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ASSESSMENT OF LATE PLEISTOCENE TO RECENT CLIMATE-INDUCED VEGETATION CHANGES IN AND NEAR SHENANDOAH NATIONAL PARK (BLUE RIDGE PROVINCE, VA)

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(Footnotes)

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Abstract

Pollen evidence from a shallow core in the Blue Ridge Mountains (Big Meadows, Virginia) and from other outcrops in and adjacent to Shenandoah National Park, indicates that from the Late Pleistocene through the Holocene (45-0 ka) regional vegetation in north-central Virginia fluctuated from warm temperate forests to fully developed taiga (boreal forest). Present day analogues to these vegetation zones can be found in the forests and forest transitions extending from central Georgia (approximately 32^0 N latitude) to central Ontario, Labrador, and northern Newfoundland (approximately 52-55^0 N latitude). It is still undetermined (on the basis of our pollen evidence) whether it was ever cold enough in the study area during this 45,000-year time interval to develop alpine tundra extensively along these ridge tops.

Current evidence from the study area suggests that the forests in and around Shenandoah National Park changed frequently in composition through the studied time interval. Most of the forests previously established in the study area were of types that favored notably cooler mean annual temperatures than the forest type that is established currently in the proximity of the Park. Although this fossil record is a partial one, the radiometric carbon evidence verifies that we now have discovered pollen assemblages of full-glacial age (last glacial maximum) in the Blue Ridge, of multiple forest types.

Background

An especially intense and prolonged summer storm in the area of Graves Mill (eastern border of Shenandoah National Park, June, 1995) created numerous debris flows and intensive scouring of streams and hillsides on the eastern front of the Blue Ridge (Morgan et al., 1999a; Wieczorek et al., 2000; study area, Fig.1). This scouring exposed numerous depositional remnants along stream banks that contained evidence of prehistoric debris flow and solifluction activity. ^{14}C analyses (Eaton and McGeehin, 1997) confirmed that these remnants were of Late Pleistocene and Holocene age.

The vegetational, climatic, and geomorphic history of the Blue Ridge during the Pleistocene and Holocene are poorly understood. We used this debris flow cluster event to begin intensive investigations of these deposits to increase our understanding of the role of debris flows in regional denudation (Eaton, 1999; Morgan et al., 1999b; Eaton et al., 2003a), the character of sediment processes in the Blue Ridge during the Late Pleistocene (Smoot, 2004a, 2004b), and a reconstruction of climate-driven vegetation change in the study area during the past 40,000 years (this report). This paper presents a first-order assessment of Late Pleistocene to Recent vegetative changes in the Blue Ridge in the area of Shenandoah National Park.

The outcrop remnants exposed by the 1995 storm are packages of sediment varying from 0.5 to 10 meters thick (Litwin et al., 2001); each deposit differs in age, but all accumulated during a relatively brief time interval. Palynological investigations coupled with ^{14}C analyses are used here to synthesize and reconstruct a chronological vegetation (proxy climate) sequence, linking prehistoric forest types with ages determined through accelerated mass spectrometric (AMS) ^{14}C analysis. Additionally, we attempted to obtain a single long reference section by vibracoring at Big Meadows, Shenandoah National Park (Fig. 1). This attempt was partly compromised by vibration-induced fluidization of sediments in the deeper drilling runs, but we still were able to discern important aspects of the prehistory of Big Meadows from the shallower runs of the core.

This report contains a description of investigations at Big Meadows and more regional considerations regarding climate and vegetation change. Questions that are addressed in this report include the following. What is the character of the shallow subsurface at Big Meadows? What are the ages of the sediment in the subsurface? What are the implications for the geologic history of Big Meadows and for archeological studies that are ongoing in the area? What are the characterization and timing of the vegetation changes within the Blue Ridge of Shenandoah National Park over the last 45,000 years? When did the forest that now occupies the park first develop? Does core evidence document previous (prehistoric) intervals of meadow vegetation at the core site? Lastly, what is an initial estimate for the minimum range of climate change established in the study area over the past 45,000 years, as documented by climate-driven changes in vegetation?

This study was undertaken in cooperation with the National Park Service, during a recent revitalization (trimming and controlled burning) of the Big Meadows site for the purpose of preventing forest encroachment on the meadow. Permission to core was granted during this revitalization, as part of a joint scientific assessment on the archaeology and climate history of Big Meadows.

Samples and results

The suite of outcrop and core samples we analyzed and interpreted for this report are presented in Figure 1, and Tables 1 and 2. Their geographic locations are shown graphically in figure 1; the locations and elevations are listed in Table 1. Where possible, they have been cross-referenced to localities originally described by Eaton (1999). The ages assigned to each sample are noted in Table 2. Most have been dated directly by AMS ^{14}C radiometric analyses of macrofossil fragments (wood, charcoal, or seeds) after handpicking directly from the pollen-bearing sediment (using a binocular microscope). The uncorrected radiocarbon ages (14-C yr) and calibrated radiometric ages (ky cal BP) are presented, along with their attendant 1-sigma and 2-sigma analytical errors. Core samples are denoted by a "©" after the sample ID name; all other samples were taken in the field by the authors from unweathered outcrop.

The raw results from the pollen analyses of the core and outcrop datasets are presented in Table 3. Pollen identifications were based on Bassett et al. (1978), Lewis et al. (1983), Lieux (1980a, 1980b, 1982, 1983), Lieux and Godfrey (1982), Richard (1970), and Traverse (1988), as well as on pollen slides prepared directly from vouchered specimens that were sampled by one of us (RJL) from the George Mason University Herbarium.

Each sediment sample was spiked with a *Lycopodium* tracer to insure our chemical processing did not destroy or degrade the fossil pollen in each sample. In addition to the counts, we have noted the forest zone type (abbreviated) that we think best matches the each sample, based on the modern forest zone criteria (below). Badly damaged, crumpled, or unknown pollen morphotypes were assigned to the category "other". Minor occurrences of other taxa (e.g., *Salix*, *Comptonia*, etc.) also were included in this category.

The total pollen per gram of sample varied markedly across the sample set. Several samples had to be standardized in their count because the abundances of pollen were low in the sample; analyses were ended after two microscope slides were counted for each sediment sample, or a tabulation of 300 specimens was reached (whichever came first). We think that some taxa (e.g., *Quercus*) are over-represented in these samples, while other taxa (e.g., *Acer* and

Fraxinus) are under-represented. Accordingly, we have used multiple presence/absence/abundance criteria for assigning each fossil sample to a probable prehistoric forest type. We used both the core and outcrop datasets to derive these pollen-based forest zone assignments.

Once we established prehistoric forest zones, we interpreted the data two ways. We examined the Big Meadows core dataset independently, to answer site-specific questions. We then combined the outcrop and core datasets to produce a compiled vegetation history. We think the compiled vegetation history is justified, as it based on a suite of well-dated point samples recovered from small depositional remnants of Quaternary age that are distributed across a small geographic area (Fig. 1) along the eastern face of the Blue Ridge.

INTERPRETATION OF PREHISTORIC VEGETATIONAL CHANGE

Use of modern analogue forest types

We base our interpretation of the pollen data on a comparison to the modern analogue suite of forests that are now established along the U.S. Atlantic Coast. At present, we have used a generalized version of the forest characterization by Küchler (1975) for the eastern United States, combined with a map of the ecoregions of Canada (Ecoregions working group, 1989; Fig. 2). Multiple characterizations exist for modern eastern U.S. forests, including those of Eyre (1980) and Braun (1950). We also refer readers to the U.S. Forest Service website, for further details and comparisons of some of these forest characterizations (http://www.fs.fed.us). For the purposes of this initial study, we found the zonation of Küchler (1975) to be the most useful for comparison to our pollen assemblages. Given that our study only includes samples younger than 50 ka, we propose that these relatively young fossil samples can be assigned accurately to existing modern forest analogues. We do acknowledge that a small number of our prehistoric pollen assemblages may have been derived from forest types with no modern counterpart.

The main forest zones that we think previously may have been established in the Blue Ridge study area are those that now occupy the U.S. Atlantic seaboard: 1) Southern Mixed Forest , 2) Oak-Hickory-Pine Forest, 3) Appalachian Oak Forest (present study area), 4) Northern Hardwoods Forest, 5) Northern Hardwoods-Spruce Forest, 6) Northeastern Spruce-Fir Forest, and 7) Boreal Forest (Fig. 2; Küchler, 1964, 1975; Ecoregions Working Group, 1989). Our fossil data set currently includes samples that we think represent each of these forest types, with the exception of Southern Mixed Forest. Although we do not yet have direct evidence, we predict that the very warmest of the forests established in the study area intermittently during the Holocene thermal maximum (~4-6 ka) possibly may have been of that type; it has not yet been investigated.

Currently we are in the process of cross-testing this initial model for transposing pollen assemblages into forest zones, by analyzing modern pollen assemblages in the modern soils associated with each of these forest types, from southern mixed forest northward through boreal forest and into subarctic tundra. The sample set we have accumulated (for this cross testing) thus far is indicated by plain white circles in Figure 2. It is hoped that these modern pollen assemblages will enable us to perform dissimilarity coefficient cross-tests on our fossil dataset to refine the pollen-to-forest zone assignments we propose in this report. The results of this cross testing and the refinement of our temperature index will be presented elsewhere; they are ongoing studies, and are not the primary focus of this report.

Modern taxa ranges

The first-order forest zone reconstruction for this study primarily was based on comparison of the composition of each of our pollen assemblages to our compilation of modern forest genera distributions within the area bounded by 20^0-60^0 N latitude and 50^0-90^0 W longitude. The generic ranges were compiled from the species distribution maps of Little (1971, 1976; Fig. 3; see also "http://www.na.fs.fed.us/spfo/pubs/silvicsmanual"). The number of species used to derive these composite ranges varied per genus, and is noted for each in Figure 3. The 31 genera we tabulated represent the cumulative mapped ranges of 147 plant species that exist between the tropics and the subarctic tundra. This compilation provided a characterization of the general plant components for each of the forest zones mapped by Küchler (1975), that we have used as our baseline modern forest analogues. We note two related points here. The first is that the zonation presented here is preliminary, and will be updated and refined as necessary. The second point is that nearly half of these genera range through all the forest types we observed, from boreal forest to oak-hickory-pine forest. Because of this, we emphasize that our assignment of fossil pollen assemblages to modern forest analogues could not be based solely on the presence/absence of particular taxa, but also had to include the relative proportions of taxa within those assemblages. Consequences of this condition are addressed elsewhere in this report (see *Discussion*, p. 38). Grasses, composites, and lower vascular plant taxa were not included in the modern genus compilation of Figure 3. The genera that potentially range through all forests from boreal forest to oak-hickory-pine forest include: *Abies, Acer, Alnus, Betula, Cornus, Corylus, Fraxinus, Juniperus, Pinus, Quercus, Sanguisorba, Shepherdia,* and *Ulmus.* Although these genera all occur within the forests above, each may be a rare to uncommon element in any of them, and may not be represented consistently in the pollen record of that forest.

We used mean annual temperature (MAT) isotherms to derive approximate temperature ranges for each genus; see Figure 3 (sources: <www5.ncdc.noaa.gov/pubs/ publications.html> and <www.kgs.ukans.edu/PRS/info/pdf/doveton.PDF>). We marked the midpoint of each genus's temperature range in Figure 3 with a diamond, to indicate its probable favored temperature regime and zone of probable abundance. The genera were arranged by decreasing midrange values ("decreasing thermal optimum", Fig. 3). The wide portion of each taxon's range bar represents one half of its total documented range, as centered on its total range midpoint. If a normal population distribution exists between the endmembers of each range (the working hypothesis), this wide bar approximates the subrange in which its populations-- and therefore its total pollen--
should be relatively more common. Again, this is a first-order assessment only, and ranges and midpoints may shift as the compiled genera are emended. For example, the range noted for the genus *Kalmia* here is based on one species distribution (*K. latifolia*) which does not extend into spruce-fir forest or boreal forest. Other *Kalmia* species (e.g., *K. angustifolia* and *K. polifolia*) do occur in boreal forest (Larsen, 1980, p. 474), but their range distribution maps were not found for inclusion here. After constructing the range chart we used the MAT isotherms to help us interpolate warm and cold boundaries for each of the forest zones mapped by Küchler (1975). These are shown as a series of horizontal bands in Figure 3 (converted to ^{0}C).

Criteria for 'pollen / forest zone' assignments

Those pollen assemblages we interpret as being derived from full boreal forest (here 'Zone 7' of Figure 2) are characterized by the following taxa: *Abies* (fir), *Acer* (maple), *Alnus* (alder), *Betula* (birch), *Cornus* (dogwood), *Corylus*, (hazelnut) *Juniperus* (juniper), *Larix* (larch), *Picea* (spruce), *Pinus* (pine), *Sanguisorba* (burnet), and *Shepherdia* (buffaloberry). *Populus* (poplar) and *Salix* (willow) also occur in this zone, but were not included in Figure 3. Larsen (1980, p. 31) additionally notes the presence of *Quercus* (oak), *Fraxinus* (ash) and *Ulmus* (elm) in the warmer, southern boreal forest. These putative occurrences are corroborated by their respective plant distribution maps in Little (1971) and distribution maps in Lewis et al. (1983), when compared to boreal forest boundaries noted by the Ecoregions Working Group (1989). *Fraxinus niger*, *Quercus macrocarpa*, *Q. rubra*, and *Ulmus americana* are all present in areas currently characterized as boreal forest (Little, 1971; Ecoregions Working Group, 1989). In general the taxa above are exceptionally cold tolerant and characterize modern boreal forest vegetation (Larsen, 1980; Porsild and Cody, 1980; Ritchie, 1987). The following pollen index taxa appear to be absent from boreal forest: *Carya* (hickory), *Castanea* (chestnut), *Fagus* (beech), *Ilex* (holly), *Juglans* (walnut), *Liquidambar* (sweetgum), *Liriodendron* (tulip poplar), *Magnolia* (magnolia), *Morus* (mulberry), *Nyssa* (black tupelo), *Ostryra-Carpinus* (ironwood and hornbeam), *Platanus* (sycamore), *Sabal* (palmetto), and *Tsuga* (hemlock)(Larsen, 1980). The relative temperature index values (i.e., a ratio of oak and ash pollen to spruce and fir pollen, (see p.16, and Figs. 4 and 5)) of fossil assemblages that we have assigned to this forest zone are less than or equal to 1.2. The most commonly represented tree taxa in this zone are *Picea*, *Larix*, *Pinus*, *Abies*, and *Betula* (Ritchie, 1987). Modern examples of this forest zone can be found in the Gaspé Peninsula, elsewhere across much of southern Quebec, eastward across most of Newfoundland and southwestern Labrador, westward across southwestern Ontario and southern Manitoba, and northwestward to Alaska.

The next warmer forest zone-- the northeastern spruce-fir forest—has all of the component taxa of the boreal forest (above). It appears to differ from boreal forest by the first appearance of two taxa that are somewhat less cold tolerant: hemlock and beech (*Tsuga* and *Fagus*). This zone also includes a minor amount of oak (*Quercus*), probably derived mostly from northern red oak (*Q. rubra*). Northern red oak is broadly distributed in almost all of the forests in this study, with the exception of restricted occurrences in boreal forest and southern mixed forest (Little, 1971). Küchler (1975) has mapped this zone in northwest and southeast Maine, and in the highest mountains in Vermont, New Hampshire, and New York (Fig. 2). Those fossil samples that we assign to this zone produce relative temperature index values between 1.2 and 1.85 (Fig. 5). Küchler (1975) described this zone as a predominantly coniferous forest (e.g., *Picea* and *Abies*), with a minor component of deciduous angiosperm taxa, including *Acer*, *Betula*, and *Populus*.

The next zone, the northern hardwoods-spruce forest ('Zone 5' of Figure 2), hosts several new taxa in addition to those noted above. *Juglans* (*J. cinerea*, butternut), *Ilex* (*I. verticillata*, common winterberry) and *Tilia* (basswood) have documented first appearances in this forest zone (Little, 1971; Küchler, 1964, 1975). A few other taxa- *Carya* (hickory), *Castanea* (chestnut), and *Liriodendron* (tulip poplar) *Ostrya-Carpinus* (ironwood and hornbeam)- were not noted in this zone by Küchler (1964), but have documented ranges that marginally overlap it (Little, 1971) and have first appearances within this zone in our fossil pollen samples. [*Ostrya* and *Carpinus* are presented in this study as a combined "form taxon" because they bear morphologically similar pollen (Ritchie, 1987, p.41).] The northern hardwoods-spruce forest lacks *Liquidambar*, *Magnolia*, *Morus*, *Nyssa*, *Platanus*, and *Sabal*. The relative temperature index values for pollen samples within this zone range from 1.85-7.0 (Figure 5). This forest type is found across north central Maine, the mountains of New Hampshire and Vermont, and across the Adirondacks of New York (excepting for its highest elevations, which are inhabited by spruce-fir forest; see Fig. 2). The Ecoregions Working Group (1989) does not differentiate the northeastern spruce-fir forest from the northern hardwoods-spruce forest, but combined the two into a High Cool Temperate Ecoclimatic Province. We have attempted to differentiate them here, on the basis of the genus-level first occurrence datums noted above.

As before, the next warmer forest zone—the northern hardwood forest ('Zone 4' of Figure 2) —contains all of the taxa of the previous zone, plus the addition of *Nyssa* (black tupelo) and *Platanus* (sycamore). *Picea* (spruce) abundance drops in this zone. This zone marginally contains the first occurrences of *Morus* (mulberry) and possibly *Magnolia* ("cucumbertree" or magnolia), based on their distribution maps (Little, 1971). The northern hardwood zone conspicuously lacks *Liquidambar* and *Sabal*. *Carya*, *Castanea*, and *Liriodendron* more regularly occur in the warmer part of this zone (southern half). It has common maple, birch, hazelnut, pine, and hemlock (*Acer*, *Betula*, *Corylus*, *Pinus*, and *Tsuga*) (Küchler, 1964). It also contains abundant oak (*Quercus*), linden (*Tilia*), and elm (*Ulmus*)(Little, 1971, 1976). This zone occurs at lower elevations across Maine, New Hampshire, Vermont, western Massachusetts, New York, and across the northern border of Pennsylvania. It extends southward across higher elevations of the Allegheny Plateau through the mountains of eastern West Virginia (Küchler, 1975; Fig. 2). Samples from our study that we assign to this zone bear relative temperature index values of 7-70 (Fig. 5). It is characterized in part by a strong admixture of deciduous hardwoods and conifers.

The Appalachian oak forest ("Zone 3" of Fig. 2) is characterized by a maximum abundance of oaks (*Quercus*), the common presence of pine (*Pinus*), hickory (*Carya*), walnut (*Juglans*), and scattered local presence of birch (*Betula*), beech (*Fagus*), and hemlock (*Tsuga*)(Küchler, 1964; Little, 1971, 1976). It contains the first appearance of *Liquidambar* (sweetgum). Additionally, the coldest parts of this forest zone host the last occurrences of spruce (*Picea*) and larch (*Larix*). *Abies* (fir), *Sanguisorba* (burnet) and *Shepherdia* (buffaloberry) appear to have their last occurrence in this forest zone; *Abies* and *Sanguisorba* occurs as a refugial cold-loving plants at the highest elevations (~3500') in the Blue Ridge. Appalachian oak forest is the zone presently established around Big Meadows, and along the crests of the Blue Ridge, the Appalachians, and much of the Allegheny Plateau (Pennsylvania), usually above elevations of approximately 1000' (~305 m; Fig. 2). Up until the middle of the last century, chestnut (*Castanea dentata*) was an important co-dominant overstory component in this forest locally as well, although it probably is underrepresented in the pollen record, even at its historic maximum abundance. Since the infestation of chestnut by the blight *Cryphonectria parasitica* (*Endothia parasitica per Anderson, 1974*), it no longer exists as a significant overstory component in forests. It persists only as a shrub-to-small tree-sized understory component, with only minor contribution to the pollen record (Anderson, 1974). The relative temperature index values in the Appalachian oak forest zone range from 70-140 (Fig. 5). The dominance of oaks in this forest zone is illustrated by the average total percentage of oak pollen in each of our Appalachian oak forest samples- 47%; in the northern hardwoods forest, northern hardwoods-spruce forest, and spruce-fir forest the respective percentages are 38%, 26%, and 16%. Küchler (1964) characterized it as a "tall, broadleaf deciduous forest" dominated by white oak (*Quercus alba*) and northern red oak (*Q. rubra*).

The next warmer forest zone, the oak-hickory-pine forest ("Zone 2" of Fig. 2), is the warmest zone for which we presently have fossil pollen evidence. This zone is characterized by the greatest relative abundance of hickory (*Carya*), dominant oak, pine, dogwood (*Cornus*), sweet gum (*Liquidambar*), tulip poplar (*Liriodendron*), black gum (or tupelo, *Nyssa*), and a marked decrease-to-absence of hazelnut (*Corylus*), hemlock (*Tsuga*), and birch (*Betula*) in the pollen record (Küchler, 1964; Little, 1971, 1976). *Corylus* and *Tsuga* have their last appearances within this forest zone. Spruce (*Picea*), larch (*Larix*), fir (*Abies*), buffaloberry (*Shepherdia*) and burnet (*Sanguisorba*) are absent from this forest zone. The warmest part of this zone hosts the first appearance of palmetto (*Sabal*); this genus is present in this forest zone along the U.S. Atlantic coast from approximately Savannah, Georgia, to Cape Fear, North Carolina. This forest zone currently is established at lower elevations (below ~305 m elevation) in the study area, on warmer valley floors and across the Piedmont (Fig. 2). The relative temperature index values from our samples range upward from 140 (Fig. 5) and their upper limit has not yet been established.

It is from this combination of presence/absence, co-occurrence, and relative maximum abundance of the diagnostic pollen taxa in our samples that we have reconstructed probable forest zones and forest zone boundaries for the pollen assemblages in this study. As noted earlier, we are in the process of directly comparing the pollen assemblages from our Blue Ridge fossil samples to modern pollen assemblages taken from modern soils within each of the forest zones Küchler (1975) has mapped (Fig. 2). This cross test includes all the major forest types established along the eastern seaboard (including boreal forest in Newfoundland and the Gaspé Peninsula). Additionally, we are trying to characterize the in-situ pollen signal beyond the boreal forest, across the forest-tundra ecotone (zonal boundary).

Analytical methods

In order to interpret the Blue Ridge's climate history, we examined fossil pollen preserved in the Big Meadows core and pollen from outcrops uncovered by recent debris flow activity in the study area (Morgan and Wieczorek, 1996; Wieczorek et al, 2000; Litwin et al., 2001; Eaton, 1999; Eaton et al., 2003b; Litwin et al., 2001; Litwin et al., 2004a, 2004b; Smoot, 2004a, 2004b). The presence and relative abundance of particular pollen taxa within these samples permitted us to derive-- stepwise-- the relative temperatures under which each sample was deposited, the probable forest succession through time, and the probable climate history of the study area.

We isolated fossil pollen assemblages from core and outcrop samples using the laboratory procedures outlined in Litwin et al. (1993). Briefly, this involves decalcification of the sample in HCl, demineralization in HF, filtration of clays through 8 μm filters, specific gravity fractionation of organic and inorganic fractions in an aqueous $ZnCl_2$ suspension by centrifugation, oxidation, slide preparation, and light microscope identification of specimens. Each sample was characterized on the basis of a standard count of 300 pollen grains per sample unless otherwise indicated. More than 14,000 specimens were counted by the senior author for this study.

The samples were categorized both by relative age and by absolute age. AMS ^{14}C dating was used to determine an absolute age (or age range) where possible for each sample. Most of our outcrop samples bore enough macrofossil carbon fragments to permit independent dating of each sample. However, the Big Meadows sample set did not contain sufficient organic material for every sample to be dated independently. In lieu of this, we constructed an age model for the core samples based on those AMS ^{14}C dates we were able to recover downhole. The core chronology we used is addressed later in this report (p. 20).

We reconstructed the relative thermal signal of each sample by developing a relative temperature index (noted earlier), based on the character of the fossil pollen assemblage within each Quaternary sediment sample. We experimented with a large number of ratios to find and construct a plausible relative measure of paleotemperature. One fairly promising model we constructed was based on the sum of the standard deviations of cold-loving taxa versus the sum of the standard deviations of warm-loving taxa in each pollen assemblage. That model was useful, but did not provide greatly different results than a simpler model that we present here; the standard deviations model will be presented elsewhere. The model we used here was based on a standardized count of 300 specimens. We tabulated the ratio of pollen specimens from selected warm arboreal taxa (*Quercus* and *Fraxinus*- oak and ash) versus the number of specimens from selected cold arboreal taxa (*Picea* and *Abies*- spruce and fir). This model, although fairly simple, provided a dependable and direct differentiation of our samples with respect to relative paleotemperature. Because some of the warmest pollen assemblages in this study had essentially no cold tree pollen taxa represented, we added a minimum denominator "correction" value of 1. Because oak pollen was strongly dominant in the samples of our study, this first-order "thermal index" initially was more sensitive in discriminating relative temperatures among pollen assemblages from warmer climate conditions. We corrected this preliminarily by plotting the index on a log scale, which increased the sensitivity for differentiating among cooler forest types, but somewhat decreased sensitivity for differentiating warmer forest types (see Fig. 4). Overall, this adjustment enabled us to differentiate relative temperature (thermal signal) among samples more effectively (y-axis, Fig. 4). This index was established as a first relative means of differentiating our sample set. Note that the dataset presented in Fig. 4 is the compilation of both subsets- core and outcrop; the relative confidence levels in their chronology are detailed below.

Our samples cluster into three categories of dating accuracy. All samples that yielded radiocarbon dates of less than 20,265 yr BP were calibrated by the computer program CALIB, according to the methods proposed by Stuiver and Reimer (1993). This program corrected our radiocarbon ages for known fluctuations in atmospheric CO_2 through time, and also enabled calculation of 2-sigma error confidence limits on the calibrated ages. These samples are preceded by the letter "A" in their sample code (ex.: "ALRA7", Fig. 4 and Table 1), and denote those ages which we think have the highest fidelity.

Radiocarbon samples that yielded ages in excess of 20,265 ^{14}C yr BP exceeded the limits of this calibration window, although they also bear 2-sigma error confidence limits. These samples, although dated as accurately as possible, are undoubtedly somewhat less accurate than those samples for which calibration was possible. The code designation for this second type of samples is preceded by the letter "B" (ex.: "BNFMR6").

Core samples for which no direct AMS ^{14}C dating was possible –interpolated dates (between datable control points) for which no confidence limits were calculated-- are preceded by the letter "C" (ex.: "CAS"). These samples denote the lowest level of chronological fidelity, but are still highly useful in determining the paleovegetation history of the Blue Ridge.

The study samples can be divided grossly into two time intervals: Holocene and Recent (0-10 ka), and the Pleistocene (10-45 ka). The Pleistocene-Holocene boundary is fixed at 10 ka by international convention (Harland et al., 1990). We have informally divided the Pleistocene interval in this report into two parts: the Late Glacial (15-45 ka), and the "transition" between the Late Glacial and the Holocene boundary (10-15 ka). This "transition" includes the Interstadial 1 warm event and the Younger Dryas cold event, as reported elsewhere (Harland et al., 1990; Dansgaard et al., 1993; Alley et al., 1993). For convenience of discussion we have further subdivided our samples into 5,000 yr increments, for a total of nine time windows (Fig. 4); each subinterval was examined for the range (extent) and frequency of forest change (see pp. 33-36).

Note that some of the carbon-bearing samples associated with the prehistoric debris flows did not yield pollen, and, therefore, yielded no proxy climate information. However, those carbon samples successfully established the age of the debris flows from which they were obtained, and indicate local periods of Quaternary deposition along the eastern flank of the Blue Ridge. They are plotted separately, adjacent to the x-axis (Fig.4, bottom).

Next we applied the presence, absence, and relative abundance criteria noted in the modern forest zonation (above) to our compiled pollen dataset (the relative temperature index graph), to derive Figure 5. The forest boundaries in Figure 5 were established internally using only our pollen dataset (Table 3). This zone assignment formed our interpretive model for characterizing the forest succession over the past 45 ky BP. The positions of the forest boundaries (with respect to our relative temperature index, along the y-axis, Fig. 5) are preliminary; each is now in the process of being cross-tested and refined by the modern soil/ forest dataset. The model will be emended in the future as necessary. The ^{14}C calibration limit is noted on the graph at 20,265 yr BP (for reference). Because so many separate questions exist regarding the geologic history and vegetation prehistory of Big Meadows, we also examined the core data subset separately to answer these site-specific questions (below).

LOCAL INVESTIGATIONS AT BIG MEADOWS

Location

The Big Meadows-Upper Rapidan River study area is located in north-central Virginia along the eastern front of the Blue Ridge Mountains (Fig. 1). The core site is situated within the

Big Meadows 7.5' topographical map (1:24,000 series). The main core was taken from near the geographical center of the meadow, at approximately 3460' elevation (Fig. 6). A second, shorter, polycarbonate-lined core was taken adjacent to the main core, in order to obtain an undisturbed sample of the very shallowest part of the section. The meadow core site is surrounded by Appalachian oak forest. Because our vibracoring locally disrupted sedimentary fabric within the core (fluidization) in the lower core runs, a 10-cm sampling interval was chosen as the closest sample spacing in the upper part of the core that was deemed likely to provide reliable (unmixed) results.

Character of the shallow subsurface

The shallow subsurface in Big Meadows is interpreted as a thin (<0.5 m) soil developed on the stratigraphic unit below it, which is also partly incorporated into the soil. The remaining 4 meters consists of a matrix-supported mixture of oxidized sand, silt, and clay, with varying concentrations of poorly-sorted, poorly-stratified, angular-to-subrounded pebbles. The top of this lower unit appears to have been reduced by the surface soil layer. The bulk of the sediment penetrated by our coring probably was deposited by cryogenic processes (solifluction, J.Smoot, USGS, pers. comm.). Smoot interprets low-relief steps and lobes on the surface of Big Meadows to be the geomorphic expression of shallowly buried solifluction features-- relict cold-climate landforms that are still visible under younger sediment. Relict Pleistocene deposits generated by cryogenic processes are more abundant in the study area than previously was recognized (Eaton et al., 2003; Smoot, 2004a; Smoot, 2004b). Although these textures and features presently are found in areas subjected to persistent ground ice (permafrost), they also can develop in somewhat warmer settings.

It appears that the character of these shallow subsurface deposits also creates heterogeneity in the soil moisture in the meadow (with depth). The top of a relatively-impermeable layer of clay-rich sediment occurs at approximately 35 cm below ground surface, and acts as a shallow aquitard which permits the lowest elevations in the center of the meadow to become a functional marsh periodically throughout the year. Effectively this turns the soil just below the meadow ground surface into a shallow perched aquifer. The increased moisture and cooler microclimate (because of the 3460' elevation) permit the growth of *Sanguisorba canadensis* (Canadian burnet, a cool-climate bog plant), *Betula populifolia* (gray birch), *Abies balsamea* (balsam fir), *Picea rubens* (red spruce) and *Cornus racemosa* (gray dogwood) to grow as refugial taxa on this ridgetop site (W. Cass, NPS, 2002, pers. comm.).

Thickness of Holocene/Pleistocene deposits

The vibracoring done at Big Meadows penetrated approximately 6 m of Holocene and Pleistocene-aged poorly consolidated sediment before refusal. Approximately 4.8 m of this interval was recovered as cored sediment. There was no indication that our coring reached bedrock (Cactoctin Formation), so the maximum depth of Pleistocene and Holocene deposition on the Catoctin Fm. at Big Meadows is as yet undetermined. The Catoctin crops out around the edge of Big Meadows, especially to the south, and even sporadically within the meadow itself (Allen,1963; Gathright, 1976; Rader and Evans, 1993). Quaternary deposits in the meadow therefore are non-uniform in thickness and distribution. Our coring suggests their thickness is a minimum of 6 m in the center of the meadow. Only the topmost sediments (upper 2.5 m) were sufficiently undisturbed by our coring to permit serial pollen analysis.

Age assignment of core samples and age-depth models

Like many of the outcrop samples we used in this study (Fig. 1), several samples from the Big Meadows core provided individual AMS ^{14}C dates; as such, their chronology is the most strongly established. However, other samples from the two cores did not provide individual dates; these were time-calibrated by interpolation between the dateable samples (Tables 1, 2). In addition, carbon from several shallow archaeological survey pits (from a study by C. Nash, James Madison University) also were analyzed by AMS to derive ^{14}C ages, in an effort to establish time control for the shallowest part of the sample set from the core (Table 1). Radiocarbon analyses were run on samples 3, 29, 36, 39, 53, 59, and 60 (see Table 1).

The results did not yield uniformly older dates with increasing depth. It is likely that some of the results were affected by contamination of reworked (older) carbon or by vertical mixing—collapse of sediment bearing younger carbon from a higher stratigraphic level down hole, during repenetration of the core hole. The first circumstance would give older than anticipated ages, and the latter would give younger than anticipated carbon ages at depth. The corrected ages and initial age results for radiocarbon samples we used in the Big Meadows core are shown in Table 2, along with all other radiocarbon samples used in this study. The samples are listed in Table 2 in order of increasing age; those that are preceded by an asterisk (also in boldface type) were used to develop age control in the Big Meadows core. The ^{14}C age results suggest that four different age models (Fig. 7) immediately may be proposed for those sediments recovered at Big Meadows.

The first model is built on the greatest possible number of ^{14}C AMS radiocarbon samples (samples 3, 5, 6, 29, 36, and 39), but favors the youngest possible age at depth. Using this age model, three of the four deepest samples (samples 53, 59 and 60) are "off-trend". They would have to have been contaminated with young carbon (from upsection, perhaps during repenetration of the hole during coring-- samples 59 and 60), or with redeposited old carbon ('dead' carbon-- sample 53). Under this first age model, we would interpret the core section at Big Meadows to be almost entirely Pleistocene in age, and overlain only by a thin veneer of late-Holocene-to-Recent organic-rich soil. It requires that three of the eight ^{14}C AMS radiocarbon analyses from the meadow be rejected as inaccurate. We note that two of the carbon dates used for age model 1 (samples 5 and 6) were averaged into a single value. The charcoal isolated from these two soil samples within Big Meadows were dated by ^{14}C AMS radiocarbon analysis in collaboration with the James Madison University (C. Nash) archaeological assessment: gridpoints 800N/475E (sample 5), and 800S/50E (sample 6, Fig. 6). The calibrated ages (per Stuiver and Reimer, 1993) for these samples were 2.61 ±0.14 ky cal BP and 2.84 ±0.08 ky cal BP, respectively. Averaged together, they set the age of the 30 cm depth interval at Big Meadows as 2.73 ±0.14 ky cal BP. The very next core sample below this depth interval (sample 29) provided a calibrated age of 23.87 ±0.77 ky cal BP, from a depth of 47 cm in Big Meadows. In this age model we therefore place a depositional hiatus in the core between 15 and 47 cm depth, and tentatively between 30 and 47 cm depth.

The second model is a variant of the first; it accepts sample 53 as one of the accurate age datums and suggests that sample 39, like samples 59 and 60, was affected by young carbon from repenetration of the hole during coring. This model suggests that all "off-trend" ages are clustered at depth, and are similarly contaminated by 'young' carbon. It also requires that three of the eight total ^{14}C AMS radiocarbon analyses from the meadow to be rejected as inaccurate. However, it proposes a significantly older age for the 320 cm depth interval (~67 ka) than is proposed for the first age model (~44 ka). This increase in age requires a tenfold drop in the net deposition rate of Pleistocene sediment below ~135 cm core depth, suggesting a major change in depositional style occurred. We do not recognize a textural fabric change or grain size change within the core in that interval that might support this.

In the third age model, samples 3 and 59 are proposed to be the most accurate ages. This model does not mandate a hiatus (paraconformity) in the core. Age model three would require that more ^{14}C AMS radiocarbon analyses from the meadow be rejected (five of eight). Using this chronology, the Holocene/Pleistocene boundary would be placed between 106 and 116 cm depth in the core (on the basis of a standardized 10 ka age). This age model requires that some of the coldest vegetation signals in the core (samples 29 and 45 through 49) -- representing some of the coldest forest types -- had to have been established in Big Meadows during the Holocene, when mean annual temperatures were much too high to sustain these forest types in the study area.

Age model four proposes that the shallowest (sample 3) and deepest (sample 60) samples provide the most accurate ages, because they define the least possible total age span. This model suggests that "old" carbon affected the results of the intermediate-depth "off-trend" samples (five samples), in a non-linear way. This solution requires that five of the eight ^{14}C AMS radiocarbon analyses from the meadow be rejected. The Holocene/Pleistocene boundary also would be placed between 163 and 173 cm depth. As before, it would require that exceptionally cold-tolerant forests be established at Big Meadows during the warm climate of the Holocene.

We have adopted model 1 for use in this study for the following reasons. It incorporates the greatest number of radiocarbon ages, and the millennial-scale chronology (absolute time context) that it defines for the warm and cold pollen assemblages in the core is consistent with known larger climate trends in the latest Pleistocene and Holocene. Age model 2 could not be substantiated by textural changes in the core, as required below ~135 cm core depth. Age models 3 and 4 require more carbon dates to be rejected, and also require the establishment of cold forests in the study area during the warmest interval of the Holocene. Because much of the Holocene interval was as warm or warmer than present climate conditions we find that scenario and those respective age models to be untenable. We think the lowest of the accumulation rates in this age model—0.8 cm/ky-- indicates the approximate position of a temporal hiatus (paraconformity), between 15 and 47 cm depth. The depth of this temporal hiatus varies. Much of the meadow has approximately 30-50 cm of Holocene sediment, expressed as the 'B2', 'B1', 'O' and 'A' soil horizons (below). In the core itself the hiatus is somewhat shallower, between 15-21 cm depth.

If we accept model 1, the lack of latest Pleistocene and early Holocene sediment in the core perhaps may be attributed to an early Holocene dry interval that is recognized elsewhere in eastern North America (Muller et al, 2003). This dry period may have affected the deposition or contributed to the erosion or deflation of the core site at Big Meadows through the 10-5 ky cal BP interval. It also may have contributed to the erosion of any sediment that had been deposited at the Big Meadows core site between 20-10 ky cal BP.

Pleistocene-Holocene vegetation history of Big Meadows

On the basis of the radiometric and fossil pollen evidence we recovered directly from the Big Meadows site, we suggest the following trends occurred in vegetation from approximately 37 ky BP to the present. The oldest pollen evidence we have from the core so far (sample CAW, number 59[1]) suggests that Big Meadows was vegetated by boreal forest at approximately 37 ka (Fig. 8; Tables 1 and 2). Big Meadows would have been vegetated similarly to what the highest peaks of the Gaspé Peninsula or Newfoundland are today. The meadow site warmed rapidly over the next 2000 years, transitioning through spruce-fir forest and northern hardwoods-spruce forest into northern hardwoods forest (sample CAV, number 58). This transitional interval would have been similar to the forests (and climates) currently found in Nova Scotia, central Maine, and upper New York state, respectively. From 36 ka to 28 ka the meadow experienced a net cooling all the way to boreal forest conditions. Three large cooling pulses occurring between 36 -33 ka (samples CAU and CAT, numbers 57 and 56), between 33-31 ka (samples CAS and CAR, numbers 55 and 54), and between 31-29 ka (samples BAQ and CAP, numbers 39 and 53). From 29.5-28 ka the meadow site was vegetated again by boreal forest (samples CAP and CAO, numbers 53 and 52). However, the evidence does not yet enable us to determine conclusively whether the Big Meadows site was unvegetated barrens, fully open alpine tundra, sparsely forested forest-tundra, or densely forested ridgetop during those past intervals when it was surrounded by boreal forest. It may have been cold enough that this ridgetop site was mostly open alpine tundra, with snowpack that melted late in the spring or summer, and was sparsely vegetated with small copses of shrubs or stunted trees (if so, then probably spruce, fir, larch, birch, buffaloberry and pine). Pollen evidence suggests it varied (see "*First occurrence of "modern"* ...", p. 29). By approximately 26 ka the site once again experienced a substantial but

[1] Although sample 59 is noted as a control point in age model 3 of Fig. 7 (at 22.78 ka), its projected age in age model 1 (used here) is 37.15 ka.

very brief warming, back to northern hardwoods forest (sample BAM, number 36). Precipitous cooling transformed the site back to boreal forest by 25 ka, a change of three forest zones in a span of only 1000 years (samples CAL and CAK, numbers 51 and 50). Evidence suggests the forests in and near Big Meadows fluctuated between 25 and 22 ka (Figs. 8, 9), changing at least twice from boreal forest through spruce-fir forest to northern hardwoods-spruce forest, then back through spruce fir forest to boreal forest again (samples CAJ to AAD, numbers 49-45 and 29). This time interval (24.5-21.5 ka) contains the coldest pollen assemblages we have been able to document so far in the Blue Ridge study (samples BMAD1 and HCR1, numbers 31 and 26). The timing of these samples correponds to a Northern Hemisphere insolation minimum (Berger, 1978; Fig. 9). These samples probably represent the vegetation in place at or very near to the time of the last glacial maximum (LGM) in the Northern Hemisphere, when the glacial terminus was only about 200 miles north of the study area.

The largest time gap we observed in the core spans from approximately 23.8 ka to ~2.73 ky cal BP. We cannot determine from core evidence alone what vegetation changes occurred in this interval. We also cannot determine if additional sedimentation had occurred at the site through part of this interval (such as during the latest Pleistocene between 23 and 10 ky cal BP), only to be stripped away later, during the middle Holocene. Core evidence by itself (sample ASHEN2, number 3) indicates that Appalachian oak forest, the forest type now surrounding Big Meadows, was in place at the site by ~2.73 ky cal BP. Outcrop evidence from elsewhere in and near Shenandoah National Park (samples AWRA, AWRD, and ALRA7, (numbers 11, 10, and 8)) provide evidence constraints for when Appalachian oak forest may have been first established in the study area (below).

AMS ^{14}C dates: implications for archaeological studies

The radiometric dates we were able to obtain from the shallow subsurface at Big Meadows have important implications for documenting native human occupation in and around Big Meadows. Four usable dates were obtained from the top meter of sediment in the meadow (samples ASHEN2, '800N', '800S', and AAD (numbers 3, 5, 6, and 29; Tables 1 and 2)). Archeological excavations from James Madison University field crews (under the supervision of Carole Nash) have recovered approximately 15 diagnostic artifacts from Big Meadows so far, objects that represent human occupation prior to European settlement of this area. Of these, Nash reported only 2-3 objects that were buried in the A/B, B-1 or B-2 soil horizons; all others were found on the ground surface. Artifacts similar or identical to all three of the most deeply-buried of the "diagnostics" had been found elsewhere in the region in association with charcoal, and were determined to be younger than 6000 yr BP (C. Nash, 2003, JMU, pers. comm.).

The radiometric ages we obtained from the top meter of sediment were from 14 cm (number 3), 30 cm (numbers 5 and 6), and ~47 cm depth (number 29; see Table 1). These four samples suggest a depositional hiatus or unconformity exists between the deepest of these samples (number 29) and the next shallower ones (numbers 5 and 6). This hiatus is noted in the age/depth plot in Fig. 7. Comparison of the depth of the oldest diagnostic objects found in the meadow with the depth and ages of the radiometric dates we obtained indicate that all diagnostics were found above our radiometric sample at ~47 cm depth, and therefore all were found above this unconformity. The oldest dates we were able to document above the unconformity are 2.61 ± 0.14 ky cal BP and 2.84 ± 0.08 ky cal BP. Both of these samples are from ~30 cm depth, but from opposite sides of the meadow (Fig. 6). They provide the averaged age of 2.73 ± 0.14 ky cal BP for the 30 cm depth horizon in our age/depth model, just above the hiatus (above, Fig. 7).

The position and ages of the radiometric evidence leads us to suggest that no true depositional context can be expected for any artifacts older than ~ 2.73 ± 0.14 ky cal BP. Any artifacts found in the meadow that bear relative ages older than this very likely will have been deposited directly on the non-depositional unconformity surface in the meadow, in a time interval between 23.87 ± 0.77 ky cal BP and ~ 2.73 ± 0.14 ky cal BP. To state this differently, we predict that all vertical succession (increased relative age with depth) for human artifacts found in Big Meadows will terminate regularly between 30 -50 cm depth below ground surface, or about 2.73 ± 0.14 ky cal BP.

First occurrence of "modern" (presently established) forest

One of the questions we hoped to answer in this study was the timing of the first occurrence of Appalachian oak forest in the Blue Ridge, within the area of our study. Our dataset is still sparse through the Pleistocene- Holocene boundary (~10 ky cal BP), and we cannot yet document that forest transition directly. The best present evidence we have that can address that question is two outcrop samples from nearby Wilson Run (Table 1, Fig. 1). Samples AWRD and AWRA (numbers 10 and 11) suggest that northern hardwoods-spruce forest was still present in the study area between approximately 12 ky cal BP and 13 ky cal BP (Fig. 5). These samples fall within the Younger Dryas climate interval, the last major cold pulse before the late Pleistocene final deglaciation. This suggests that Appalachian oak forest likely became established in the study area only more recently than 12 ky cal BP. An earlier pollen study done by Craig (1969) suggested that the southern part of the Shenandoah Valley changed from forests heavily populated with spruce and pine to forests dominated by oak approximately 9520 ±200 BP. When we correct Craig's radiometric date for atmospheric CO_2 flux (per Stuiver and Reimer, 1993), it suggests that the time of that transition may be closer to 10.748 ±510 ky cal BP (2 sigma error). The older end of this calibrated age (11.258 cal ky BP) is fairly close to some ages suggested for the young boundary of the Younger Dryas (Alley et al., 1993; Freidrich et al., 2001; Hajdas et al., 2003). The very earliest date that Appalachian oak forest could have existed in the study area is bounded by a third Wilson Run sample, sample AWRB2 (number 13). That sample suggests that a cold tolerant forest--northeastern spruce-fir forest-- was established in the study area at approximately 17 ky cal BP (Fig. 9). It is feasible, but as yet undocumented, that Appalachian oak forest first could have existed in the study area briefly, during the more sparsely documented interval between 17 ky cal BP and 13 ky cal BP.

Evidence of prehistoric meadows

Although a hiatus in sedimentation exists at Big Meadows, we can make an indirect assessment of when in the past this site may have been a meadow. There appear to be several times when this may have been likely- each may have been intermittent, and lasted less than a millennium. The first opportunity may have been times of the most intense cold climate in the study area. We are still trying to determine how cold the ridge tops became during periods of maximum glaciation in the Northern Hemisphere. It may have been cold enough that they could have become alpine meadow, alpine tundra or forest-tundra type open parkland. This is still equivocal; solifluction deposits in the meadow may not have required permafrost to form (French, 1996, p.151), suggesting that the climate could have been warmer than the -1^0 C mean annual temperature isotherm (the southern limit of permafrost, Figs. 2, 3; Brown et al., 1997). If it had been alpine meadow, alpine tundra, or open parkland during the coldest periods, the most likely intervals would be 37.5-36.5 ka, 30-28 ka, and intermittently between 25.5-22 ka.

Fossil pollen provides some limited evidence to address this directly. Five samples from the Big Meadows core probably represent boreal forest conditions. We tested these five core samples by comparing two pollen indicators within each of them to the values of those same two indicators in the present-day soil at Big Meadows. The two measures for comparison were the percentage of grasses (Poaceae) and the percentage of all herbaceous taxa (here, Poaceae, composites, and amaranths). The surface soil in the present-day Big Meadows contains approximately 9% grass pollen, and a combined herbaceous pollen total of 18%. Only one of the five 'boreal forest' core samples had percentages that approached these modern analogue values. Sample CAK (number 50) contained approximately 13% grass pollen and 13% total herbaceous pollen. We think this sample most probably represents open (alpine) meadow surrounded by boreal forest, at approximately 25.17 ka. At the moment, the present evidence collected for this study does not enable us to answer conclusively whether meadow or alpine tundra existed at this ridgetop during the peak of the last glaciation (last glacial maximum).

Another set of conditions that might favor meadow development could be those brief periods of intense climate change. These are identified by large shifts in forest type over a relatively short period (1-2 ky duration). Open meadow may have developed at the Big Meadows site because the climate might have been shifting faster than forests could adapt to the environmental stress of rapidly changing temperature and precipitation. During such times, shorter-generation plants-- herbaceous plants, grasses, and low shrubs—might tolerate such stresses relatively better than closed-story forest, which would die off and create an open-story environment advantageous for opportunistic herbs and grasses. A series of strong or abrupt shifts are found at 37.5-35.5 ka, 33-29 ka, 26-23 ky ka, and 21.5-20 ky BP (Fig. 8). We have identified eight possible times in our core sample set when the Big Meadows site may have been a meadow, based on the same two pollen indicators used above. Three of these fossil samples exceeded modern analogue values in both criteria. Because of this, open meadow almost certainly occurred at the site at those times- 2.3 ky cal BP (sample ASHEN2, number 4), 23.87 ka (sample AAD, number 29), and 31.7 ka (sample CAR, number 54; Fig 9, Table 1). The latter two samples are from intervals of strong climate shifts, and suggest the site was open meadow surrounded by northern hardwoods-spruce type forest. The first of these three samples is of Holocene age, and probably represents temperate open meadow surrounded by Appalachian oak forest (as today). Three totally different core samples did exceed the modern percentage of grasses with respect to their pollen totals, but did not meet or exceed the total herbaceous percentage of our modern analogue soil sample. Accordingly, these probably (but less definitely) represent meadow; they occurred at 24.21 ka (sample CAF, number 45), 24.81 ka (sample CAI, number 48), and 25.17 ka (sample CAK, number 50, noted earlier). The first two were surrounded by northern hardwoods-spruce forest and the third was surrounded by boreal forest. The final two core samples have values that approach- but are somewhat less than- the modern meadow values for both pollen criteria. These both represent northern hardwoods forest and were found at 25.53 ka (sample BAM, number 36) and 35.85 ka (sample CAV, number 58). These two samples may represent intervals of meadow, or of open-story woodland at the site. All of the likely prehistoric meadow horizons are noted in a schematic of the Big Meadows core (Figure 8).

VEGETATION RESPONSIVENESS TO CLIMATE

Compiled vegetation history

We have attempted to address questions of scale and context regarding the Blue Ridge's vegetation responsiveness to 'geologic-scale' climate change by compiling our core and outcrop datasets (Figs. 4, 5, and 9). We have done this by integrating our samples on the basis of (calibrated) radiometric age. By necessity, those samples whose age exceeded present calibration limits, or which were derived through interpolation (core samples), are plotted with different symbols. Because the sample set is generally well-constrained with independently-derived ages, and is recovered from a localized geographic area, we have used it as a compiled dataset to synthesize the vegetation history (proxy climate history) of the Blue Ridge in the study area (Figs. 9, 10).

Range of forests per time increment

We were able to document and to compare the probable number of different forest zones that existed in the study area during each successive 5 ky increment from 45 ka to the present (Fig. 9). We counted all forest zone changes linearly—i.e., where we possessed pollen evidence of two geographically non-contiguous forest types within a specific time increment, we acknowledged the implicit presence of all intermediate forest types, occupying the temporal position between those two data points. For example, prehistoric boreal forests in the study area that experienced climatic warming did not directly become Appalachian oak forest, but probably transitioned through three other forest phases first (Figs. 5, 9). This permitted us to estimate the total vegetation variability within each time increment, as an approximate measure of the high and low temperature extremes (amplitude of change) occurring within it.

Some 'range-through' occurred across time interval boundaries. In several instances, the youngest documented sample in a given time increment represented a different forest zone than the oldest documented sample in the next younger time increment. In order for us to derive an estimate that did not overcount or undercount the probable number of forest zones that occurred within each time increment, we systematically assigned all such boundary 'range-through' to the next younger zone. The only exception to this was the time interval 10-5 ky cal BP; no dated pollen evidence fell within this interval at all, so we deferred assigning a forest zone range value to it.

The range of forest types observed within these 5 ky 'windows' varied, partly as a function of data saturation.

The increment 45-40 ka bore only one forest type, whereas the next younger interval (40-35 ka) bore four—all of them colder than the forests presently established in the area (Fig. 9). 35-30 ka provided evidence of two forest types: the next younger interval (30-25 ka) produced four forest types within its 5 ky 'window'. The absolute coldest forest types noted in this study occurred between 25-20 ka; this time interval provided evidence of four different forest types. The interval 20-15 ky cal BP provided evidence of three forest types, but importantly, they generally were warmer forest types than would be predicted if the Last Glacial Maximum (LGM) occurred at 18 ky cal BP, a commonly accepted date (CLIMAP, 1976; Dreimanis, 1977; Delcourt and Delcourt, 1981). We think the LGM is now more appropriately placed approximately 25.5-20.5 ky cal BP, perhaps even 24.5-21.5 ky cal BP, where the strongest evidence of boreal forest occurs in our data set, and where Northern Hemisphere solar insolation was at or near minimum values (Berger, 1978; Fig. 9). The interval 15-10 ky cal BP shows evidence of two forest zones (one of them a range-through), but the next younger interval (10-5 ky cal BP) provided no direct evidence of the range of its forests. Interpolation of those samples immediately older and younger than this interval suggests that a minimum of two forests may be inferred in this data gap, but in the absence of any fossil evidence in this interval at all, we assigned no forest range value. Finally, the most recent time increment (5-0 ky cal BP) provided evidence of two forest types. We qualify this by noting that oak-hickory-pine forest presently is established in the lowest elevations of the study area (below ~1000' elevation) and sample 4 may be assigned marginally to that forest type.

These fossil assemblages (Fig. 9) indicate that many time intervals within the Late Pleistocene portion of our study experienced a variety of forest conditions, and not just uniformly cold boreal forest. This suggests climatic fluctuation was common during the Late Pleistocene. In addition to determining forest range within each increment, we also tried to determine how frequently forests shifted in the study area over the past 45,000 years.

Frequency of forest change

Whereas the range of forest change was an approximate measure of the amplitude of climate change, frequency of forest change is an approximate measure of how often climate changed enough to force a turnover in forest type. On the basis of the data accumulated at present, the number of forest zone changes observed appears to be in part a function of the data saturation within any given time window. Although our data are still accumulating, we have seen evidence of a minimum of 37 forest shifts in the study area over the past 40,0000 years, suggesting that forests experienced climate-related turnover on average less than every 1100 years (Fig. 9). Up to 14 forest zone changes (13 plus 1 range-through) can be documented within one 4-ky time increment (26-22 ka), suggesting that forest composition may have responded to climatic changes in the study area as frequently as every ~285 years. This high frequency of change is similar to the rates found in two shorter time intervals in the core. Three different forest zones have occupied the study area within the 500-year period from 26-25.5 ka, and up to four different forest zones have occupied the study area within the 500-year period from 25.5-25ka. These indicate vegetational response rates (forest changes) of 0.17 ky and 0.125 ky, respectively. From this we conclude that the vegetation shifts probably were in phase or nearly in phase with climate changes, and that no appreciable vegetational 'lag' was present. This recently also has been documented in Switzerland, in central and southern Europe, in the Netherlands, and in the Canadian Maritime region (Ammann et al, 2000; Freidrich et al., 2001; Hoek, 2001; Williams et al., 2002). This 'in phase' trend of vegetation response to climate does not appear to conform to the vegetation disequilibrium model suggested for southern Ontario, which simulated a vegetation lag response to climatic warming since the Little Ice Age (Campbell and McAndrews, 1993).

We also made an initial estimate of the frequency of change within each of the 5 ky subintervals (Figs. 5, 9). Evidence of forest changes varied considerably among the time increments. The oldest increment, 45-40 ka, had no evidence of forest change. The next younger increment, 40-35 ka, had six shifts. 35-30 ka had one forest zone shift. The next increment, 30-25 ka, had eight. The cold interval between 25-20 ky cal BP recorded sixteen forest zone shifts (for an average forest shift frequency of 312 years, Fig. 9). The period of 20-15 ky cal BP recorded three full transitions. The period of 15-10 ky cal BP recorded 1 full transition. No forest transitions were directly recorded from 10-5 ky cal BP (due to a data gap), but inference suggests the interval had to have included at least 2 transitions. The final increment recorded 2 full transitions, albeit marginally. The maximum frequency of forest change within any of these defined 5 ky increments (312 years) is a similar sub-millennial scale to the vegetation response rates we noted spanning shorter time intervals in the dataset (125 and 170 years). The absolute magnitude of these response times is about the lifespan of a single tree; it suggests that climate change stresses certainly acted on the individual plants in these forests at century-scale or perhaps decade-scale. It also suggests that climate probably was a steady and persistent agent of change in these forests over the studied time interval (0-45 ka). Accordingly, we suspect that Blue Ridge forests may have changed significantly in composition -- with sub-millennial frequency-- throughout the 45-ky interval of our study. We predict that such shorter rates of change likely will be documented within additional time increments as we are able to increase the robustness of our data set through those intervals.

Discussion

It would be highly implausible for forests to change at sub-millennial frequency if forest change occurred only at the ecotone (fringe) between two forest zones, as an advancing or retreating “wavefront”. Such a mechanism could not shift forests along a changing climatic gradient with the frequency we observed in our data. Instead, one of us (RJL) thinks the mechanism that enables forest zones to change in-phase or nearly in-phase with climate shifts must happen internally and locally or extra-locally within each forest zone, within embedded microenvironments. The key to vegetative responsiveness to climate very likely can be found in the distribution of refugial plants such as those at Big Meadows. Plants that occupy environments that are at the extremes of their climatic tolerance can expand their ranges quickly and exponentially when climate does shift toward conditions more favorable to their survival and population growth. This "embedded" refugial growing stock, along with ungerminated (dormant) seeds from rare or recently extirpated plants in the soil, probably enables fairly rapid restructuring of plant communities and whole forests in a "mosaic-style" or kaleidoscopic transformation. For example, sustained strong climatic cooling at the Big Meadows site would favor the growth and expansion of populations of balsam fir (*A. balsamea*), red spruce (*Picea rubens*), Canadian burnet (*Sanguisorba canadensis*), gray dogwood (*Cornus racemosa*) , eastern hemlock (*Tsuga canadensis*), eastern white pine (*Pinus strobus*), bigtooth aspen (*Populus grandidentata*), and gray birch (*Betula populifolia*) at the expense of populations of blackjack oak (*Quercus marilandica*), scarlet oak (*Quercus coccinea*), chestnut oak (*Quercus prinus*), post oak (*Quercus stellata*), pin oak (*Quercus palustris*), American holly (*Ilex opaca*), mulberry (*Morus rubra*), pignut hickory (*Carya glabra*), mockernut hickory (*Carya tomentosa*), black walnut (*Juglans nigra*), shortleaf pine (*Pinus echinata*), and Virginia pine (*Pinus virginiana*). All occur within the Appalachian oak forest, but taxa in the first group are much more characteristic elements of cooler forest zones, such as northern hardwoods forest, northern hardwoods-spruce forest, etc. Such a mosaic pattern may be seen near the present southern boundary of the boreal forest zone (Larsen, 1980).

Another mechanism that apparently may enhance and hasten forest transformation is a "leveraging" effect of increased sensitivity when tree taxa are shifted to the very limits of their climatic tolerance. They not only suffer increased mortality due to physical climate stress (changes in temperature and precipitation), but more rapidly succumb to biologic stressors such as insect and fungal attack. Examples of a biological leveraging effect on the mortality rates of already climatically-stressed taxa probably include the current insect infestations of hemlock wooly adelgid (*Adelges tsugae*) on the eastern hemlock, balsam wooly adelgid (*Adelges picea*) on the fraser fir population of the Great Smoky Mountains, and red oak borer (*Enaphalodes rufulus*) on northern red oak and black oak, as well as fungal infestations of dogwood anthracnose (*Discula destructiva*) on flowering dogwood, beech bark disease (*Nectria coccinea* var. *faginata*) on American beech, and butternut canker (*Sinococcus clavigigenti-juglandacearum*) on butternut. Examination of the most abundant pollen (plant) taxa in our samples show that each has fluctuated in abundance in response to climate throughout the entire geologic interval we studied, frequently over rather short geologic intervals. Figures 8-10 illustrate this biological responsiveness; Figure 10 is a local synthesis of the climate-driven vegetation response in the Blue Ridge study area over the past 45 ky. To our best knowledge it is the longest such synthesis ever reconstructed for the Blue Ridge.

Minimum range of climate change

Current fossil evidence suggests that a total of six different forest types can be documented to have existed in the study area over the past 45 ky (Fig. 9). The data suggest that the area experienced climatic conditions ranging from those that supported a warm-temperate oak-hickory-pine forest to those that supported boreal (taiga) conditions, during the past 45 ky. As an initial estimate, this suggests that the mean annual temperatures (MATs) in the study area varied *at least* 11.5^0 C (20^0 F) over this 45-ky interval (the approximate temperature range spanning the coldest limit of oak-hickory-pine forest (~13^0 C or 55^0 F) to the warmest limit of the low boreal forest (~1.5^0 C or 35^0 F); Fig. 2). The evidence also indicates that this serial vegetational change (proxy climate change) was not gradual or unidirectional through this time period. Forests of nearly every type were developed repeatedly in the study area, especially forest types that were markedly colder than those presently established there. Several short temporal intervals (1-2 ky) show evidence of abrupt warming or cooling (spanning three or four different forest zones). The evidence demonstrates that the late Pleistocene climate in the study area was *not* uniformly cold, nor was Holocene climate uniformly warm in the study area.

A modern geographic analogue that spans the minimum climatic range that we can document in our fossil evidence (to date) would extend from the base of the Blue Ridge Mountains in Virginia to central Ontario or Newfoundland. From the current evidence we cannot demonstrate conclusively that the climate in the immediate study area got cold enough for permafrost to develop during this 45-ky time interval. We currently are in the process of testing and refining our model, through finer-scale pollen analyses of another local core of full-glacial age (from Kinsey Run). We are comparing the pollen assemblages within it to pollen in modern soil samples from low, middle, and high boreal forest. It is within the zone of high boreal forest that climate conditions support the establishment of permafrost; this corresponds approximately to the -1^0 C mean annual temperature isotherm (Brown et al., 1997). This core also should provide an additional test of the shorter-term responsiveness of vegetation to climate change.

CONCLUSIONS

We conclude the following from the current results of our climate history study component for the landslide hazards study of the Blue Ridge Province:

A.) Forests currently developed on the Blue Ridge are not characteristic of forests that have been present in this area over the past 45,000 years. Evidence preserved in and around Shenandoah National Park suggests that demonstrably cooler forests were established in the study area from approximately 45,000 years ago to as recently as 12,000 years ago.

B.) Appalachian oak forest probably existed along the Blue Ridge intermittently over the past 15,000 years, and commonly over the past 10,000 years. We found no evidence that this forest type existed in the study area at all prior to 15 ky cal BP. During the warmest part of the Holocene, from approximately 6 ka to 4 ka, the ridgetop forests may have shifted periodically to oak-hickory–pine forest or even to southern mixed forest. No direct evidence has yet been found to corroborate this prediction, however; studies are ongoing.

C.) Forest zones have changed rapidly and frequently in composition over the time interval studied. Our composite climate history evidence, although still fragmentary and quite incomplete, already documents approximately 37 forest zone changes in the study area over the past 45,000 years. Several intervals indicate that forests in the study area may have responded to climate change as frequently as every 125-300 years. Late Pleistocene forests in the Blue Ridge were not uniformly cold, but fluctuated strongly in response to regional-scale climate shifts, over short geologic time intervals.

D.) We have demonstrated that it is possible to create a moderately long serial record of Pleistocene to Holocene vegetation change for higher elevation regions in the eastern U.S., despite the general lack of individual sites favorable for recovering long Quaternary core records.

E.) The *minimum* range of climate change established in the study area over the past 45,000 years-- on the basis of the coldest and warmest modern analogue forest types we recognize in our prehistoric samples-- probably exceeds a range of 11.5^0 C (20^0 F) in mean annual temperature. The current MAT of the study area (at the base of the Blue Ridge) is approximately 13^0 C (55^0 F). We note these figures are preliminary- we are still working to document and to quantify the most probable absolute temperature shifts for the study area.

F.) Our evidence currently supports an older age for the last glacial maximum (LGM) in the Northern Hemisphere, based on radiometrically-dated pollen assemblages ~ 200 miles south of the LGM terminal moraine. The coldest vegetation assemblage we recognize in this study definitely occurs from 20.5-25.5 ky cal BP, and possibly from 21.5-24.5 ky cal BP. Our evidence does not appear to support placement of the last glacial maximum at 18 ka.

G.) Archaeological evidence appears to compare somewhat equivocally with radiometric evidence we have recovered at shallow depth in the Big Meadows core. At present we think the oldest relatively dated archaeological tool evidence was deposited on a non-depositional surface (unconformity) that may have developed at Big Meadows during the warmest interval of the Holocene. This unconformity may represent as much as 20 ky of geologic time.

H.) Clay-rich intervals at shallow depth in the meadow, deposited during the Late Pleistocene by solifluction and/ or gelifluction, created an aquitard that now increases soil moisture at the ground surface of the meadow throughout much of the year, in the lowest parts of the depression. This perched water table, combined with the cooler microclimate of the high elevation ridgetop (~3500') helps to enable the growth of refugial taxa in the meadow, specifically *Sanguisorba canadensis* (Canadian burnet, a cool-climate bog plant), *Betula populifolia* (gray birch) and *Cornus racemosa* (gray dogwood), both of which favor moist soils.

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FIGURE 1. Site map of study area, Shenandoah National Park and environs, VA. Outcrop localities noted by small white circles. Sample numbers correspond to Table 1. The boundary between the warmer oak-hickory pine forest and the cooler Appalachian oak forest approximates the 1000' elevation contour (lower right corner).

Figure 1. Site map of study area, Shenandoah National Park and environs, VA

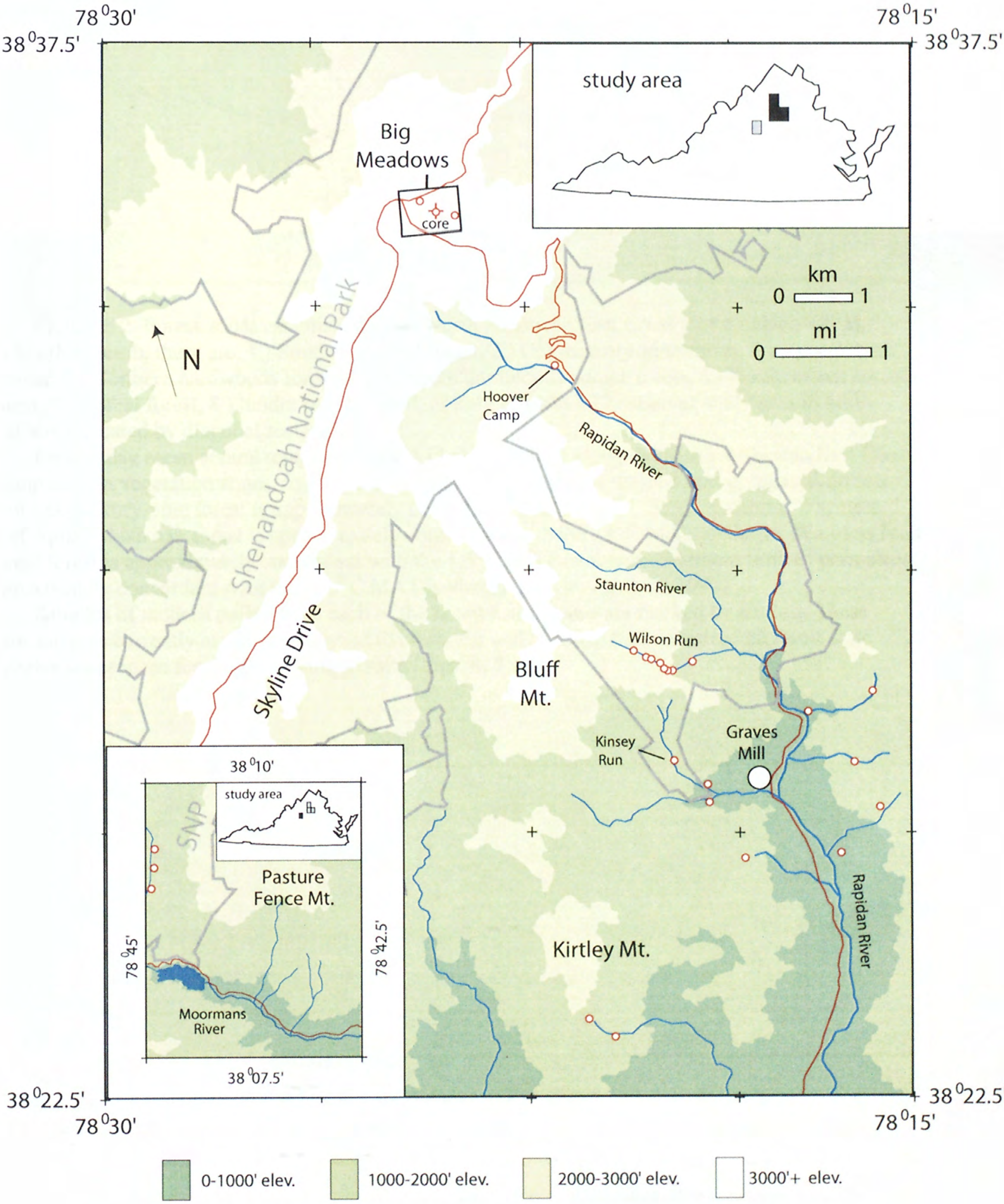
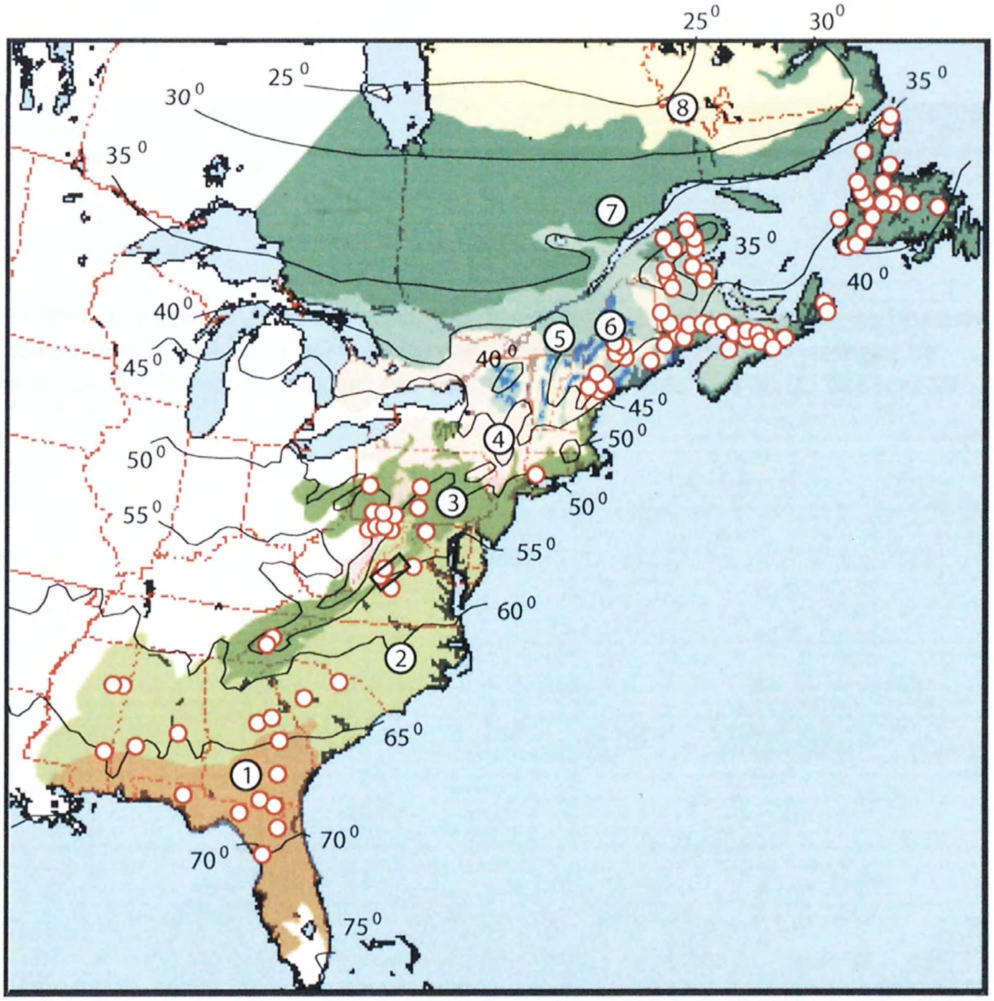


FIGURE 2. Forest zones established along North American East Coast (per Küchler, 1975). From South to north, these are: 1.) Southern mixed forest, 2.) Oak-hickory-pine forest, 3.) Appalachian oak forest, 4.) Northern hardwoods forest, 5.) Northern hardwoods-spruce forest, 6.) Northeastern spruce-fir forest, 7.) Boreal forest, 8.) tundra (not forested, or only sparsely). Location of study area in north-central VA indicated by diagonal rectangle.

Present day mean annual temperature (MAT) gradient (^{0}C) along the North American East Coast superimposed on vegetation zones, to illustrate temperature controls on major forest groups. Warmest limit of oak-hickory-pine forest is approximately concordant with the 18^0 C MAT isotherm. Warmest limit of Appalachian oak forest is approximately concordant with the 13^0 C MAT isotherm. Warmest limit of boreal forest is approximately concordant with the 1.5^0 C MAT isotherm. Southern limit of permafrost is approximately concordant with the -1.0^0 C MAT isotherm (per Brown et al., 1997).

Samples of modern pollen from each of the noted forest zones are marked by circles. These modern samples currently are being analyzed to cross-test and to refine the reconstructed forest zone boundaries we propose for the fossil sample suite (Figs. 4, 8).

Figure 2. Forest zones established along the North American East Coast (per Küchler, 1975)



Study area- Shenandoah National Park

(1) Forest zones (per Kuchler, 1975)

55⁰ Mean Annual Temperature isotherms (degrees Fahrenheit)

FIGURE 3. Approximate Mean Annual temperature limits for selected plant genera and Eastern U.S. forest types. Data derived from Little (1971, 1976) and Küchler (1975). Taxa are arranged by decreasing mid-range value. Forest zone bands are abbreviated along left side of Y-axis. See text for explanation.

Figure 3. Approximate Mean Annual Temperature Limits for Selected Plant Genera and Eastern U.S. Forest Types (this study)

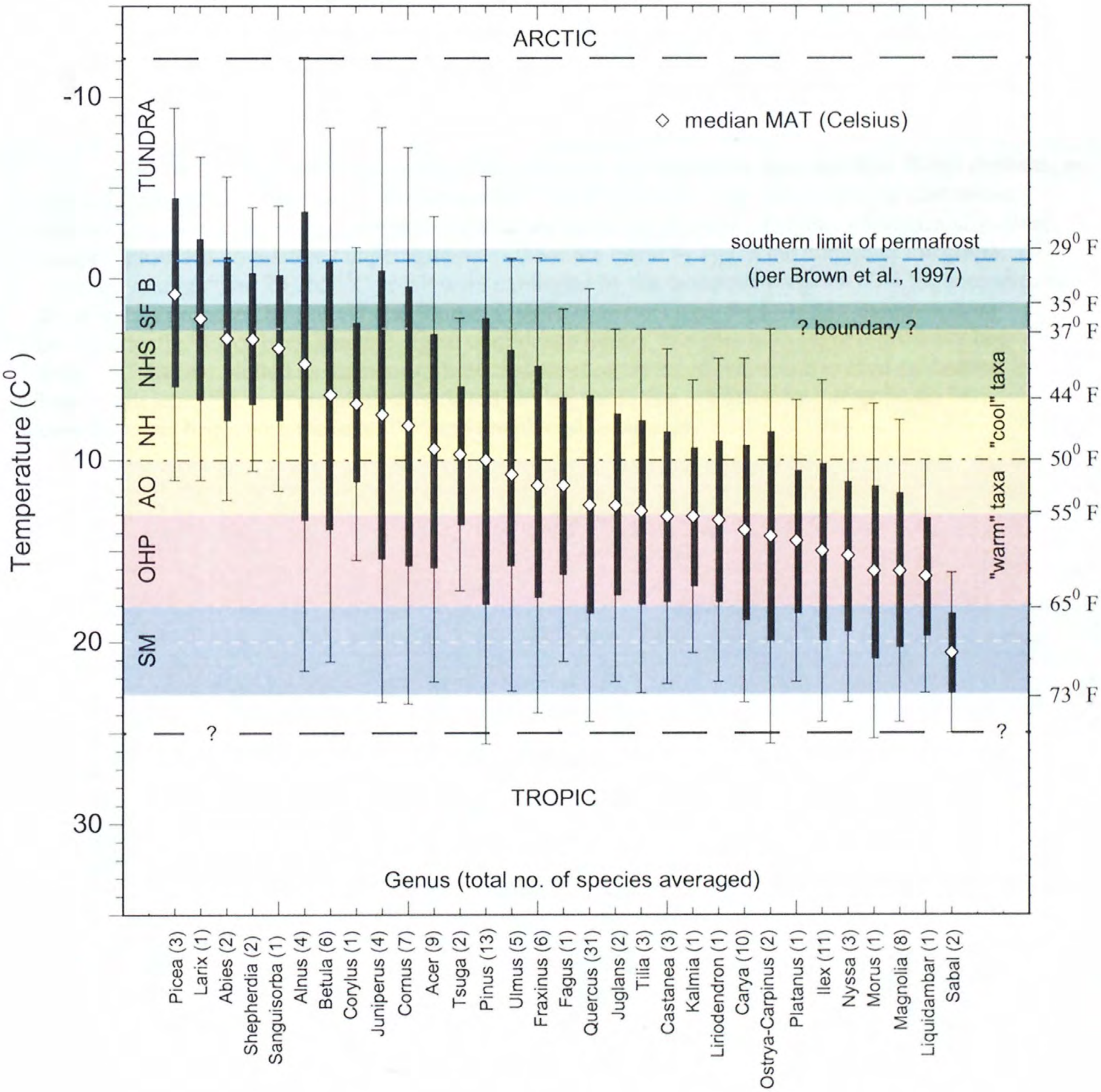


FIGURE 4. Relative temperature trends from the Big Meadows core and Blue Ridge deposits, as derived from pollen. Time interval of study (0-45 ka) divided into 5 ky increments for discussion; number of pollen samples per time increment given along top of graph. Eleven radiometrically-dated samples provided no relative temperature data--these are listed by age at the bottom of the graph. All samples younger than 20,265 ^{14}C yr BP were calibrated by the computer program CALIB, according to the methods proposed by Stuiver and Reimer (1993), to correct ages for CO_2 flux in atmosphere prehistorically. Error bars denote 2-sigma confidence limits. Samples with highest accuracy begin with letter "A" and are plotted as diamonds; those that are directly dated but which exceed calibration limits begin with letter "B" and are plotted as closed circles; those that are dated by interpolation between control points begin with the letter "C" and are plotted as squares.

Figure 4. Relative temperature trends from Big Meadows core and Blue Ridge deposits, as derived from pollen

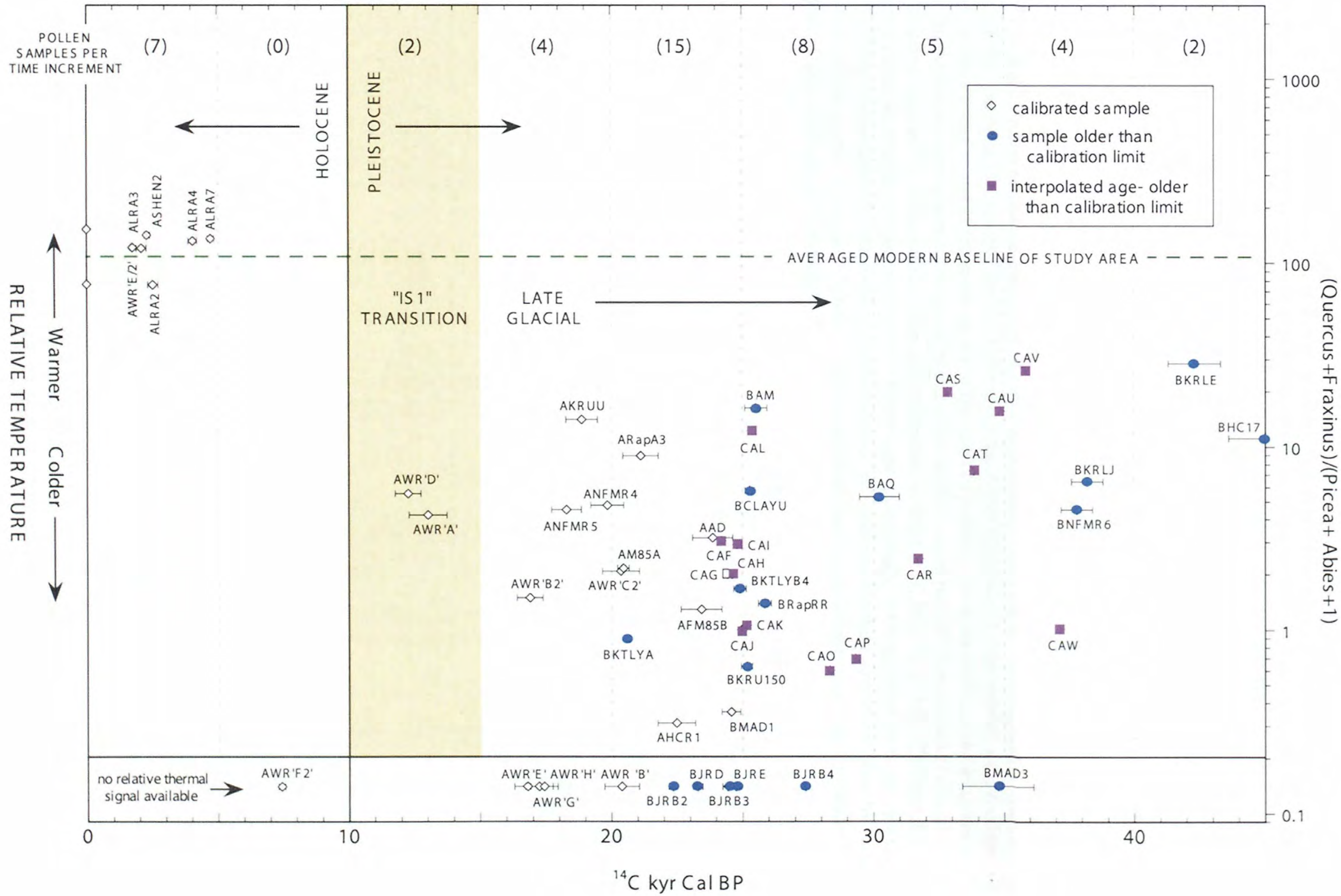


FIGURE 5. Initial estimated forest boundaries (per Küchler, 1975) for pollen samples recovered from Blue Ridge deposits. Horizontal dashed line within the Appalachian oak forest indicates the modern averaged baseline forest signal in the study area (on the basis of pollen). Samples include core analyses from the Big Meadows core and outcrop samples elsewhere in the central part of Shenandoah National Park. Temporal limit of ^{14}C AMS radiocarbon age calibration is fixed at 20,265 ^{14}C yr BP. Calibrated samples corrected per Stuiver and Reimer (1993). First occurrence datums (FODs) noted along left y-axis (see text). Eleven radiometrically-dated samples provided no paleovegetation data--these are listed by age at the bottom of the graph. Error bars denote 2-sigma confidence limits; radiometric age fidelity ranking as in Figure 3; plot symbols as in Figure 4.

Figure 5. Initial estimated forest boundaries (per Küchler, 1975) for pollen samples recovered from Blue Ridge deposits (this study)

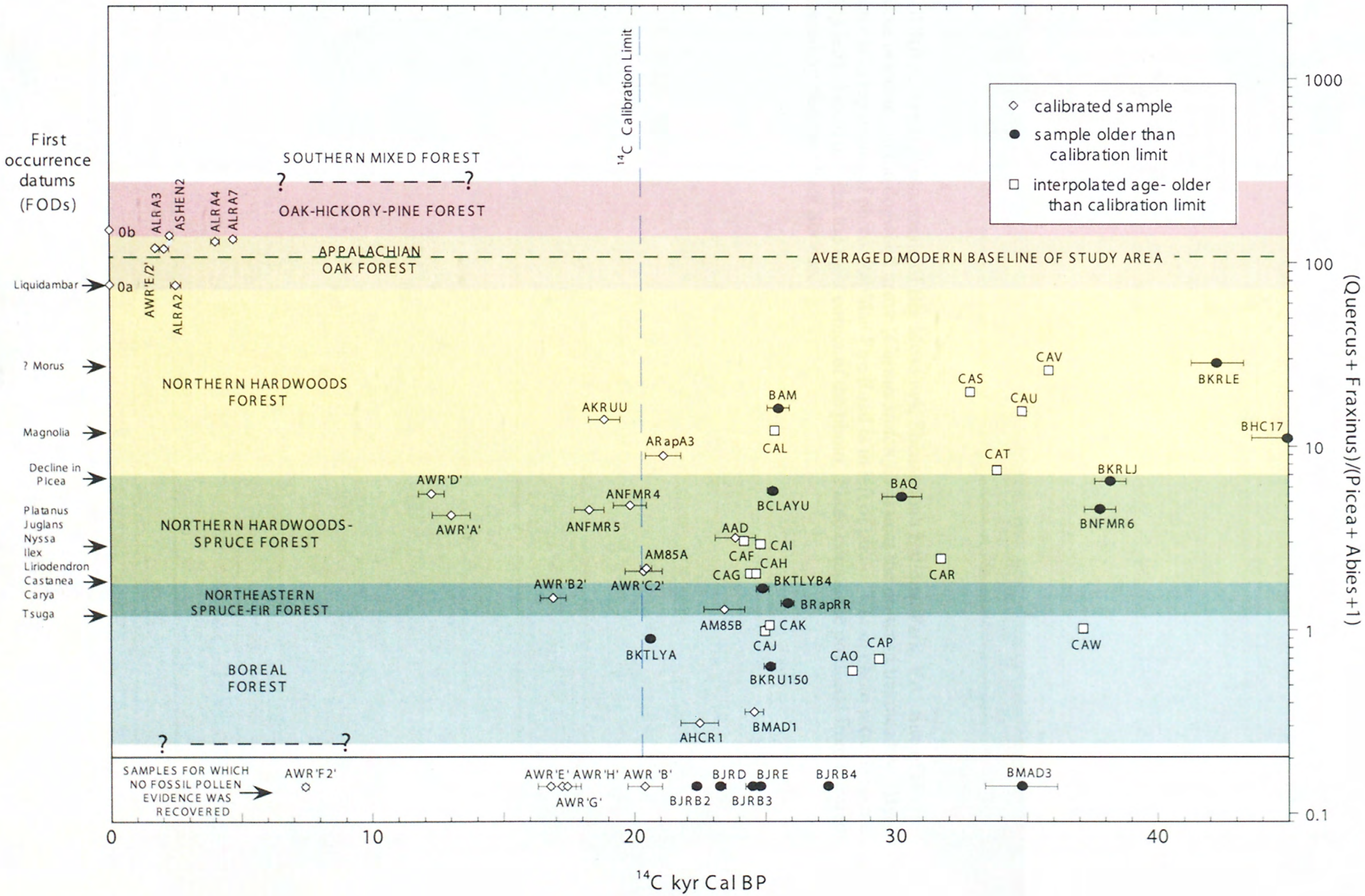
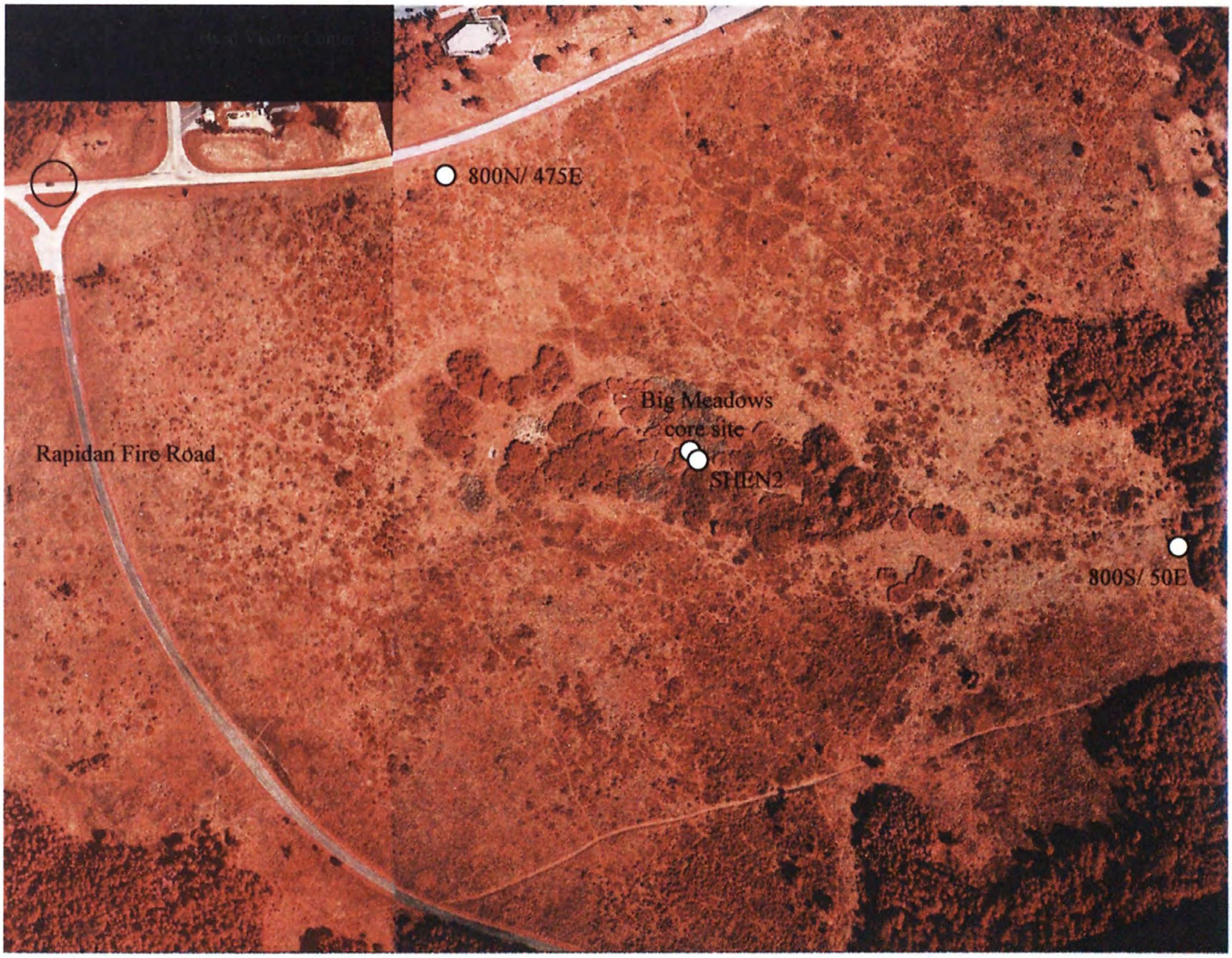


FIGURE 6. Aerial photomosaic of Big Meadows, Shenandoah National Park, VA. Site of Big Meadows core is located in the dogwood grove (*Cornus stolonifera*) near the center of the meadow. Byrd Visitor Center is in top center of photo. Rapidan Fire Road is in left of photo. Car in photo provides scale (in circle, top left). North is to the top right corner of the photo. Photo composite produced from infrared photos provided by National Park Service.

Figure 6. Aerial photomosaic of Big Meadows, Shenandoah National Park, VA



(base photos courtesy NPS)

FIGURE 7. Age/depth models for Big Meadows study area, based on AMS radiocarbon results from samples in the Big Meadows core. Model #1 is used for our initial interpretation of age relationships within the core. Only the age control points used for each model are illustrated. Gross accumulation rates between control points are given in italics, with discussion in text. Models #1 and #2 propose a temporal hiatus at shallow depth in Big Meadows. This hiatus varies in depth from ~15-21 cm depth in the Big Meadows core itself to ~30-50 cm depth elsewhere across Big Meadows. The oldest Holocene samples we analyzed from the meadow were no older than 2.84±.08 ky cal BP. Some archaeological evidence from the JMU survey of the meadow has been assigned an age older than this (~6 ka). This age assignment was based on similarity to stone tool fragment evidence found elsewhere in the region that was in contextual relationship with carbon that could be dated radiometrically (C. Nash, JMU, pers. comm, 2003). We interpret this apparent discrepancy to reflect deposition of archaeological evidence on an erosional or non-depositional surface during the mid-Holocene. The temporal hiatus we propose spans from ~ 23 ka to ~2.8 ka; this depositional hiatus does not preclude human occupation of the meadow site prior to 2.84±.08 ky cal BP.

The control point of 2.73 ky cal BP is an average of two dated samples from the 30 cm depth interval elsewhere in the meadow (see text and Fig. 6). Those samples yielded ages of 2.61±.14 ky cal BP and 2.84±.08 ky cal BP. This averaged age control point in the age/depth graph, although not assessed directly from the Big Meadows core, permits a more generally useful assessment of the deposits across the entire meadow.

FIGURE 7. Depth vs. Age Models: Big Meadows

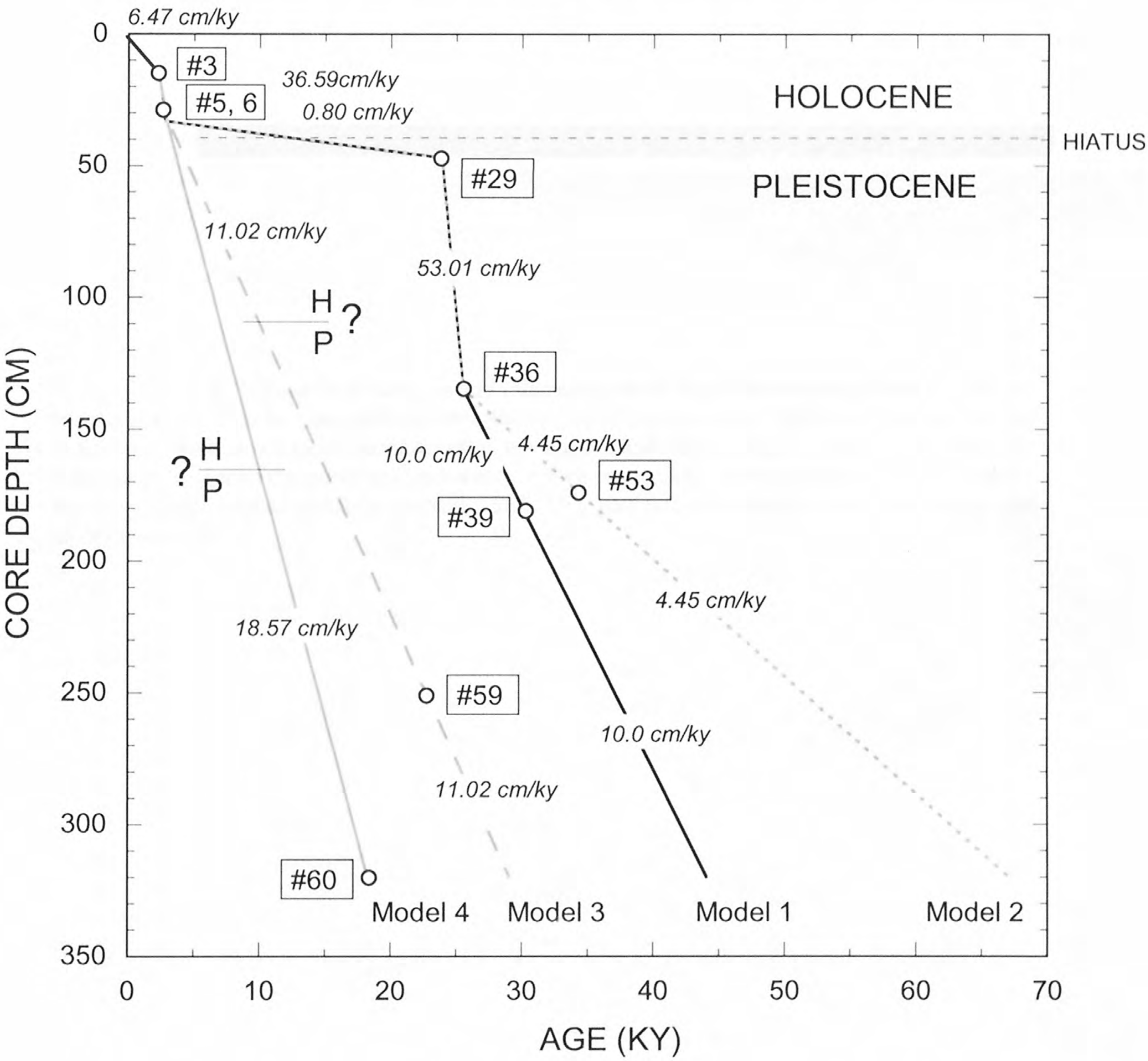
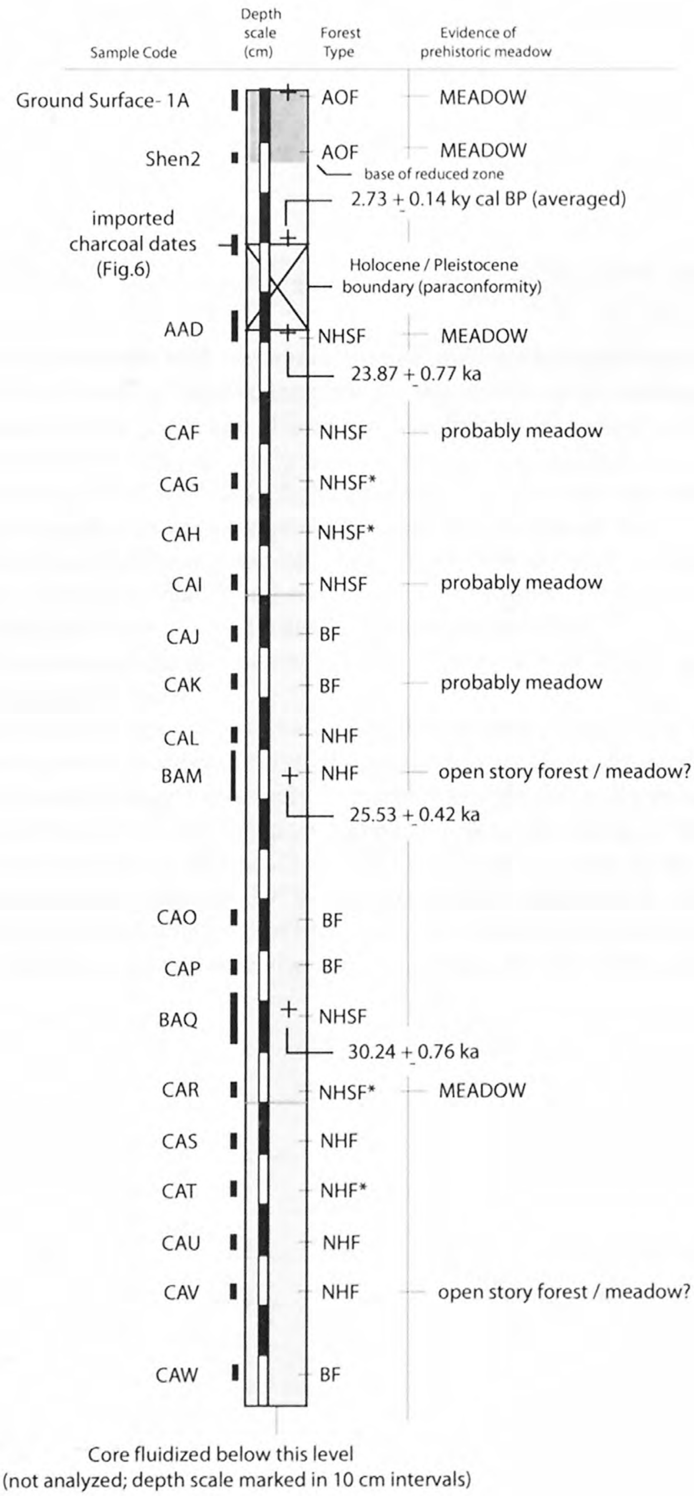


Figure 8. Schematic of samples and interpretation of Big Meadows core Shen #1. Black bars to left of core schematic indicate samples and sampling intervals. Abbreviations on the right indicate the prehistoric forest reconstruction we back-calculated for each sample. Core intervals that met or exceeded the grass and herbaceous pollen percentages in the modern meadow soil at the site are indicated as possible, probable, and likely past intervals when this site previously was an open meadow.

Figure 8. Schematic of samples and interpretation of Big Meadows Core Shen #1



* denotes sample is placed at cold end of range
for assigned forest type (nearly the next colder forest)

FIGURE 9. Blue Ridge dataset summary with reconstruction of prehistoric forest zones, observed first occurrence datums (FODs, based on relative temperature thresholds only), and sequence and timing of climate-driven vegetation change (0-45 ka). These samples form a composite serial record of climate history for Big Meadows and the Blue Ridge study area. Although they are not from a single point source geographically (lake core, etc.) they are from a tightly constrained geographical area and have good radiometric control. Where longer data gaps are present within this record we have connected data points by dashed lines, to indicate important time intervals where more data are needed for this climate history model. Sites have been identified locally and work is now in progress for recovering additional pollen and ^{14}C data from the three youngest of these data gaps (intervals "G1", "G2", and "G3"). The FODs are based on relative temperature thresholds only, as these taxa exhibit first occurrences within our pollen dataset. Plot symbols per Figure 4.

The current data compilation suggests that most of the forests that existed in this study area of the Blue Ridge over the past 45 ky generally were more cold tolerant than the forests currently established within the Park. It also suggests that forests changed relatively frequently and dramatically throughout this 45 ky interval. LGM indicates the best current evidence we have to suggest the timing of the interval of coldest climate (thermal minimum or last glacial maximum (LGM)) experienced in the study area. It appears to coincide with an insolation minimum (Berger, 1978), that elsewhere is associated with the LGM. The hiatus within the core also is approximately coincident with an insolation maximum that immediately precedes the Holocene, and is associated with the late Pleistocene Northern Hemisphere deglaciation.

Figure 9. Blue Ridge dataset summary with reconstruction of prehistoric forest zones, observed first occurrence datums (FODs), and sequence and timing of climate-driven vegetation change (0- 45 ka)

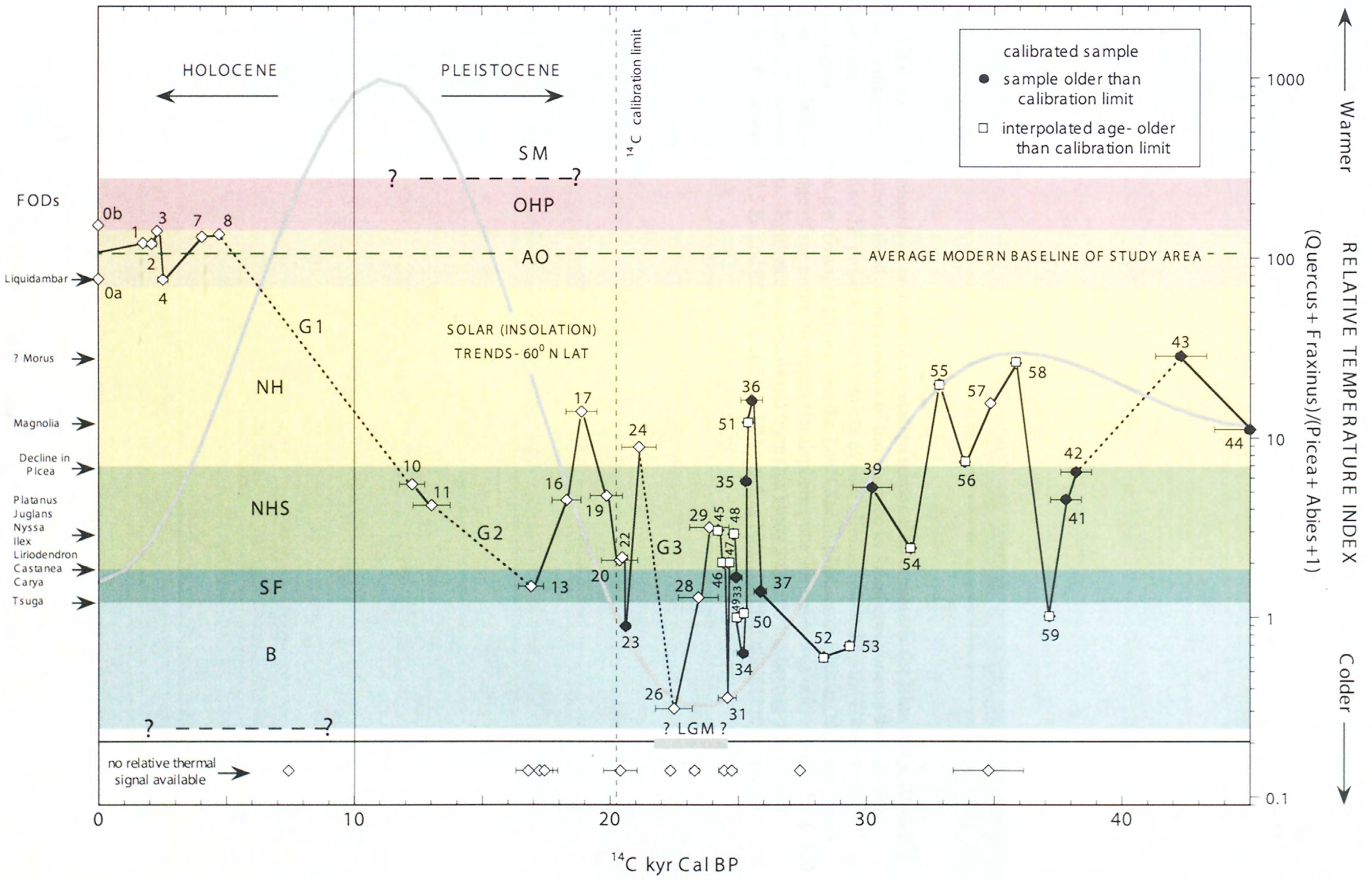


FIGURE 10. Synthesis of prehistoric vegetation response to climate in the Blue Ridge (0-45 ka). This pollen diagram illustrates the dynamic nature of the changes in forest components through time, from the Late Pleistocene to the present. Two intervals of cold climate (preceding the Holocene) are shaded in gray. These are the Younger Dryas, and the Last Glacial Maximum. During the Last Glacial Maximum, the leading edge of the entire Northern Hemisphere polar ice sheet was only ~200 miles (~320 km) north of the study site. Evidence we recovered from this study suggests the timing of the LGM probably falls between 25.5 ka and 20.5 ka, and not 18 ka as has been adopted elsewhere (see text).

Figure 10. Synthesis of prehistoric vegetation response to climate in the Blue Ridge (0- 45 ka)

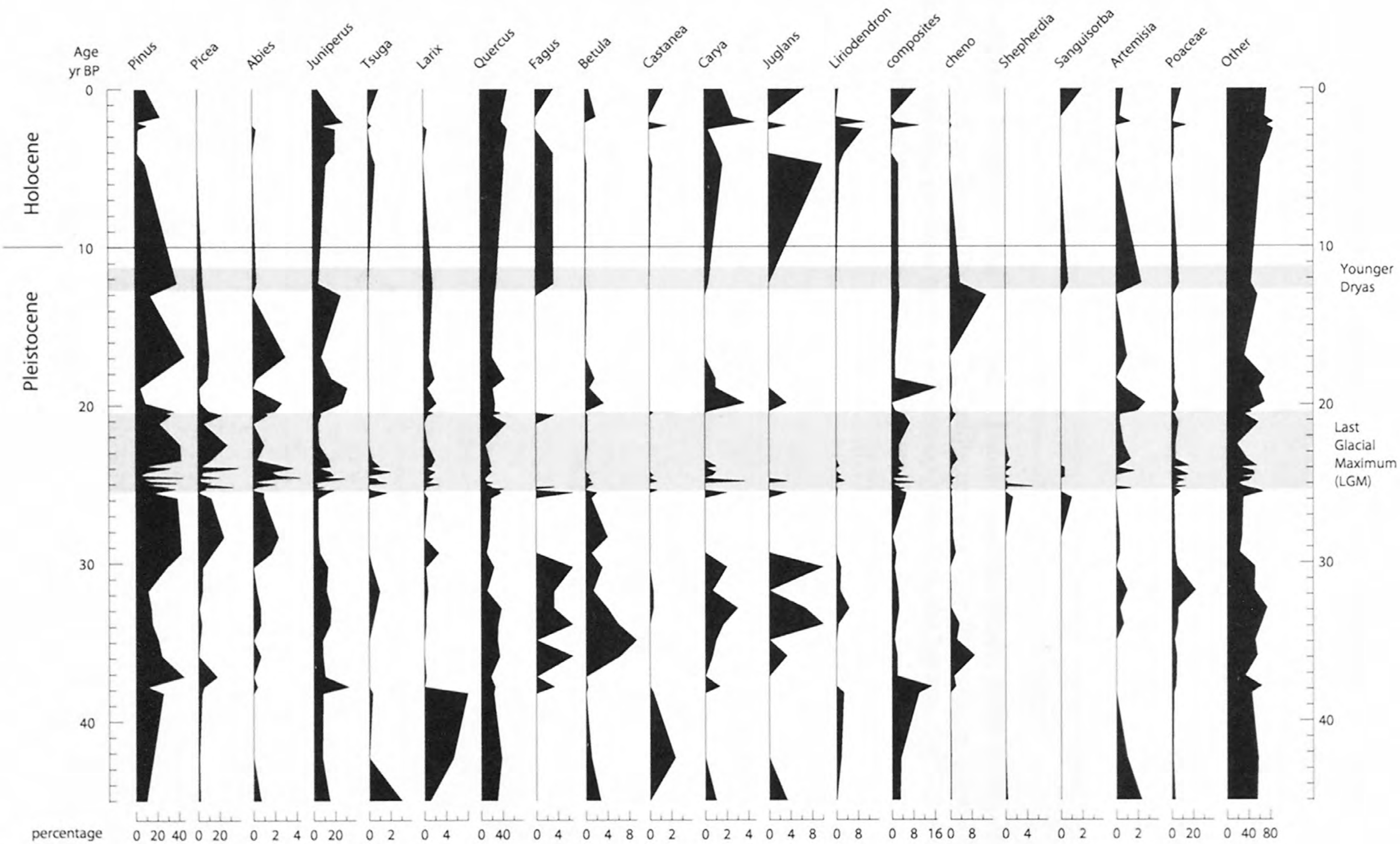


TABLE 1. Locality data for samples used this study. Latitude and longitude, where given, are derived from field values provided by Global Positioning Satellite receiver. The first column assigns the sample number (in order of increasing geologic age) as referenced in the text, the figures, and Table 2. Samples followed by a "©" indicate core samples; all other are outcrop samples.

TABLE 1. LOCALITY DATA FOR RADIOMETRIC SAMPLES USED THIS STUDY

	SAMPLE ID	Latitude (N)	Longitude (W)	Elev. (ft)	reference	Reference/Comment
1	AWRE2	38° 26.4114'	78° 22.5872'	1523'	This study	Wilson Run
2	ALRA3	38° 25.8833'	78° 21.1167'	1210'	Eaton, 1999	Eaton, 1999, Site O
3	AShen2 ©	38° 30.8333'	78° 26.2333'	3460'	This study	12-14 cm depth
4	ALRA2	38° 25.8833'	78° 21.1167'	1210'	Eaton, 1999	Eaton, 1999, Site O
5	800N/475E	38° 30.95'	78° 25.8333'	3480'	This study	B-2 soil, 30 cm (JMU)
6	800S/50E	38° 31'	78° 26.3833'	3500'	This study	B-2 soil, 30 cm (JMU)
7	ALRA4	38° 25.8833'	78° 21.1167'	1210'	Eaton, 1999	Eaton, 1999, Site O
8	ALRA7	38° 25.8833'	78° 21.1167'	1210'	Eaton, 1999	Eaton, 1999, Site O
9	AWRF2	38° 26.5667'	78° 23.3167'	1950'	Eaton, 1999	Eaton, 1999, Site B
10	AWRD	38° 26.5667'	78° 23.3167'	1925'	This study	~Younger Dryas
11	AWRA	38° 26.3362'	78° 23.2115'	2029'	This study	~Younger Dryas
12	AWRE	38° 26.3362'	78° 23.2115'	1890'	Eaton, 1999	Eaton, 1999, Site C
13	AWRB2	38° 26.4049'	78° 23.3516'	2176'	This study	Wilson Run
14	AWRG	38° 26.6667'	78° 23.55'	2160'	Eaton, 1999	Eaton, 1999, Site A
15	AWRH	38° 26.6667'	78° 23.55'	2160'	Eaton, 1999	Eaton, 1999, Site A
16	ANFMR5	38° 09.1666'	78° 44.5662'	1191'	This study	N. Fork, Moormans R.
17	AKRUU	38° 25.4283'	78° 23.2174'	1166'	Eaton, 1999	Appendix 1, Site D
18	ANFMR4a	38° 09.2668'	78° 44.5291'	1152'	This study	N. Fork, Moormans R.
19	ANFMR4b	38° 09.2668'	78° 44.5291'	1152'	This study	N. Fork, Moormans R.
20	AWRC2	38° 26.4497'	78° 23.4719'	2293'	This study	Wilson Run
21	AWRB	38° 26.55'	78° 24.05'	1890'	Eaton, 1999	Eaton, 1999, Site C
22	AM85A	38° 24.8'	78° 24.4333'	1035'	Eaton, 1999	Eaton, 1999, Site F
23	BKTLYA	38° 23.1167'	78° 24.1'	1210'	Eaton, 1999	Eaton, 1999, Site K
24	ARAPA3	38° 24.8'	78° 21.35'	1035'	Eaton, 1999	Eaton, 1999, Site F
25	BJRB2	38° 25.2833'	78° 20.85'	1120'	Eaton, 1999	Eaton, 1999, Site N
26	AHCR1	38° 29.55'	78° 24.8167'	2280'	B. Morgan, unpubl. data	Rapidan R., Camp Hoover
27	BJRD	38° 25.2833'	78° 20.85'	1120'	Eaton, 1999	Eaton, 1999, Site N
28	AM85B	38° 24.8'	78° 24.4333'	1035'	Eaton, 1999	Eaton, 1999, Site F
29	AAD ©	38° 30.8333'	78° 26.2333'	3460'	This study	44-50 cm depth
30	BJRB3	38° 25.2833'	78° 20.85'	1120'	Eaton, 1999	Eaton, 1999, Site N
31	BMAD1	38° 25.4283'	78° 23.2174'	1166'	Eaton, 1999	Eaton, 1999, Site D
32	BJRE	38° 25.2833'	78° 20.85'	1120'	Eaton, 1999	Eaton, 1999, Site N
33	BKTLB4	38° 23.25'	78° 24.3167'	1620'	Eaton, 1999	Eaton, 1999, Site H
34	BKRU150	38° 25.4283'	78° 23.2174'	1166'	This study	Kinsey Run, upper
35	BCLAYU	38° 26.3667'	78° 20.6833'	930'	Eaton, 1999	Eaton, 1999, Site R
36	BAM ©	38° 30.8333'	78° 26.2333'	3460'	This study	130-140 cm depth
37	BRapRR	38° 26.1333'	78° 21.3333'	910'	Eaton, 1999	Eaton, 1999, Site Q
38	BJRB4	38° 25.2833'	78° 20.85'	1120'	Eaton, 1999	Eaton, 1999, Site N
39	BAQ ©	38° 30.8333'	78° 26.2333'	3460'	This study	177-187 cm depth
40	BMAD3	38° 25.4283'	78° 23.2174'	930'	Eaton, 1999	Eaton, 1999, Site E
41	BNFMR6	38° 09.4'	78° 44.9167'	1240'	This study	N. Fork, Moormans R.
42	BKRLJ	38° 25.4283'	78° 23.2174'	930'	This study	Kinsey Run, lower
43	BKRLE	38° 25.4283'	78° 23.2174'	930'	This study	Kinsey Run, lower
44	BHC17	38° 29.55'	78° 24.8167'	2280'	This study	Camp Hoover
45	CAF ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	66-69 cm depth
46	CAG ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	76-79 cm depth
47	CAH ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	86-89 cm depth
48	CAI ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	96-99 cm depth
49	CAJ ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	106-109 cm depth
50	CAK ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	116-119 cm depth
51	CAL ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	126-129 cm depth
52	CAO ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	161-164 cm depth
53	CAP ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	171-174 cm depth
54	CAR ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	196-199 cm depth
55	CAS ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	206-209 cm depth
56	CAT ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	216-219 cm depth
57	CAU ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	226-229 cm depth
58	CAV ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	236-239 cm depth
59	CAW ©	38° 30.8333'	78° 26.2333'	3460'	interpolated age	251-254 cm depth
60	**BC ©	38° 30.8333'	78° 26.2333'	3460'	14-C age rejected	This study; 320-325 cm
	**CAW ©	38° 30.8333'	78° 26.2333'	3460'	14- C age rejected	Sample #59, above
	**CAP ©	38° 30.8333'	78° 26.2333'	3460'	14 C age rejected	Sample #53, above

TABLE 2. ^{14}C AMS radiometric age data for samples used this study. Ages are given as thousands of years (ky), corrected per Stuiver and Reimer (1993). Calibration was possible where initial ^{14}C ages were less than 20,265 ^{14}C yr BP. 1 sigma and 2 sigma error values also are given in thousands of years (ky). Four samples that may have been contaminated are listed at the bottom of table, in order of increased analytic age. Samples preceeded by an asterisk (and in bold typeface) were used as control points for the core recovered from Big Meadows. Ages of interpolated samples not included here, as they were not dated directly. Samples are listed by increasing (calibrated) age. Samples followed by a "©" indicate core samples; all other are outcrop samples.

TABLE 2. RADIOMETRIC AGES USED THIS STUDY (KY)

	SAMPLE ID	14-C yr	1 sigma	ky cal BP	2 sigma	citation	Comment
1	AWRE2	1.755	0.031	1.65	0.083	This study	
2	ALRA3	2.08	0.05	2.098	0.196	Eaton, 1999	calibrated this study
3	***AShen2** ©	2.33	0.04	2.32	0.106	This study	12-14 cm depth
4	ALRA2	2.43	0.06	2.54	0.197	Eaton, 1999	calibrated this study
5	***800N/475E**	2.54	0.04	2.61	0.14	Avg., This study	B2-soil, 30 cm
6	***800S/50E**	2.72	0.04	2.84	0.083		B2-soil, 30 cm
7	ALRA4	3.7	0.05	4.06	0.165	Eaton, 1999	calibrated this study
8	ALRA7	4.24	0.05	4.746	0.121	Eaton, 1999	calibrated this study
9	AWRF2	6.52	0.06	7.439	0.124	Eaton, 1999	no pollen
10	AWRD	10.33	0.04	12.27	0.493	This study	~Younger Dryas
11	AWRA	11.1	0.11	13.03	0.36	This study	~Younger Dryas
12	AWRE	13.99	0.06	16.799	0.487	This study	no pollen
13	AWRB2	14.09	0.04	16.91	0.482	This study	
14	AWRG	14.37	0.07	17.241	0.542	Eaton, 1999	no pollen
15	AWRH	14.53	0.07	17.427	0.523	Eaton, 1999	no pollen
16	ANFMR5	15.28	0.06	18.3	0.565	This study	
17	AKRUU	15.8	0.07	18.89	0.6	Eaton, 1999	calibrated this study
18	ANFMR4a	16.55	0.06	19.743	0.63	Avg., This study	
19	ANFMR4b	16.75	0.06	19.972	0.636		
20	AWRC2	17.1	0.14	20.37	0.709	This study	
21	AWRB	17.12	0.08	20.395	0.658	This study	no pollen
22	AM85A	20.47	0.11	20.47	0.22	Eaton, 1999	beyond calibration
23	BKTLYA	20.66	0.07	20.6	0.14	Eaton, 1999	beyond calibration
24	ARAPA3	17.76	0.07	21.13	0.671	Eaton, 1999	calibrated this study
25	BJRB2	22.35	0.08	22.35	0.16	Eaton, 1999	calibrated this study
26	AHCR1	18.92	0.06	22.49	0.72	Eaton, 1999	calibrated this study
27	BJRD	23.3	0.09	23.3	0.18	Eaton, 1999	Eaton, 1999, Site N
28	AM85B	19.76	0.11	23.45	0.782	Eaton, 1999	calibrated this study
29	***AAD** ©	20.17	0.12	23.87	0.771	This study	44-50 cm depth
30	BJRB3	24.45	0.11	24.45	0.22	Eaton, 1999	Eaton, 1999, Site N
31	BMAD1	24.57	0.18	24.57	0.36	Eaton, 1999	beyond calibration
32	BJRE	24.74	0.11	24.74	0.22	Eaton, 1999	Eaton, 1999, Site N
33	BKTLB4	24.91	0.12	24.91	0.24	Eaton, 1999	beyond calibration
34	BKRU150	25.17	0.11	25.17	0.22	This study	beyond calibration
35	BCLAYU	25.29	0.09	25.29	0.18	Eaton, 1999	beyond calibration
36	***BAM** ©	25.53	0.21	25.53	0.42	This study	130-140 cm depth
37	BRapRR	25.86	0.12	25.86	0.24	Eaton, 1999	beyond calibration
38	***BAQ** ©	30.24	0.38	30.24	0.76	This study	177-187 cm depth
39	BMAD3	34.77	0.69	34.77	1.38	Eaton, 1999	beyond calibration
40	BNFMR6	37.8	0.3	37.8	0.6	This study	beyond calibration
41	BKRLJ	38.2	0.3	38.2	0.6	This study	beyond calibration
42	BKRLE	42.3	0.5	42.3	1	This study	beyond calibration
43	BHC17	45	0.7	45	1.4	This study	beyond calibration
	**BC ©	15.24	0.074	18.25	0.571	sample 60, Table 1	contaminated?
	**CAW ©	22.78	0.16	22.78	0.32	sample 59, Table 1	contaminated?
	**CAP ©	34.07	0.39	34.07	0.78	sample 53, Table 1	contaminated?

TABLE 3. Pollen census data from Blue Ridge study area (upper Rapidan River drainage, VA). Samples are listed by increasing (calibrated) age. Sample IDs followed by a "©" indicate core samples; all other are outcrop samples. Core samples with ages followed by an asterisk indicate interpolated ages.

Table 3. Pollen census data from Blue Ridge study area (upper Rapidan River drainage, VA), and probable forest zone assignments

Table 1 no.	Sample ID	Forest Type	Picea	Larix	Abies	Shepherdia	Sanguisorba	Alnus	Betula	Corylus	Juniperus	Cornus	Acer	Tsuga	Pinus	Ulmus	Fraxinus	Fagus	Quercus	Juglans	Tilia	Castanea	Kalmia	Liriodendron	Carya	Ostrya_Carp	Platanus	Ilex	Nyssa	Morus	Magnolia	Liquidambar	ChenoAM	Composites	Poaceae	Other	Total	
0A	modern	AOF	1	0	0	0	6	3	2	1	14	2	3	3	30	2	0	1	153	2	1	4	1	3	5	1	0	6	0	0	0	1	0	28	27	7	300	
OB	modern	OHP	0	0	0	0	0	2	0	1	4	0	0	1	46	0	0	0	152	4	0	1	0	1	11	3	0	0	0	1	0	0	0	9	11	53	300	
1	AWRE/2	AOF	0	0	0	0	0	2	6	1	67	0	0	0	70	1	0	0	121	0	0	0	1	0	8	0	0	0	0	0	3	0	1	0	6	13	300	
2	ALRA3	AOF	0	0	0	0	0	0	0	0	85	0	1	0	5	0	0	0	120	0	0	0	0	33	14	0	0	0	0	0	0	0	0	5	3	34	300	
3	ASHEN2 ©	AOF	0	0	0	0	0	1	0	1	25	0	0	1	33	0	3	0	138	1	0	5	0	0	7	0	0	2	0	0	1	1	2	31	40	8	300	
4	ALRA2	AOF	0	2	1	0	0	0	0	0	63	1	0	0	9	0	0	0	152	0	0	0	0	30	1	0	0	0	0	0	2	0	0	2	7	33	300	
7	ALRA4	AOF	0	0	0	0	0	1	0	0	62	0	0	1	7	0	0	1	131	0	0	0	0	9	4	0	0	0	1	1	3	0	1	0	7	71	300	
8	ALRA7	AOF	0	0	0	0	0	3	1	0	37	0	0	2	29	0	2	1	133	3	0	1	0	4	5	0	0	0	0	0	3	1	0	8	1	66	300	
10	AWRD	NHSF	14	5	1	0	2	0	0	1	15	2	1	0	115	0	0	1	88	0	0	0	0	0	1	0	0	0	0	0	0	0	11	8	20	37	300	
11	AWRA	NHSF	18	5	0	0	0	0	1	2	78	0	0	0	41	0	0	0	80	0	0	0	0	0	0	0	0	0	0	0	0	0	40	9	4	45	300	
13	AWRB2	SFF	33	3	9	0	0	1	0	0	23	0	0	0	136	0	0	0	64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	6	66	300	
16	ANFMR5	NHSF	28	6	1	0	0	1	5	1	51	0	0	0	49	0	0	0	135	0	0	0	0	0	3	0	0	0	0	0	0	0	2	4	9	40	300	
17	AKRUU	NHF	4	2	0	0	0	0	2	0	95	0	0	0	13	0	2	0	68	0	0	0	0	0	3	0	0	0	5	0	10	0	2	50	7	43	300	
19	ANFMR4	NHSF	8	7	8	0	0	0	10	5	80	0	1	0	28	0	0	0	81	1	0	0	0	0	11	0	0	0	0	0	0	0	0	0	19	64	300	
20	AWRC2	NHSF	30	2	6	0	0	0	0	1	30	0	0	0	107	0	0	0	77	0	0	0	0	0	1	0	0	0	0	0	0	0	3	4	11	66	300	
22	AM85A	NHSF	47	5	3	0	0	0	0	0	18	0	0	0	81	0	0	0	110	0	0	1	1	0	0	0	0	0	0	0	0	0	3	8	1	77	300	
23	BKTLYA	BF	66	2	4	0	0	2	1	3	21	4	0	0	98	0	0	0	61	0	0	0	0	0	0	0	0	0	0	0	0	0	6	14	8	82	300	
24	ARapA3	NHSF	15	0	0	0	0	1	1	2	13	8	0	0	66	0	1	0	141	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	18	29	300	
27	AHCR1	BF	81	2	3	0	0	1	1	1	16	0	0	0	124	1	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	10	112	300	
29	AM85B	SFF	36	6	1	2	0	2	0	0	43	0	0	1	126	0	0	0	49	0	0	0	0	0	0	0	0	0	0	0	0	0	8	8	10	53	300	
30	AAD ©	NHSF	8	4	9	0	0	1	0	2	47	0	0	3	23	0	0	0	57	0	0	0	0	3	3	0	0	2	0	0	0	0	2	13	47	97	300	
47	CAF ©	NHSF	13	6	5	0	1	0	0	1	48	0	0	6	31	0	0	0	58	0	0	0	0	0	3	0	0	0	0	0	0	0	0	11	26	116	300	
48	CAG ©	NHSF	10	3	7	0	1	1	2	1	56	0	2	0	11	0	0	0	36	0	0	1	0	5	2	0	0	0	0	0	0	0	1	5	45	132	300	
33	BMAD1	BF	59	2	13	2	1	0	1	0	17	0	0	0	132	0	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	2	18	7	97	300	
49	CAH ©	NHSF	5	5	6	0	0	0	2	0	87	0	12	2	17	0	0	0	24	0	0	0	0	3	0	0	0	0	0	0	0	0	5	0	14	134	300	standardized
50	CAI ©	NHSF	9	3	0	0	0	1	3	2	23	0	1	3	43	0	0	0	29	1	0	2	0	9	11	0	0	1	0	0	0	0	1	5	34	131	300	
35	BKTLB4	SFF	36	0	2	1	0	35	0	1	0	0	0	5	114	0	0	0	65	0	0	0	0	0	0	0	0	0	0	0	0	0	2	25	5	48	300	
51	CAJ ©	BF	14	8	6	0	0	4	4	2	12	0	0	0	16	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	18	220	300	standardized
36	BKRU150	BF	97	0	0	15	0	4	0	0	9	0	1	0	92	0	0	0	62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	6	118	300	
52	CAK ©	BF	16	1	1	0	0	1	1	0	30	0	0	0	45	0	0	?1	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39	165	300	standardized
37	BCLAYU	NHSF	21	1	0	1	0	7	0	3	0	0	0	0	110	0	0	0	126	0	0	0	0	1	0	0	0	0	0	0	0	0	0	14	3	36	300	
53	CAL ©	NHF	7	0	0	0	0	5	0	1	57	0	1	1	86	0	2	0	95	0	0	2	0	1	0	0	0	1	0	0	1	0	2	7	16	22	300	
38	BAM ©	NHF	3	0	3	0	0	3	6	5	40	0	0	5	48	0	0	2	113	1	0	0	0	1	6	0	0	0	0	0	0	0	1	16	24	29	300	
39	BRapRR	SFF	37	2	3	4	3	24	3	6	14	0	0	0	116	0	0	2	57	0	0	0	0	0	0	0	0	0	0	0	0	0	2	15	7	54	300	
54	CAO ©	BF	72	0	7	0	0	2	12	0	14	0	1	0	125	0	0	0	48	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	9	85	300	
55	CAP ©	BF	40	8	5	0	0	2	3	4	18	0	6	0	127	0	0	0	31	0	0	0	0	0	0	0	0	0	0	0	0	0	6	5	10	88	300	
41	BAQ ©	NHSF	13	1	0	0	0	1	9	11	40	0	0	1	86	0	1	2	73	3	0	0	0	5	6	0	0	1	0	0	0	0	0	3	16	42	300	
56	CAR ©	NHSF	12	2	1	0	0	4	4	2	36	0	0	3	34	0	0	1	34	0	0	1	0	4	2	0	0	2	0	0	0	0	1	7	66	99	300	
57	CAS ©	NHF	3	1	2	0	0	0	12	4	49	0	0	2	43	0	6	1	113	2	0	1	0	14	9	0	0	0	0	0	0	0	1	8	18	17	300	
58	CAT ©	NHF	10	1	2	0	0	0	18	3	46	2	1	1	46	0	0	2	95	3	0	0	0	2	5	0	1	0	1	0	0	0	10	5	17	42	300	
59	CAU ©	NHF	5	0	0	0	0	0	28	3	25	0	0	0	63	1	1	0	92	0	0	0	0	0	3	0	0	0	0	0	1	0	7	3	8	65	300	
60	CAV ©	NHF	1	0	2	0	0	3	19	5	26	0	3	0	72	0	0	2	104	1	0	0	0	0	2	0	0	0	0	0	0	0	27	6	14	16	300	
61	CAW ©	BF	52	1	0	0	0	0	0	0	32	0	0	0	133	1	0	0	54	0	0	0	0	0	0	0	0	0	0	0	0	0	4	6	13	57	300	
43	BNFMR6	NHSF	15	0	1	0	0	2	1	0	97	0	1	0	32	0	0	1	77	0	0	0	0	0	4	0	0	0	0	0	0	0	6	44	11	24	300	
44	BKRLJ	NHSF	10	24	0	0	0	22	0	6	26	1	1	1	76	1	0	0	71	0	0	1	0	8	0	0	0	0	0	0	0	0	0	30	6	50	300	
45	BKRLE	NHF	3	16	0	0	0	24	3	6	24	0	0	0	48	0	0	0	114	0	0	7	0	5	0	0	0	0	0	2	0	0	1	10	4	52	300	
46	BHC17	NHF	5	3	2	1	0	1	8	7	44	0	0	9	29	0	0	0	89	1	2	0	0	0	3	0	0	1	0	0	0	0	1	9	9	87	300	