accumulated only during the highest floods. Peat layers accumulated when the water table was at or above the ground surface, and sedges and willows grew in a wet-meadow environment. Peat layers in Exposure HF98–2 represent a similar setting, but the character of deposition at the site was controlled by mass wasting off the cirque headwall to the east and south. Coarser layers in this section represent proximal debris-flow deposits, while finer layers represent more distal sedimentation.

### Chronology

The oldest date (sample HF98–1-26) of 10415–10305 cal. BP (9370 ± 70 BP, Beta-125001), on a fragment of *Salix* wood from the basal peat layer immediately above diamicton in Exposure HF98–1, indicates that sedimentation began behind the end-moraine dam in the earliest Holocene (Table 1; Figure 2). A second date (HF99–01) of 9662–9478 cal. BP (8570 ± 80 BP, Beta-134567), also on *Salix* from the lowest peat layer in Exposure HF98–1, indicates that peat accumulation spanned at least 800 years. Two AMS dates (AA32843 and AA32835) on thin peat layers higher in the section reflect continued deposition until at least the middle Holocene (Table 1). A date of 8135–7980 cal. BP (7310 ± 70 BP, Beta-125003) from the lowest peat layer (HF98–2-15) in Exposure HF98–2 indicates that accumulation of organics began ~2000 years later at the higher-elevation site. The youngest date (HF98–2-11) of 4805–4435 cal. BP (4070 ± 70 BP, Beta-125002), on a peat layer near the top of the exposure, demonstrates that deposition continued until at least the middle Holocene. Ages for intervening pollen-bearing strata were estimated by linear interpolation from the bracketing radiocarbon ages (Table 2). Extrapolation was required for the youngest sample (HF98–2-13).

### Modern climatic regime

Mean annual precipitation (MAP) at the 16 SNOTEL sites in the Uinta Mountains ranges from 546 to 1067 mm (mean of 766 mm). The correlation between station elevation and MAP is quite weak ($r^2 = 0.24$), indicating that elevation is not the major control on precipitation. However, there are consistent patterns in the spatial distribution of seasonal precipitation (Figure 4). Areas in the eastern Uintas have a summer-wet/winter-dry precipitation regime today, receiving 5–10% more of their annual precipitation in the summer than in the winter. In contrast, parts of the western Uintas receive 10% more of their annual precipitation during the winter months. The boundary between the two climatic regimes, signified by the 0 contour in Figure 4, passes through the upper Henrys Fork basin, indicating that modern precipitation in the study area is equally divided between the summer and winter months.

### Pollen analysis

*Pinus* (pine) pollen dominates the arboreal component (33–52%) of the modern pollen spectra, with lesser amounts of *Picea* (spruce, 6–21%) and *Abies* (fir, <3%). Minor amounts of *Quercus* (oak), *Betula* (birch) and *Alnus* (alder) are also present. *Artemisia* (sagebrush, 8–17%) and Poaceae (grass, 5–18%) comprise most

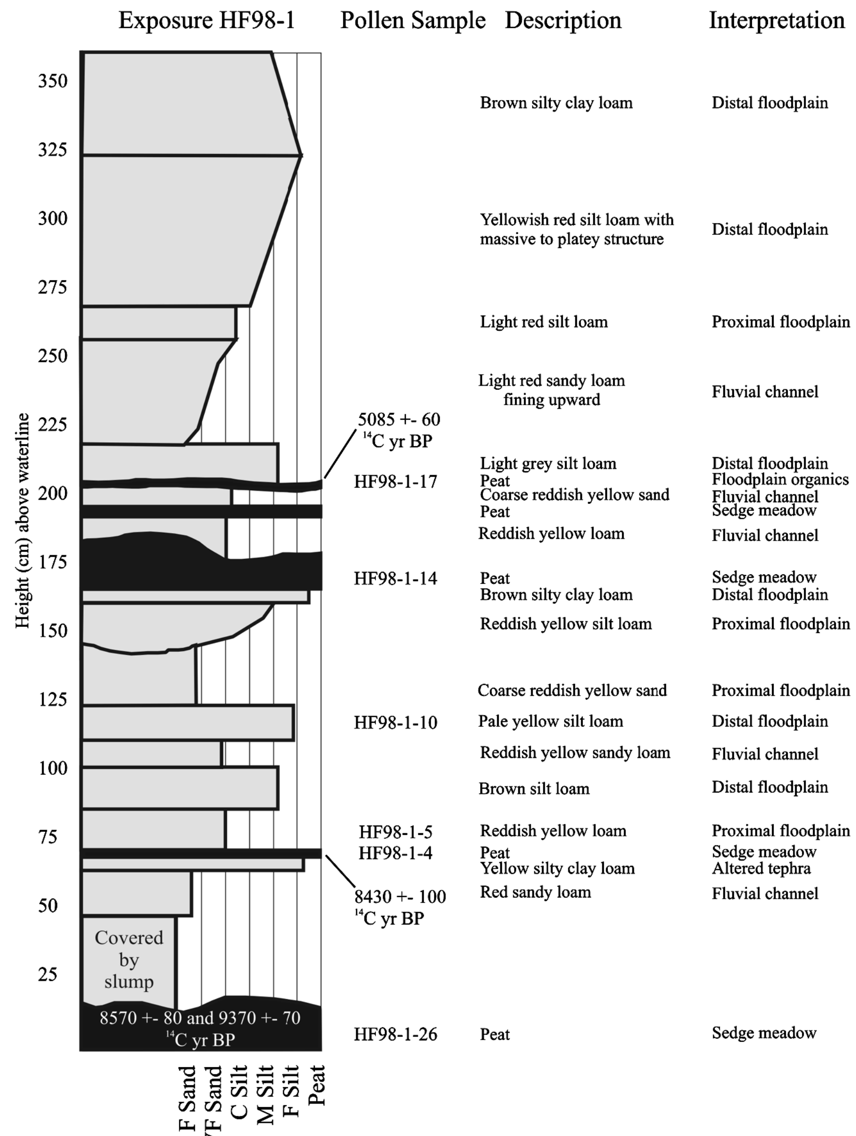



**Figure 2** Stratigraphy and radiocarbon dates for Exposure HF98–1 (vertical scale in cm above the water level). Interpretations of depositional environment are based on sedimentology.

of the non-arboreal component, although *Ambrosia* (ragweed, 2–11%) and Cheno-Ams (combined Chenopodiaceae and Amaranthaceae, 2–5%) are also present. *Salix*, a common element of the modern floodplain community, makes up 2–9% of the pollen sum, while Cyperaceae, which dominates the saturated wet-meadow environments, comprises 5–27% of the total number of grains counted in the four samples from wet surfaces. Minor amounts of *Polygonum* (probably *P. bistortoides*; alpine bistort), Rosaceae (rose family), Caryophyllaceae (pink family) and Saxifragaceae (saxifrage family) reflect the presence of these plants in the upper basin. Finally, *Sarcobatus* (greasewood) and *Ephedra* (joint fir; both *E. nevadensis* and *E. torreyana*) are also present in minor quantities, reflecting long-distance transport of these pollen types from drier, lower-elevation sites, probably the Green River Basin in southwestern Wyoming.

Palaeopollen data are presented in Figure 5 (Section HF98–1) and Figure 6 (Section HF98–2) as percentages of the pollen sum (exclusive of Cyperaceae). All samples are dominated by *Pinus* pollen with subordinate *Picea*. *Pinus* pollen comprises 18–49% of the pollen sum, while *Picea* percentages range from 7 to 39%. Samples from the higher-elevation section HF98–2 have generally higher percentages of *Salix* pollen (mean of 9% in HF98–2 versus 5% in HF98–1), suggesting that this location has always been vegetated by willows. Although it was not included in the pollen sum, Cyperaceae, which was probably growing on the site, dominates samples HF98–1-4 (62% of total grains identified) and HF98–1-10 (60%). These values are greater than those of the modern wet-meadow surface samples (~20%) indicating that the site of Exposure HF98–1 was a sedge fen at times in the past.

To facilitate integration of samples from the two sites, percentages of key pollen types (*Pinus*, *Picea*, *Artemisia*, Cheno-Ams) were normalized to their mean modern values and plotted against time (Figure 7). The estimated ages assigned to each sample represent a combination of calibrated radiocarbon dates and linear interpolations presented in Tables 1 and 2. *Pinus* ratios were lower than modern in the early Holocene and increased in younger sediments. *Picea* ratios fluctuated considerably through the period of record, reaching a maximum about 6.6 ka cal. BP. *Artemisia* ratios varied in the early Holocene, but stayed essentially constant at half their modern value from 8 to 4 ka cal. BP.

## Discussion

### Palaeoclimate reconstructions

Maher (1963) demonstrated that, in the San Juan Mountains of Colorado, the ratio of *Picea* to *Pinus* pollen varies predictably with elevation above timberline. *Picea* pollen grains are consider-

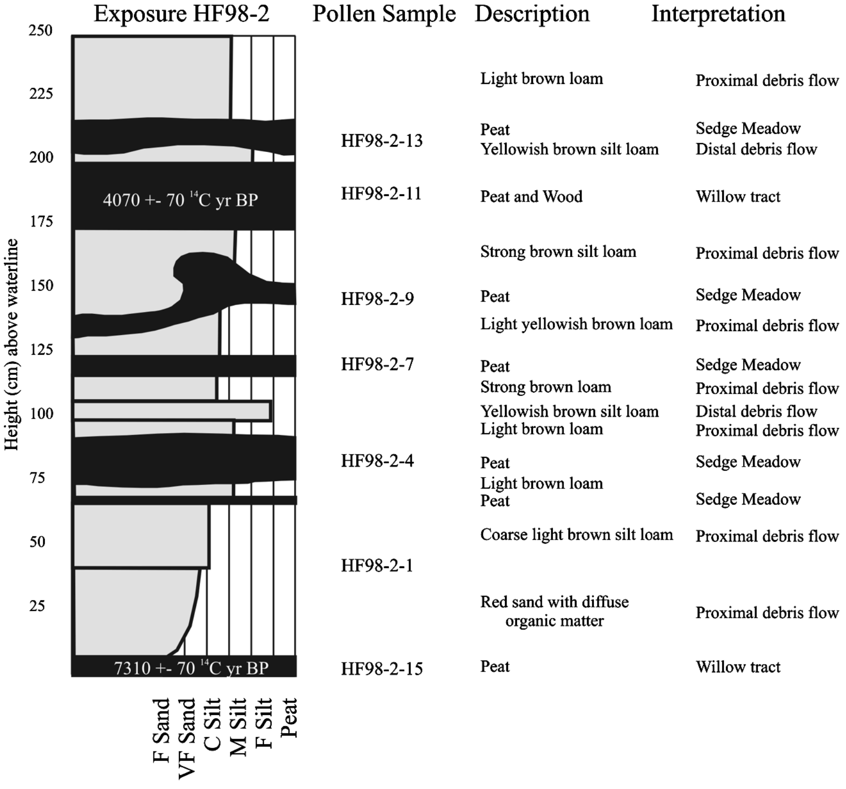



**Figure 3** Stratigraphy and radiocarbon dates for Exposure HF98–2 (vertical scale in cm above the water level). Interpretations of depositional environment are based on sedimentology.

**Table 1** Radiocarbon dates from the Henrys Fork sections

| Sample | $^{14}C$ age ± 1 sg (yr BP) | Sample material | 1 sigma range | Lab. no. |
|---|---|---|---|---|
| HF98-1-17 | 5085 ± 60 | woody peat | 5906–5752 | AA32835 |
| HF98-1-04 | 8430 ± 10 | woody peat | 9531–9302 | AA32843 |
| HF90-01 | 8570 ± 80 | *Salix* | 9662–9478 | Beta-134567 |
| HF98-1-26 | 9370 ± 70 | *Salix* | 10415–10305 | Beta-125001 |
| HF98-2-11 | 4070 ± 70 | woody peat | 4805–4435 | Beta-125002 |
| HF98-2-15 | 7310 ± 70 | woody peat | 8135–7980 | Beta-125003 |

The 1 sigma ranges were determined from CALIB 4.3 (Stuiver *et al.*, 1998; 2000).
AA is the NSF-AMS facility at the University of Arizona.
Beta is Beta Analytic.

**Table 2** Interpolated ages* from the Henrys Fork sections

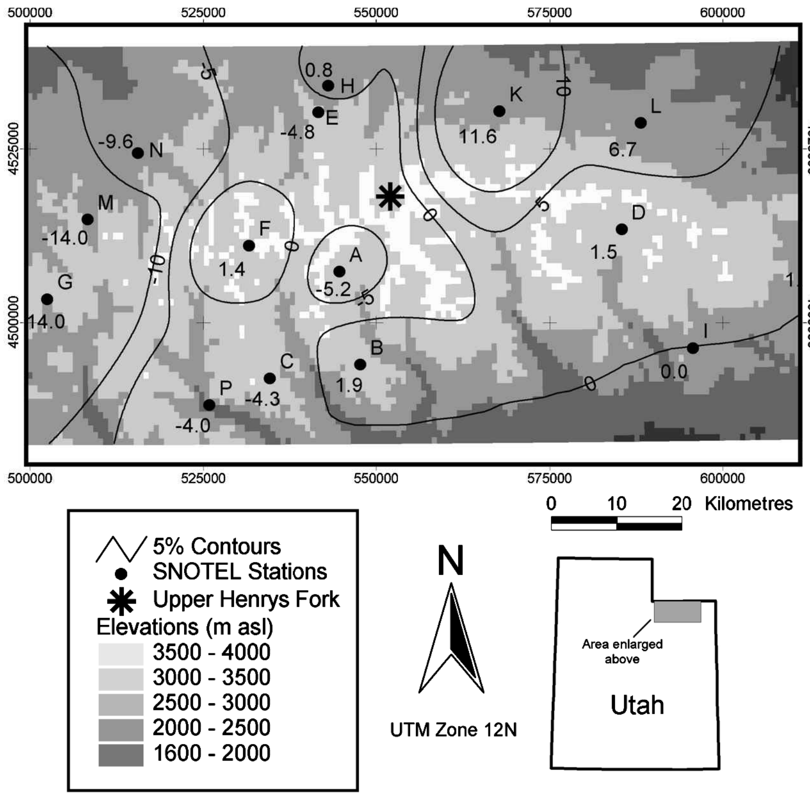
| Sample | Interpolated $^{14}C$ age | Sample material | Calendar age |
|---|---|---|---|
| HF98-1-14 | 5816 | peat | 6650 |
| HF98-1-10 | 7179 | organic silt loam | 7990 |
| HF98-1-5 | 8294 | organic silt | 9330 |
| HF98-2-13 | 3500 | peat | 3750 |
| HF98-2-9 | 4674 | peat | 5400 |
| HF98-2-7 | 5200 | peat | 5950 |
| HF98-2-4 | 5813 | peat | 6570 |
| HF98-2-1 | 6601 | organic-rich sand | 7500 |

*Interpolated ages were computed using DEP-Age v. 3.9 (Maher, 1992; 1998).

ably larger than *Pinus* grains, and do not travel as far from their source (Fall, 1992). In addition, the lighter *Pinus* pollen is produced in greater quantities. Therefore, the *Picea/Pinus* ratio varies with altitude, reaching a maximum value at timberline and decreasing with elevation above (and below) timberline (Maher, 1963).

To investigate how the elevation of timberline varied in the northern Uintas during the Holocene, *Picea/Pinus* ratios were calculated for the six surface samples from the upper Henrys Fork. Modern ratios for the higher-elevation site HF98–2 average 0.15 ($s$ = 0.01). Surface samples from near Exposure HF98–1 have larger ratios (0.51, 0.19 and 0.19), as would be expected given its closer proximity to timberline (i.e., more *Picea*). The sample with the highest ratio (0.51) was collected from a wet surface along the modern Henrys Fork that was probably inundated during the nival flood. Deposition of additional *Picea* grains, or preferential removal of lighter *Pinus* grains, may explain the higher *Picea/Pinus* ratio in this sample. Given the close correspondence of the other two ratios from this site, this value was discarded, and the modern ratio at Exposure HF98–1 was considered to be 0.19.

To determine the relative elevation of palaeotimberline during the first half of the Holocene, *Picea/Pinus* ratios for 10 peat layers in Exposures HF98–1 and HF98–2 were normalized to the mean modern values (0.19 and 0.15) at the two sites. This technique allowed samples from both locations to be considered simultaneously, providing an integrated view of how palaeotimberline varied in the upper Henrys Fork. Mosimann confidence intervals (95%) on these ratios were determined using the program MOSLIMIT (Maher, 1997). Three samples, HF98–1-5, HF98–1-10 and HF982–1, were excluded from this analysis because they are relatively organic-rich clastic sediments representing different depositional environments than the peat layers, which probably accumulated in wet meadows (Table 1). The *Picea/Pinus* ratio rose rapidly after 10.2 ka cal. BP, reaching a maximum more than 4 times the modern value between 9.4 and 8.1 ka cal. BP (Figure




| SNOTEL Name | Elevation m | Letter | MAP mm | J/J/A mm | D/J/F mm | J/J/A % | D/J/F % | Difference * | Strength | Pattern |
|---|---|---|---|---|---|---|---|---|---|---|
| Five Point Lake | 3309 | A | 864 | 152 | 197 | 17.6 | 22.8 | -5.2 | moderate | winter wet |
| Lake Fork #1 | 3303 | B | 673 | 165 | 152 | 24.5 | 22.6 | 1.9 | weak | summer wet |
| Brown Duck | 3212 | C | 876 | 178 | 216 | 20.3 | 24.6 | -4.3 | moderate | winter wet |
| Chepeta | 3121 | D | 838 | 165 | 152 | 19.7 | 18.2 | 1.5 | weak | summer wet |
| Steel Creek Park | 3061 | E | 787 | 152 | 191 | 19.4 | 24.2 | -4.8 | moderate | winter wet |
| Lakefork Basin | 3061 | F | 927 | 229 | 216 | 24.7 | 23.3 | 1.4 | weak | summer wet |
| Trial Lake | 3018 | G | 1067 | 178 | 330 | 16.7 | 31 | -14.3 | strong | winter wet |
| Hewinta | 2879 | H | 645 | 143 | 138 | 22.1 | 21.3 | 0.8 | weak | summer wet |
| Mosby Mtn. | 2879 | I | 762 | 165 | 165 | 21.7 | 21.7 | 0 | weak | none |
| Trout Creek | 2848 | J | 724 | 152 | 140 | 21.1 | 19.3 | 1.8 | weak | summer wet |
| Hole in the Rock | 2773 | K | 546 | 152 | 89 | 27.9 | 16.3 | 11.6 | strong | summer wet |
| Hickerson | 2758 | L | 572 | 146 | 108 | 25.6 | 18.9 | 6.7 | strong | summer wet |
| Hayden Fork | 2758 | M | 866 | 114 | 241 | 13.2 | 27.9 | -14.7 | strong | winter wet |
| Lily Lake | 2742 | N | 794 | 140 | 216 | 17.6 | 27.2 | -9.6 | strong | winter wet |
| Kings Cabin | 2645 | O | 711 | 152 | 152 | 21.4 | 21.4 | 0 | weak | none |
| Rock Creek | 2394 | P | 597 | 140 | 165 | 23.7 | 27.7 | -4 | moderate | winter wet |

**0-3 = weak*
*3-6 = moderate*
*>6 = strong*

**Figure 4** Map of the difference between modern summer and winter precipitation at 16 SNOTEL stations in the Uinta Mountains. Background is 1 km grid showing elevations. Contours are based on the difference between % of mean annual precipitation falling in the summer and % falling in the winter; negative numbers represent dominance of winter precipitation. Areas at the eastern end of the Uintas are influenced by the monsoon and receive more of their annual precipitation in the summer than in the winter. The western end of the range receives more precipitation the form of winter storms. The upper Henrys Fork study area (asterisk) is located on the boundary between these precipitation regimes and has equally distributed precipitation throughout the year.

8). The 95% confidence interval on this ratio ranges from 3.5 to 6 times the mean value for the modern surface sites. Such an extreme *Picea/Pinus* ratio indicates either a dramatic increase in the abundance of *Picea* pollen or a decrease in the abundance of *Pinus.* Yet, because *Picea* pollen fails to travel far from its source (Maher, 1963), spruce must have been present in the upper Henrys Fork by 9.4 ka cal. BP. *Picea* must also have grown closer to the elevation of Exposure HF98–2, and therefore timberline must have been above its modern level.

Given the location of the upper Henrys Fork basin at the boundary between summer-wet/winter-dry and summer-dry/winter-wet climatic regimes, and the apparent stability of this boundary during the Holocene (Whitlock *et al.*, 1995), this higher early-Holocene timberline is interpreted as a response to warmer-than-modern summer temperatures. This inference is supported by studies of modern timberlines, which have concluded that the upper limit of tree growth is controlled primarily by growing-season temperatures (e.g., Troll, 1973). The modern distribution of *Picea engelmannii* in the central Rocky Mountains is limited to areas where the mean annual temperature ranges from –1 to 2°C, and the July temperature from 10 to 13°C (Burns and Honkala, 1990). Based on modern lapse rates in the northern Uintas (J.S. Munroe, unpublished analysis of SNOTEL data), projected mean annual and mean July temperatures at the elevation of Exposure HF98–1 (3300 m a.s.l.), which is located at modern timberline, fall just within this range (–0.6 and 10.5°C). Temperatures at HF98–2 (3500 m a.s.l.), ~200 m above timberline, are too low (–1.6 and 9.1°C). Therefore, a minimum warming of ~1°C would be required for *Picea engelmannii* to grow at the elevation of HF98–2.

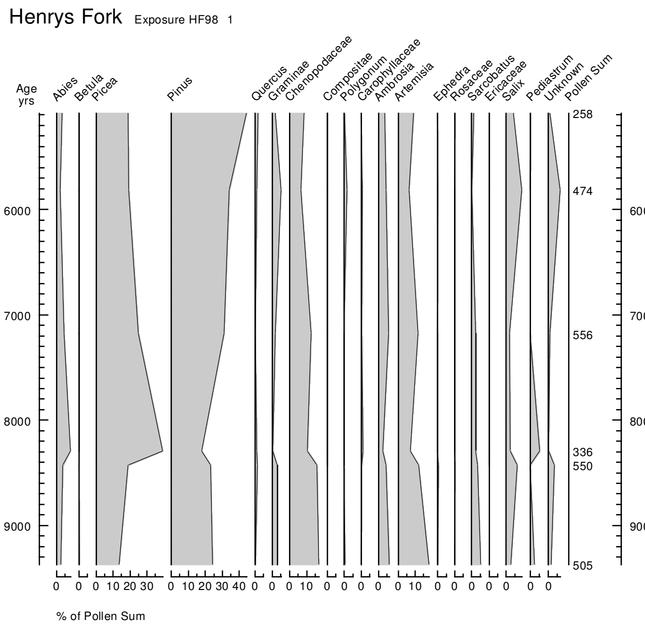



**Figure 5** Pollen diagram for Exposure HF98–1. Values are shown as percent of the pollen sum (excluding Cyperaceae). Ages are in $^{14}$C years BP.

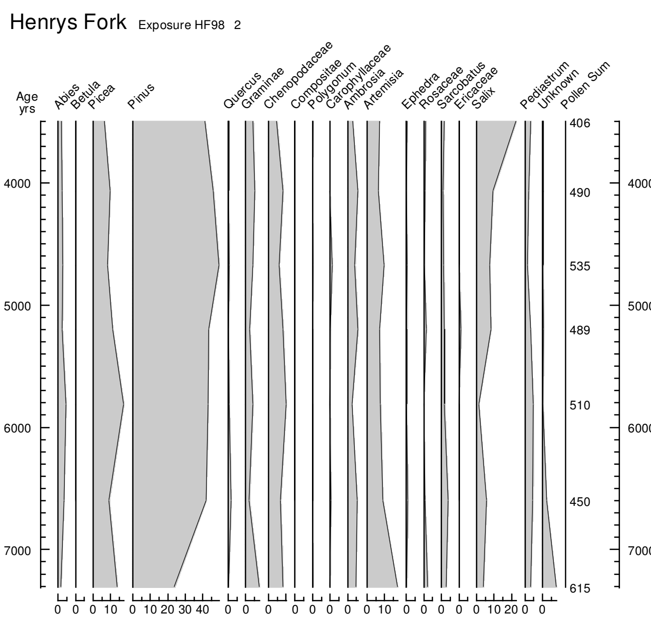



**Figure 6** Pollen diagram for Exposure HF98–2. Values are shown as percent of the pollen sum (excluding Cyperaceae). Ages are in $^{14}$C years BP.

The extreme *Picea/Pinus* ratios between 10.2 and 6.7 ka cal. BP must also be due, in part, to low amounts of *Pinus* pollen. The percentage of *Pinus* pollen in samples from the lower part of Exposure HF98–1 (Figure 7) is considerably less than the percentage in younger samples, suggesting that *Pinus* increased in abundance during the period of record. A similar trend was noted by Maher (1999), who determined that the proportion of *Pinus* pollen in the Colorado Front Range increased during the Holocene, and that subalpine forests dominated by high-altitude pines are a relatively recent (late-Holocene) occurrence. Accordingly, *Picea/Pinus* ratios in the Colorado Front Range during the early Holocene were twice their modern values. This difference is not quite as dramatic as that seen in the records from the upper Henrys Fork, but it supports an interpretation of *Picea* at or near modern timberline and lower-than-modern *Pinus* abundance in the Uintas during the early Holocene.

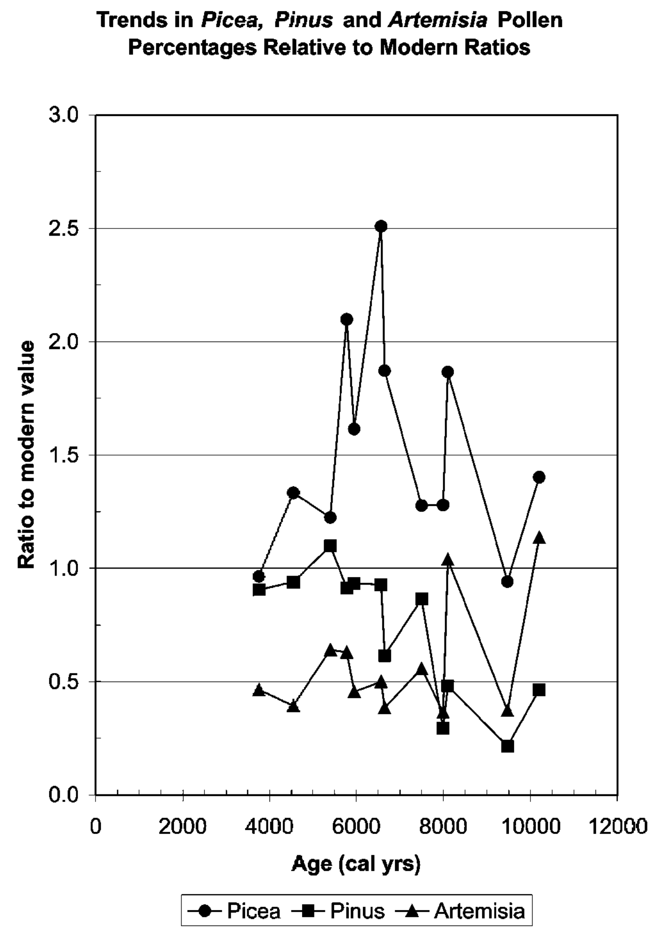



**Figure 7** Percents of *Picea*, *Pinus* and *Artemisia* pollen for samples from the Upper Henrys Fork, normalized to their modern values.

The record of Cheno-Ams provides additional information about the early-Holocene forest in the upper Henrys Fork. High abundance of Cheno-Ams has been interpreted as indicating warmer and drier conditions during the early Holocene (Davis *et al.*, 1986; Beiswenger, 1991). High values of Cheno-Ams were also taken as evidence of relatively open parkland at timberline in Yellowstone National Park (Whitlock, 1993) and in northwestern Colorado (Feiler *et al.*, 1997) before the establishment of a closed forest. Values of Cheno-Am pollen from the two sites were normalized to their mean percentages in the modern samples and plotted against age (Figure 8). Cheno-Am pollen was most abundant in the first half of the Holocene, simultaneous with the highest *Picea/Pinus* values, and dropped toward modern levels by 5.5 ka cal. BP. This correspondence supports an interpretation of a *Picea* parkland environment in the early Holocene, probably promoted by warmer-than-modern summer temperatures.

Finally, the record of total arboreal/non-arboreal pollen (AP/NAP) also suggests an early-Holocene *Picea* parkland environment. Modern arboreal pollen at timberline in the upper Henrys Fork is almost entirely coniferous and is essentially the sum of *Picea* and *Pinus* pollen. Non-arboreal pollen (excluding Cyperaceae) is dominated by *Artemisia*, a shrub growing both at elevations below the subalpine forest (as *Artemisia tridentata*), and above in the alpine zone (as *Artemisia scopulorum*). Cheno-Ams, Poaceae and *Ambrosia* make a minor contribution to the non-arboreal sum. Because the non-arboreal component of the AP/NAP ratio reflects both local (alpine and subalpine) pollen types (Artemisia and Poaceae), and long-distance transport of exotic pollen (Cheno-Ams and *Sarcobatus*) on upsloping winds (e.g., Markgraf, 1980: Fall, 1992), it is assumed that AP/NAP would decrease with elevation above timberline, i.e., with distance

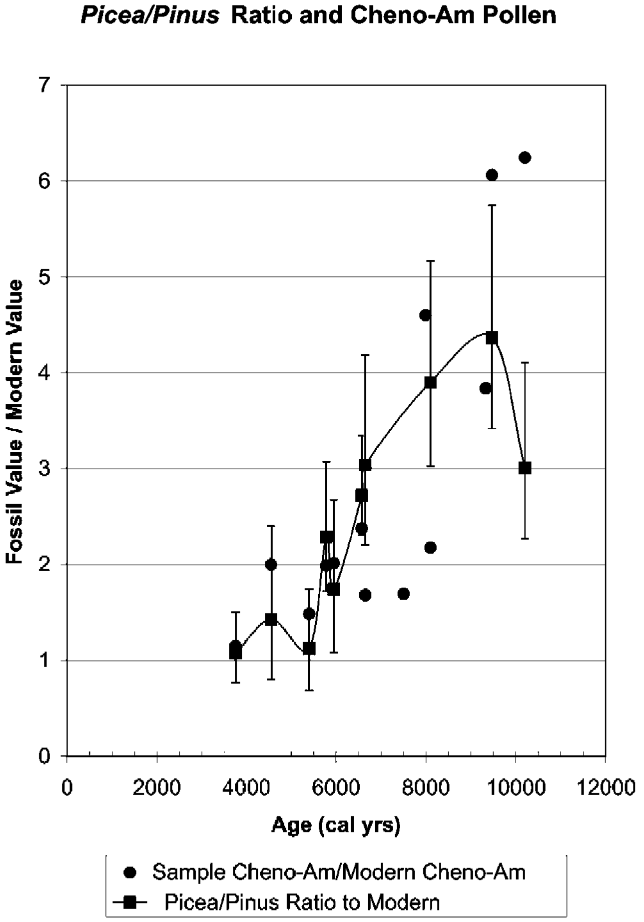



**Figure 8** *Picea/Pinus* ratios through the Holocene normalized to their modern values for the upper Henrys Fork (squares) with 95% confidence intervals. Values of Cheno-Am pollen (circles, also normalized to their modern values) decrease through the period of record.

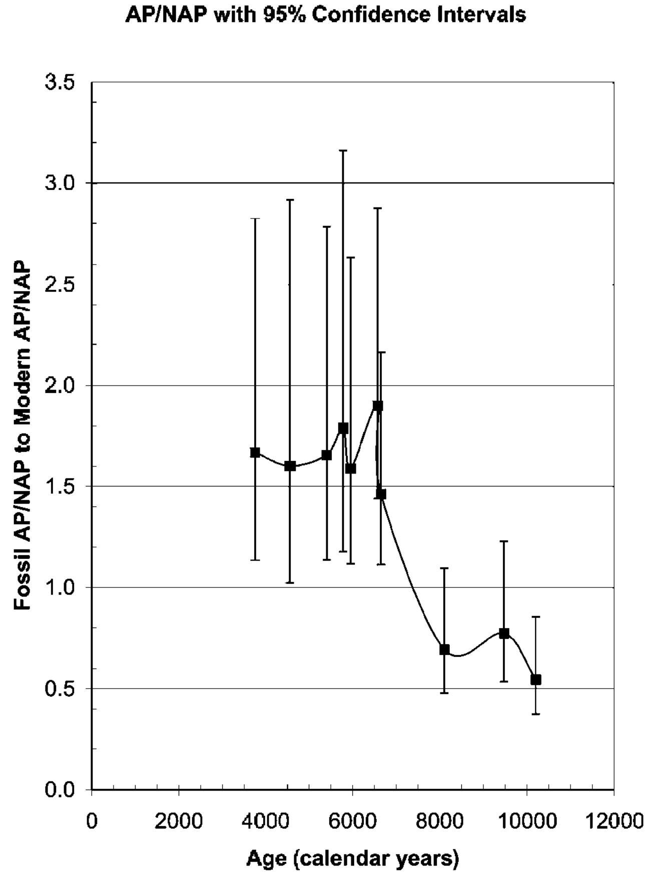



**Figure 9** Ratio of arboreal to non-arboreal pollen normalized to modern values with 95% confidence intervals.

from the source of the arboreal component. Therefore, values of AP/NAP were normalized to their mean modern values at the two sites, and plotted against age (Figure 9). Confidence intervals (95%) were determined with MOSLIMIT (Maher, 1997). AP/NAP values were low from 10 to 8 ka cal. BP, and surpassed modern levels around 7.5 ka cal. BP, after which they remained above modern levels through the remainder of the record. The co-occurrence of high *Picea/Pinus* ratios and low AP/NAP ratios is best explained by an open parkland dominated by *Picea* with lower-than-modern amounts of *Pinus*. Over time, *Pinus* gradually invaded this early-Holocene *Picea* parkland, decreasing the *Picea/Pinus* ratio and increasing the AP/NAP ratio into the middle Holocene.

## Palaeoenvironmental history

The glacier that occupied the Henrys Fork drainage at the last glacial maximum had disappeared (or at least retreated above 3300 m a.s.l.) prior to ~10 ka cal. BP, leaving a till surface and a recessional moraine near Dollar Lake (Figure 1). Wet meadows dominated by Cyperaceae and *Salix*, analogous to those found along the modern drainages, developed on the till surface, as indicated by extreme Cyperaceae pollen contents in samples HF98–1-4 and HF98–1-10 (>1000 grains outside the pollen sum), and the *Salix* wood and pollen in sample HF98–1-26. *Picea* arrived in the upper cirque basins by ~10 ka cal. BP, as recorded by the rapid rise of the *Picea/Pinus* ratio in the lower part of Exposure HF98–1. An open *Picea* parkland extending to elevations above modern timberline was established by 9.5 ka cal. BP as evidenced by high *Picea/Pinus* values (>4 times modern), lower-than-modern AP/NAP ratios and high *Artemisia* percentages. Aggradation at the site of Exposure HF98–1 continued as coarse sand derived from eroding till and weathering talus upstream was deposited whenever the Henrys Fork migrated towards the site. Finer slackwater deposits accumulated when the main channel migrated away from the site, and peat layers accumulated when the water table was at (or above) the surface. Given the floodplain setting, the level of the water table may reflect proximity of the Henrys Fork channel, and need not have direct climate forcing. *Pinus* extended its range to higher elevations in the northern Uintas after ~8 ka cal. BP, diluting the *Picea/Pinus* ratio and increasing AP/NAP to modern values by 7.5 ka cal. BP.

Sedimentation at the site of Exposure HF98–2 began ~8 ka cal. BP as *Salix* and Cyperaceae colonized a swale behind a dam deposited by a debris flow derived from the cirque headwall. Aggradation continued at this location until at least 4 ka cal. BP as peat formation alternated with debris-flow deposition. *Picea* percentages at both sites reached a maximum around 6.5 ka cal. BP, and then fell to near-modern levels by 5.4 ka cal. BP, simultaneous with the collapse of *Picea/Pinus* ratios to modern levels.

Breaching of the moraine dam near Dollar Lake terminated sedimentation sometime after 5.8 ka cal. BP at Exposure HF98–1. Near-modern conditions prevailed over the final ~1000 years of the record (till 3.8 ka cal. BP), although AP/NAP values remained ~1.7 times greater than modern. At least two debris flows deposited sediment above the younger dated peat layer in Exposure HF98–2, but incision of the upper Henrys Fork after ~3.8 ka cal. BP lowered the water table, reducing the potential for organic-matter accumulation and preservation at this site. Subsequent debris flows have apparently failed to reach the location of the exposure, or have been eroded away.

## Regional comparisons

This synthesis augments previous summaries of the Holocene palaeoclimatic history of the Uintas (Figure 10). Elias and Short (1995) deduced that conditions on the southern slope of the Uintas were cooler-than-modern from 6.2 to 5.7 ka cal. BP (5300 to 5100 $^{14}$C yr BP), followed by decreasing *Picea* percentages and declining *Artemisia/Pinus* and Poaceae/*Pinus* ratios, suggesting increasing *Pinus* abundance. At the eastern end of the range, Carrara *et al.* (1985) concluded that conditions were cooler than modern from the start of the record ~7.3 ka cal. BP (6500 $^{14}$C BP) until 5.3 ka cal. BP (4600 $^{14}$C BP), then became warmer through 0.6 ka cal. BP, with the peak of warmth before 2.1 ka cal. BP. Although the earliest parts of both these records suggest cooler climates, both records indicate warming after ~5.5 ka BP. Research from elsewhere in the northern Uintas, including lacustrine evidence for a massive fire ~5.5 ka cal. BP, with a second fire at 4.5 ka cal. BP, and possible drying of a shallow kettle lake ~6.0 ka cal. BP (J.S. Munroe, unpublished data) support the inference that conditions were warm and dry in the middle Holocene. None of these records extends to the earliest Holocene, making recognition of the onset of longer warming trends difficult. However, the longer discontinuous pollen record from the Henrys Fork exposures indicates that the warming actually began before 9.4 ka cal. BP. The Holocene climatic optimum in the Uintas may, therefore, have been manifest by an extended period of warm conditions that began before the onset of the classic Altithermal (*c.* 7.0 ka BP) as defined by Antevs (1948) for the Great Basin, and continued until the middle Holocene.

For regional comparison, Fall *et al.* (1995) inferred a similar lengthy warm period for the Wind River Range, ~250 km north of the Uintas (Figure 10). Based on a pollen record from an upper subalpine lake, climate was warmer than modern from 10.6 to 3.0 ka BP, with temperatures ~1.0°C warmer by 10.6 ka BP and a period of maximum warmth and aridity around 5.4 ka BP. Specifically, alpine tundra around the lake was replaced by open *Pinus albicaulis* (whitebark pine) parkland by 11.3 ka BP. *Picea* and *Abies* grew with *Pinus* in a subalpine forest after 10.6 ka BP, although the dominance of *Pinus albicaulis* began to wane after 9.1 ka BP. *Abies* pollen began to decline after 5.2 ka BP, and *Picea* remained a major component of the subalpine forest until 3.0 ka BP.

Fall *et al.* (1995) concluded that early-Holocene warming produced growing-season temperatures ~1.0°C greater than modern, an estimate similar to the amount required to allow *Picea* to reach the elevation of Exposure HF98–2 in the upper Henrys Fork. In addition, the period of maximum warmth ~5.4 ka BP inferred for the Wind River Range matches the timing of the peak in AP/NAP ratio and depression of *Picea* percentages to modern levels in the upper Henrys Fork. This correspondence suggests a strong similarity in the Holocene palaeoclimatic history of the two areas. Fall *et al.* (1995) note that the Wind River Range is positioned astride the modern precipitation boundary, with some areas receiving summer monsoonal moisture, and others receiving the majority of their annual precipitation as winter snowfall. Analysis of SNOTEL station records from the range, following the methodology outlined earlier, reveals that stations on the west side of the mountains have winter precipitation maxima, as would be expected given the orientation of the range perpendicular to prevailing moisture transport. Stations in the southeast sector have summer precipitation maxima, reflecting abundant monsoonal moisture. The site studied by Fall *et al.* (1995) may therefore be positioned along the modern precipitation boundary similar to the upper Henrys Fork basin.

For further comparison (Figure 10), Elias (1985) used fossil insect assemblages to infer that timberline was at or above modern limits in the Colorado Front Range by 9.0 ka BP, and that conditions were at least as warm as their modern values by that time. The Holocene warm interval apparently lasted from 8.5 to 5.0 ka BP, followed by an abrupt climatic deterioration to 3.0 ka BP. These interpretations are supported by a pollen study (Short, 1985) suggesting warm conditions in the Colorado Front Range between 9 and 3.5 ka BP, with a timberline peak at 6.5 ka BP. A separate Front Range pollen study also concluded that the middle Holocene featured warmer than modern temperatures (Nichols,

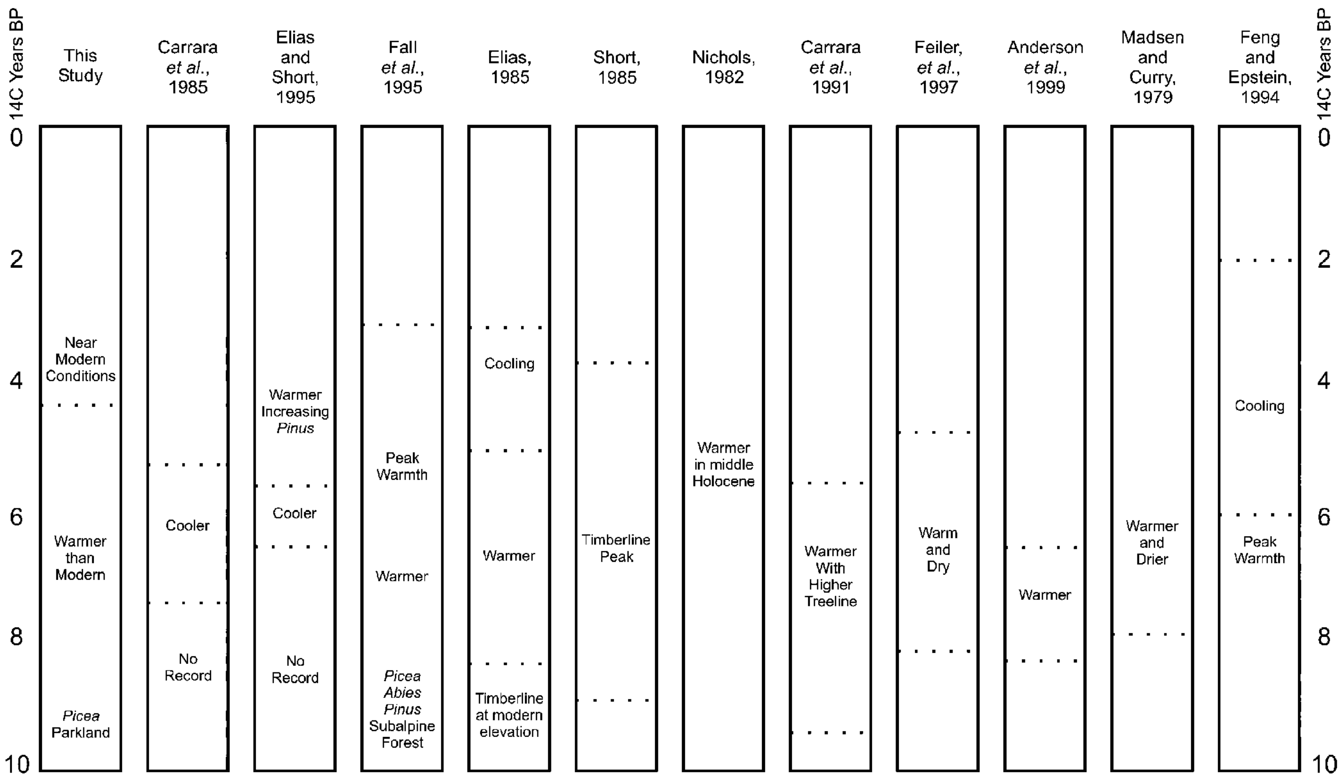



**Figure 10** Comparison of this palaeoclimate reconstruction for the upper Henrys Fork with other studies from the Wind River Range, Colorado, Utah and the Sierra Nevada. Details and interpretations are given in the text.

1982). Carrara *et al.* (1991) argued from radiocarbon dated wood fragments that treeline was at least 80 m higher than modern levels from 9.6 to 5.4 ka BP, and fell to near-modern levels between 5.4 and 3.5 ka BP. Mean July temperatures during this period were estimated to have been 0.5 to 0.9°C warmer than modern values. In northwestern Colorado, Feiler *et al.* (1997) concluded that warm and dry conditions began after 8100 BP and continued till 4600 BP. In southern Utah, Anderson *et al.* (1999) interpreted a decline in *Abies* pollen and fluctuations in *Picea* and *Pinus* as indicating warming conditions between 8500 and 6400 years ago. To the west of the Uintas, Madsen and Currey (1979) determined that conditions became warmer and drier after 8000 BP in the Wasatch Mountains. Finally, in the Sierra Nevada, Feng and Epstein (1994) used hydrogen isotopes in treerings from extremely long-lived *Pinus longaeva* (bristlecone pine) trees to infer that a Holocene climate optimum was reached about 6.8 ka BP, followed by continued cooling until 2.0 ka BP.

All of these locations recorded conditions similar to, or warmer than, modern at some point during the early/middle Holocene in response to increased insolation during the growing season. While the insolation changes affected the entire region, however, both the timing and duration of the postglacial climatic optimum varied spatially. Notably, areas located at the modern boundary between the summer-wet/winter-dry and summer-dry/winter-wet precipitation regimes, such as the upper Henrys Fork basin and the part of the Wind River Range studied by Fall *et al.* (1995), appear to have recorded longer warm periods, starting before 9 ka cal. BP with development of an open parkland at an elevation at or above modern timberline, and continuing through the middle Holocene. In contrast, the interval of greatest warmth appears to have been shorter in areas located within the summer-dry/winter-wet regime such as the Sierra Nevada (Feng and Epstein, 1994) and the Wasatch Range (Madsen and Currey, 1979). This dichotomy reflects the complicating effects of local changes in the seasonal distribution of precipitation that can be driven by regional insolation changes.

## Conclusions

Study of the sedimentology and palaeoenvironmental record preserved in two exposures in the upper Henrys Fork basin supports several inferences about the postglacial history of the area.

(1) Sediment revealed in these two exposures accumulated behind local obstructions (moraine-dam and debris-flow deposits) that persisted through the first half of the Holocene. Late-Holocene incision (after 4 ka cal. BP) reflects final breaching of these obstructions, and is not necessarily related to changes in precipitation.

(2) The organic sediments, including subfossil wood, were deposited in wet-meadow environments, similar to those present today in other parts of the upper Henrys Fork basin. High water table, low surface slope, low temperatures and abundant *Salix* and Cyperaceae are common components of these situations.

(3) Postglacial invasion of the wet meadows and floodplains of the upper Henrys Fork by willows and sedges was complete by *c.* 9 ka cal. BP.

(4) An open *Picea* parkland, represented by high *Picea/Pinus* ratios, lower-than-modern *Pinus* percentages and high amounts of *Artemisia*, had developed in the upper Henrys Fork, and presumably at timberline across the northern Uintas, by 9.5 ka cal. BP. Mean annual and July temperatures at this time were ~1.0°C warmer than modern values.

(5) *Pinus* infiltrated the *Picea* parkland into the middle Holocene and a period of maximum warmth was reached shortly after ~5.5 ka cal. BP, simultaneous with evidence of warmer palaeoclimate presented in other studies from the Uintas and overlapping with the latter third of the Altithermal period originally defined by Antevs (1948).

(6) The Holocene climatic optimum in the Uintas was manifest by a long period of warm conditions that began before the onset of the classic Altithermal (*c.* 7.0 ka BP) as defined by Antevs (1948) for the Great Basin, and continued until the middle Holocene.

(7) The Holocene climatic optimum may have lasted longer in areas located astride the modern boundary between the summer-wet/winter-dry and summer-dry/winter-wet precipitation regimes than in areas currently dominated by winter precipitation.

## Acknowledgements

Eric Carson, Mike Devito, Daniel Douglass and Diane Munroe provided field assistance at the Henrys Fork sections. Grain-size analyses were performed in the University of Wisconsin-Madison Quaternary Laboratory under the direction of Ben Laabs. The NSF-AMS Radiocarbon Laboratory at the University of Arizona-Tucson provided the AMS radiocarbon dates, while grants from the Geological Society of America and the US Forest Service supported the conventional radiocarbon dates. Louis Maher provided assistance with the palynology and Alex Wiederhoeft at the US Forest Products Laboratory identified the wood fragments. Scott Anderson, Cathy Barnosky and Louis Maher provided helpful criticism of early drafts of the manuscript.

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