RADIOCARBON DATING OF GLACIAL MORAINES
USING THE AEOLIAN BIOME: TEST RESULTS AT
BISHOP CREEK, SIERRA NEVADA, CALIFORNIA

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Abstract: Radiocarbon measurements on fossilized remnants of the aeolian biome, incorporated in glacial moraines in the Sierra Nevada of California, are consistent with the relative order of moraines at Bishop Creek, on the eastern slopes of the Sierra Nevada. Holocene 14C ages correspond with periods of more effective moisture according to paleoecological and treeline data in the range, whereas Pleistocene ages are pencontemporaneous with Heinrich Events in the North Atlantic. These findings must be interpreted with caution, however, owing to a number of uncertainties, including: evidence that younger contaminants are added to till matrix; the possibility of older contaminants; the effects of pretreatment on aeolian biome remains; and processes by which organics undergo diagenesis within till matrices in different biogeochemical settings. [Key words: aeolian biome, Heinrich Events, moraines, radiocarbon dating, Sierra Nevada.]

INTRODUCTION

Glacial chronology is a central issue in a wide range of fields, including physical geography (Mahaney, 1990), paleoclimatology (COHMAP, 1988), geology (Birkeland, 1984), and the interdisciplinary effort to understand the nature of global environmental change (Broecker, 1994). Radiocarbon dating has been the backbone of efforts to correlate Wisconsinan and Holocene glacial chronologies and to integrate them into other studies of global climate. Even so, comprehensive reviews (Fullerton, 1986; Sibrava et al., 1986; Davis, 1988; Clapperton, 1990) reveal a large number of glacial sequences in mid- and low-latitude alpine settings where glaciers did not intersect treeline, so woody material is unavailable for radiocarbon dating. This paper explores a new approach to the age determination of glacial moraines: radiocarbon dating of components of the aeolian biome, mostly fossil arthropods, that become entombed in the matrix of alpine moraines.

The aeolian biome is part of the allobiosphere where life depends on nutrients carried by wind from the adjacent eubiosphere (Hutchinson, 1970). The aeolian biome is composed of nival, aquatic, and terrestrial subsystems (Swan, 1967, 1992). Much more than algae (Tazaki et al., 1994) exists in the nival ecosystem that includes snow and glaciers. Insects are common (Mani, 1968). Himalayan glacier ponds contain fairy shrimp, collemboala, midge larvae, and a wingless midge (Kohshima, 1984); snow worms were present in Pleistocene glaciers (Tynen, 1970). In and
around proglacial water, Swan (1992, p. 265) observed: “Here I have witnessed clouds of flying stoneflies (Plecoptera) and found their filter-feeding naiads concentrated (more than I have ever seen in cleaner waters) under the rocks imbedded in the muddy glacial silt . . .”

The diversity of life in the nival ecosystem is striking, ranging from glacial margin carabid and staphylolin beetles (Elias, 1991) to the many species that fallout and live in ice (Catrans and Starmer, 1991; Edwards, 1987). Rates of aeolian deposition of arthropods, for example, are up to 1500 per square meter on snow patches in the Central Pyrenees, Spain (Antor, 1994), and over 12,500 per square meter on a snowfield in the Sierra Nevada of California (Papp, 1978).

Chitin is an amino-sugar polysaccharide that is second only to cellulose as a biosynthesized product, in terms of global biomass (Cohen, 1987). Chitin is preserved well in some Quaternary (Elis and Toolin, 1990; Elis, 1992; Miller et al., 1993) and older (Bada et al., 1994) deposits. Fossil arthropods have been used extensively as a tool to reconstruct Quaternary environments (Coope, 1986; Morgan and Morgan, 1987; Schimmelmann et al., 1993; Elis, 1994) and to date glacial recession (Elis et al., 1991). Fossil arthropod chitin is preserved within glacial ice and has been radiocarbon dated (Lockwood et al., 1991, 1992; Naftz et al., 1993). Since much of the material in lateral moraines is supraglacial in origin (Small, 1983; Ostmark, 1992), it should not be surprising that moraines might contain disseminated organic remains from the aeolian biome.

The primary purpose of this paper is to assess the presence of aeolian biome fallout in the Pleistocene and Holocene till matrix of semiarid environments, to determine whether it can be successfully extracted and its radiocarbon content measured, and to compare these radiocarbon ages with independent age control.

The importance of this paper rests in the potential for providing radiocarbon ages for moraines in mid- and low-latitude ranges that lack woody material in till. One of the greatest uncertainties in the analysis of global climatic change rests in analyses that assume moraines in different areas are truly penecontemporaneous (COHMAP, 1988), where in reality little numerical age control exists to support this assumption. New surface-exposure dating methods are making it possible to test this assumption (e.g., Phillips et al., 1990; Dorn et al., 1991; Nishizumi et al., 1993; Kurz and Brook, 1994; Zreda et al., 1994). These techniques, however, assume moraine surface stability (Dorn and Phillips, 1991; Zimmerman et al., 1994; Zreda et al., 1994). If it is possible to obtain reliable $^{14}$C ages on fossilized remains of the aeolian biome, it may also be possible to test assumptions of moraine stability using material from the till matrix.

STUDY SITE EVALUATION AND SELECTION

Assessing $^{14}$C measurements on aeolian biome material requires independent chronometric information by which to gauge the accuracy and precision of the results. The eventual objective, however, must be kept in mind: to obtain $^{14}$C ages for Holocene and latest Pleistocene till in settings that lack woody material.

Several high-latitude, forested sites in the world have excellent $^{14}$C age control to test this method. Unfortunately, environmental conditions probably are not comparable to relatively arid areas where trees and peat bogs are lacking. Forested moraines often contain moraines from regolith organics, and could make the reliability of any other dissection of these geochonological histories of radiocarbon procedures: a summary, as a not to mix “drylands and drylands.

Unfortunately, in the context of investigating interior of the region, this region has a range in the history of sequence of events.

A good example of Nevada of California (Blackwelder, 1995) and Bach and Elsasser techniques used (Berry, 1994; evaluation of techniques).

In summary, it may be likely inappropriate for the situation for the series of independent digests of Nevada of California (Fisher, 1993; Blackwelder, 1993; Zreda, 1993). The terminal moraine is about 11 km long, found at elevation derived from a metamorphic complex, and the extent of the complex. It
moraines often have a soil moisture surplus and acidic soils, which contrast with moraines from continental ranges with alkaline soils and annual soil-moisture deficits (Marchand, 1974; Ellis, 1980; Baes and Bloom, 1988; Chesworth, 1992; Wakatsuki and Rasyidin, 1992). Organic acids also probably differ between forested and scrubland soils (Braids and Miller, 1975; Campbell and Claridge, 1992).

The amount of water flowing through till, modifying soil (Dixon, 1986) and regolith organics (Mahaney et al., 1986; Eswaran et al., 1993; Hedges et al., 1993), could make results in forested moraines of questionable value in testing the reliability of the method in drier tills. For example, I did not find arthropods or other disseminated organic remains in till matrix samples from wet sites, namely Peyto Glacier (Luckman et al., 1993), Hoh Glacier (Heusser, 1957), and at Glacier Peak (Beget, 1984). The lack of arthropods could reflect the mobility of chitin in these geochemical settings. This issue also can be placed within the context of the history of radiocarbon dating, which has revealed that different pretreatment procedures are necessary in different environmental contexts (Taylor, 1987). In summary, as a first test of aeolian biome material in till matrix, a decision was made not to mix “apples and oranges” and, therefore, to work only with moraines in drylands.

Unfortunately there is a paucity of sites with independent 14C age control in the context of interest, namely glaciated ranges in mid-latitude settings such as the interior of the conterminous western United States. Holocene till matrix 14C ages in this region have been questioned with regards to their reliability (Davis, 1988). No range in the conterminous western United States has till matrix 14C ages for a sequence of Pleistocene moraines.

A good example of the dating problem inherent in arid sites is found in the Sierra Nevada of California. After decades of extensive study, there are only a few maximum and minimum 14C constraints on the moraines (Fullerton, 1986; Clark et al., 1995) and a couple of 14C ages on organics found in till matrix (Dorn et al., 1990; Bach and Elliott-Fisk, 1996). Soils, weathering rinds, and other relative dating techniques used in the Sierra Nevada to evaluate post-depositional modification (Berry, 1994; Birkeland, 1994; Erel et al., 1994) are not sufficiently precise to use in an evaluation of the reliability of till matrix 14C ages (Kiernan, 1990).

In summary, the lack of good test sites for dryland moraines, combined with the likely inapplicability of control sites in forested moraines, creates a difficult situation for testing this method. The solution chosen here was to select a site with a series of independent chronometric indicators: Bishop Creek in the eastern Sierra Nevada of California, about midway between Reno, Nevada and Los Angeles, California (Fig. 1). These moraines have a long history of study (Knopf, 1918; Blackwelder, 1931; Sheridan, 1971; Rahm, 1964; Bateman, 1965; Phillips et al., 1992; Zreda, 1993; Berry, 1994; Zreda et al., 1994; Bach, 1995) and are easily accessible. The terminal moraine complex is located downslope from site A in Figure 2 or about 11 km west of the town of Bishop at ~1600 m, with additional moraines found at elevations up to ~3600 m. The moraines are composed of glacial till derived from a basin underlain by about 90% granodiorite with some basalt and metamorphic clasts (Bateman, 1965). The moraines at Bishop Creek typify environments in the conterminous western United States that have lacked 14C age control.
Moraines at lower elevations have an assemblage of Great Basin perennial species: mountain mahogany (Cercocarpus ledifolius), bitterbrush (Purshia tridentata), and sage brush (Artemesia tridentata). The average annual precipitation at the town of Bishop is 144 mm (1951–1980) (Powell and Klieforth, 1991), but precipitation over the nearby eastern slopes of the Sierra Nevada is higher (Berry, 1994) owing to elevation, which allows the growth of Jeffrey pine (Pinus jeffreyi) on the terminal positions of the latest Pleistocene moraines. The overall aridity, however, has helped moraine morphology remain fairly intact.

Lower Bishop Creek is adjacent to the Coyote Downwarp, a tectonic feature that channelled Pleistocene ice flow along Bishop Creek in several directions at different times. This resulted in the preservation of at least 14 distinct Pleistocene glacial moraines (Phillips et al., 1992). In contrast, only two or three different Pleistocene stages have been recognized in most other canyons in the Sierra Nevada (Fullerton, 1986), owing to obliterator overlap in topographically constrained glaciers (Gibbons et al., 1984). In addition, there are four or more Holocene moraines with different relative ages. Regardless of the lack of numerical chronology, a detailed relative age sequence is available to test the relative order of $^{14}$C ages on aeolian biome remains.

There are also three types of independent numerical ages available at Bishop Creek. $^{36}$Cl surface-exposure ages have been determined for boulders on Pleistocene moraines (Phillips et al., 1992; Zreda, 1993; Zreda et al., 1994). $^{14}$C ages have been determined for organic matter encapsulated in rock weathering rinds (see below). Relative ages based on boulder size have been calibrated with relative sequence and possible mismatching of continental ice stages.

Moraines at lower elevations have a relative age sequence that has been used for glacial geomorphic studies (Phillips et al., 1992) for P...
Fig. 2. Oblique aerial photograph looking west toward moraines of the Bishop Creek glacial system, eastern Sierra Nevada, California (center: 37°15' N; 118°35' W). Letters correspond to Table 1.

(see below). Lastly, woody material has been found within two Holocene tills and has been radiocarbon dated (detailed later in this paper). Although these methods have uncertainties addressed later in the paper, the combination of a detailed relative sequence and independent numerical ages makes Bishop Creek a good site to gauge the reliability of results of dating aeolian biome remains in dry continental ranges.

Moraines were sampled in relative stratigraphic order, up-basin from the moraine that Bateman (1965) mapped as Older Tioga. Because synchronicity between glacial canyons in the Sierra should not be assumed, I use the local geographic names for Holocene moraines and the local names of Phillips et al. (1992) for Pleistocene tills. Canyon-specific nomenclature avoids confusion in possible miscorrelations and follows tradition in glacial geomorphology (R.S. Sharp, pers. comm., 1993). Of the extensive upper basin, the Treasure Lakes fork of Bishop Creek was sampled because two Holocene moraines there contained wood.

Overlapping and inset morphostratigraphic relationships establish a relative sequence that indicates the Sand Canyon moraine is older than Little Egypt lateral, Little Egypt recessional, and Shreve lateral moraines (Fig. 3). At the upper and youngest end of the system, the Mt. Johnson I moraine is inset into the Mt. Johnson II moraine, which is younger than the Hurd Peak moraines. Morphostratigraphic relationships between the aforementioned moraines and the
Treasure Lakes and South Lake tills are unclear. The Treasure Lakes moraine is the terminus of a small glacier that would not have been in contact with Holocene glaciers advancing out of the Mt. Johnson cirque. The South Lake till is eroded, does not have a clear moraine form, and could be: (1) equivalent to the Shreve moraine; (2) an eroded terminal moraine (possibly, but not likely poorly sorted outwash) from the South Fork drainage; or (3) an eroded lateral moraine from the Treasure Lakes drainage. The Treasure Lakes and South Lake tills were sampled, however, because of their moraines.

Extracting Arthropods

The method for extracting arthropods is the same as for Coleoptera and more silty, since arthropods need to minimize oxidation. The tills from moraines were sieved with greater and finer sieves than from moraines, plotted, and counted; however, could not be identified to moraines, they were still interesting on this basis.

The samples were dried down into a small mass, then loosen fragments were decanted on a glass filter paper, the arthropods and their biomass content were measured, and the mass spectrometer analysis of the arthropods was dependent upon their concentration. For multiple samples, conventional methods were used.

Whether the arthropods process samples from the growth of the tills or the same as from the tills or both, arthropods and other macroinvertebrates (in microscopy, and micro-invertebrates of younger) must become attached to tills for arthropods and other macroinvertebrates.

Arthropods were separated from tills using radioisotopes (Fairchild et al., 1970). The arthropods become attached to the tills through the formation of the tills.

Radiocarbon

Wood was also sampled from moraines. Two
however, because their elevations rested between the Hurd Peak and Shreve moraines.

METHODS

Extracting Aeolian Biome Remains from Till Matrix

The method of extracting aeolian biome material from till was modified from Coleoptera analysis (Coope, 1986). It is best to sample from facies of till that are more silty, since fewer fossils are found in sandy/gravelly matrix. In order to minimize oxidation or contamination from bioturbation, samples from Pleistocene moraines were collected from stream or road exposures at a depth of 2 m or greater and cut back 1.5 m. Where cuts were not available, on the Holocene moraines, pits were dug to a depth of 1.5 to 2 m. The very youngest moraines, however, consist of large till boulders without significant till matrix; in these moraines, the aeolian biome-bearing sediment consists of piles of silt-sand-gravel resting on the large till boulders.

The sample size depends upon arthropod concentration, which initially is determined in the field. The removed sample was placed in a bowl and broken down into a slurry with water. It is usually necessary to stir the slurry repeatedly to loosen fragments from the sediment. The organics that float to the surface are decanted onto glass filter paper or manually picked out of the water and placed on glass filter paper. The glass filter paper then is air dried and examined for aeolian biome content. Since only a few milligrams of carbon are necessary for accelerator mass spectrometry (AMS) $^{14}$C dating (Linick et al., 1989), the size of the sample depends upon the observed abundance of organic remains and the funds available for multiple measurements. In a few cases, enough remains were present for conventional $^{14}$C analysis.

Whether the flotation occurs in the laboratory or in the field, it is important to process samples as soon as possible, or to dry and freeze them, in order to prevent the growth of newer algae or fungi (Coope, 1986). Laboratory flotation is essentially the same as that described above for the field. Once the sample is dried, the arthropods are picked off the glass filter paper viewed under low-power stereomicroscopy, and placed in glass vials. In only the most recent (Hurd Peak and younger) moraines were complete arthropods found; only fragments of arthropods and other aeolian biome remains occur in older moraines.

Arthropods were subject to pretreatment with HCl, NaOH, and HF before radiocarbon dating. HCl is necessary to remove pedogenic and in situ carbonate (Fairchild et al., 1993). NaOH helps extract traces of younger secondary organic acids (Taylor, 1987), which are extremely small (Osterberg et al., 1993) and could become attached to organic remains (Gillespie, 1991). HF was used because clay-sized phyllosilicates were seen within arthropod remains, and clays can adsorb organics that move with vadose water (Hedges et al., 1993). HF was not used on two of the Hurd Peak samples discussed later.

Radiocarbon Dating of Wood

Wood was collected from between boulders of the Mt. Johnson I and II moraines. Two pieces of wood (2 cm diameter by 10 cm long; 3.5 cm diameter by
15 cm long) were found, both of which were pinned between till boulders at a depth of <0.5 m but could be seen because of the minimal till matrix. The lack of soil matrix surrounding the wood, and its crushed appearance, suggests that the woody tissue was not growing in situ on the moraines. The unidentified wood could have originated as part of a perennial plant before avalanching from the cirque headwall onto a past glacier. The wood was crushed in the laboratory, dispersed in deionized water and treated with HCl and NaOH before conventional 14C dating by Beta Analytic Inc.

**Radiocarbon Dating of Organics Encapsulated in Rock Weathering Rinds**

Organics are deposited within the pores of weathering rinds of rocks by epilithic, chasmolithic, and endolithic organisms (Friedmann, 1980; Krumbein and Dyer, 1985). These remains can be entombed by rock coatings—for example, amorphous silica (Farr and Adams, 1984; Friedmann and Weed, 1987), manganiferous rock varnish (Dorn, 1994a), and even archaeologic paintings on rock walls (Chaffee et al., 1994).

Organics in weathering rinds were sampled from two contexts. Organics encapsulated by rock varnish were collected from Little Egypt and Sand Canyon moraines, and were processed for 14C measurement with HCl, NaOH, and HCl, with details presented elsewhere (Dorn, 1994a). The organic carbon content of the interior parts of each boulder was measured by powdering material collected 5 cm beneath the surface; the powder then was subjected to the same pretreatment procedure and combusted (Dean, 1974).

In the Shreve moraine, 20 boulders were collected from depths of 2 to 3.5 m beneath the till surface and their outermost perimeter (rinds) were chipped in the field. A combustion procedure (Dean, 1974) determined that organic matter was detectable in the weathering rinds of 3 of the 20 boulders; the sample with the highest concentration of organic carbon was subjected to the same pretreatment procedure as aeolian biome samples, and its 14C content was analyzed by AMS.

**RESULTS**

Extracted aeolian biome materials in the Mt. Johnson I and II and Hurd Peak tills are preserved well enough for identification of arthropods. Dr. S.A. Elias of the University of Colorado at Boulder identified some of the arthropods from the Mt. Johnson I and II moraines as ladybird beetle (*Hippodamia convergens*) moth wing; head capsule and body of a fly; wasp; grasshopper leg; and others. For the Treasure Lakes till, it was possible to separate only pieces of arthropods.

For South Lake and older tills, aeolian biome remains had undergone diagenesis to a point where, aside from a few fragments of arthropods, the material was particulate organic matter. In other words, it is difficult in the older tills to identify exactly what arthropod material is being radiocarbon dated. Although the aeolian biome material sent for 14C measurement from these moraines consisted of arthropod fragments, other aeolian biome remains also were found, such as leaves, moss, seeds, and conifer needles.
Table 1. Radiocarbon Ages of Aeolian Biome Samples at Bishop Creek, California

<table>
<thead>
<tr>
<th>Climatic Episode</th>
<th>Possible Sierra Correlations</th>
<th>Bishop Creek Stage</th>
<th>Elevation</th>
<th>$^{14}C$ Age</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little Ice Age</td>
<td>Matthes</td>
<td>Mt. Johnson II</td>
<td>3640 m</td>
<td>140 ± 50 (Beta 67935)</td>
<td>Sampled from inner loop</td>
</tr>
<tr>
<td>Little Ice Age</td>
<td>Matthes</td>
<td>Mt. Johnson II</td>
<td>3640 m</td>
<td>600 ± 60 (CAMS 12413)</td>
<td>Sampled from outer loop</td>
</tr>
<tr>
<td>Neoglacial</td>
<td>Recess Peak</td>
<td>Hurd Peak</td>
<td>3400 m</td>
<td>1330 ± 60 (CAMS 11532)</td>
<td>Lateral</td>
</tr>
<tr>
<td>Neoglacial</td>
<td>Recess Peak</td>
<td>Treasure Lakes</td>
<td>3400 m</td>
<td>1460 ± 60 (TO1628)</td>
<td>Terminal</td>
</tr>
<tr>
<td>Younger Dryas?</td>
<td>Hilgard?</td>
<td>South Lake</td>
<td>3100 m</td>
<td>7351 ± 83 (NZA 3887)</td>
<td>Original surface not preserved</td>
</tr>
<tr>
<td>Heinrich</td>
<td>Tioga</td>
<td>Shreve</td>
<td>2425 m</td>
<td>13,870 ± 70 (CAMS 12047)</td>
<td>Terminal at 2350 m</td>
</tr>
<tr>
<td>Event H1</td>
<td></td>
<td>Little Egypt</td>
<td>1980 m</td>
<td>15,760 ± 70 (CAMS 11535)</td>
<td>Only moraine with a few trees (Pinus jeffreyi)</td>
</tr>
<tr>
<td>Heinrich</td>
<td>Tioga</td>
<td>Little Egypt</td>
<td>1920 m</td>
<td>15,670 ± 70 (CAMS 11535)</td>
<td>Terminal not preserved</td>
</tr>
<tr>
<td>Event H2A</td>
<td></td>
<td>Max* (lateral)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heinrich</td>
<td>Tenaya</td>
<td>Sand Canyon</td>
<td>1890 m</td>
<td>31,900 ± 480 (Beta 67103)</td>
<td>Equivalent to Bateman (1965), older Tioga</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(terminal)</td>
<td></td>
<td>35,420 ± 470 (CAMS 11533)</td>
<td>36,600 ± 560 (CAMS 11534)</td>
</tr>
</tbody>
</table>

4Including possible correlations with global climatic episodes (Bryson, 1993; Broecker, 1994) and Sierra nomenclature (Sharp and Birman, 1963; Burke and Birkeland, 1983; Fullerton, 1986).
4Letters correspond to locations in Figures 2 and 3.
4Beta Analytic Inc. lab numbers measured by conventional decay counting; all others measured by accelerator mass spectrometry.

Radiocarbon ages of the aeolian biome samples are presented in Table 1, along with speculative correlations with climatic episodes (Bryson, 1993; Broecker, 1994) and other Sierra glacial deposits (Burke and Birkeland, 1983). Table 2 compares ages on aeolian biome remnants with wood $^{14}C$, weathering rind $^{14}C$, and the in situ buildup of $^{38}Cl$.

DISCUSSION

Comparison of Results from Different Methods

An important intuitive check on the reliability of numerical ages is whether they are consistent with relative position in a moraine sequence. The relative sequence
Table 2. Comparison of Numerical Ages at Collection Sites, Bishop Creek, California

<table>
<thead>
<tr>
<th></th>
<th>^14C ages on</th>
<th>^36Cl ages</th>
<th>Wood</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>aeolian biome</td>
<td>weathering</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(see Table 1)</td>
<td>rind organics</td>
<td></td>
</tr>
<tr>
<td>Mt. Johnson II</td>
<td>50–100 B.P.</td>
<td>160 ± 60 (Beta 67091)</td>
<td></td>
</tr>
<tr>
<td>(terminal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mt. Johnson II*</td>
<td>−600 B.P.</td>
<td>560 ± 80 (Beta 67098)</td>
<td></td>
</tr>
<tr>
<td>(terminal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hurd Peak*</td>
<td>1250–1600 B.P.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(lateral &amp; terminal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treasure Lakes*</td>
<td>2500–2700 B.P.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(terminal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Lake*</td>
<td>7200–10,700 B.P.</td>
<td>10,700 B.P.</td>
<td></td>
</tr>
<tr>
<td>(eroded till)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shreve*</td>
<td>13,800–15,800 B.P.</td>
<td>14,360 ± 70 (CAM 15931)</td>
<td></td>
</tr>
<tr>
<td>(lateral)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Little Egypt*</td>
<td>19,600–20,900 B.P.</td>
<td>19,660 ± 190 (AA 6899)</td>
<td>15,300c</td>
</tr>
<tr>
<td>(recessional)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Little Egypt</td>
<td>−23,600 B.P.</td>
<td>24,480 ± 210 (AA 6917)</td>
<td>17,100c</td>
</tr>
<tr>
<td>Max* (lateral)</td>
<td></td>
<td>23,590 ± 230 (NZ 2363)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>25,830 ± 270 (NZ 2362)</td>
<td></td>
</tr>
<tr>
<td>Sand Canyon*</td>
<td>35,000–38,000 B.P.</td>
<td>37,700 ± 740 (NZ 2276)</td>
<td></td>
</tr>
<tr>
<td>(terminal)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

*aLetters correspond to locations in Figures 2 and 3.
*bBeta Analytic Inc. lab numbers measured by conventional decay counting; all others measured by accelerator mass spectrometry.
*cMaximum boulder ages, from Zreda et al. (1994).
*dMeasurements on the same boulder.

of aeolian biome ^14C ages in Table 1 (except youngest ^14C age in Treasure Lakes till) is consistent with the morphostratigraphic position of the moraines.

The youngest arthropods yielded ^14C ages that overlap with wood samples from within the same till (Table 2). The wood samples, however, must pre-date moraine age, since they probably were added by avalanching of the woody tissue of perennial plants onto the glacier before incorporation into till. Similarly, arthropods could have a prior residence time, either by avalanching older animals “stored” in soils on slopes or within the glacier. For example, insects in present-day glacial ice in Wyoming yield ^14C calibrated ages of ~1450 A.D., 1640–1954 A.D. (Lockwood et al., 1991) and ~1715 A.D. (Naftz et al., 1993).

Correlations with independent age controls are unclear for the Pleistocene. There appears to be a good correspondence with organisms encapsulated in weathering rind and the periglacial peat. However, radioactivity from the organics are unknown.

The system is, perhaps acting in an older hillside avalanche (col) and host clasts were not used. There also is the potential for deposition in periglacial glaciers. The analysis of ^36Cl from hillside avalanches is possible that is sensitive to the host glacial fabric. The weathering rate of only 1–8% of the radioactivity since age calibrations appear to be accurate, however, based on Pleistocene moraines (Bach, 1995). ^14C is sensitive to the pleistocene because of its

Uncertainties

There are several uncertainties in the arthropods, including older direct dates and age issues.

Like any direct dates in the field, the fallout calculation of ^14C ages in Table 2, regolith above the nunataks above the aerolitic soils, have added difficulties. In addition, the radiocarbon ages for exposed radioactivity from the modern alpine core, as hundreds of years old. It is possible that the calculated ages for 1400 A.D. (Bach, 1995) are possible that the Pleistocene alpine core is not older than 1400 A.D. (Bach, 1995).
weathering rinds (Table 2). The relative order for $^{14}$C ages and $^{36}$Cl ages is the same, and the percentage difference between the two Little Egypt moraines is similar. However, radiocarbon ages for aeolian biome organics and weathering rind organics are systematically older than the $^{36}$Cl ages.

The systematic offset between $^{14}$C and $^{36}$Cl could be the result of several factors, perhaps acting in tandem. It is possible that both the aeolian biome and weathering rind organics could potentially have a mean residence time that is “inherited” from an older hillslope position, before these organics fell onto the glacier in an avalanche (cf. Shakesby, 1989). This would require that the weathering rinds on clasts were not abraded by either mass wasting or glacial transport/deposition. There also is some transport time between supraglacial addition of the detritus and deposition in a moraine; this time would be greater for the larger Pleistocene glaciers. There also are uncertainties as to how best to pretreat samples for $^{14}$C analysis (Gillespie, 1991). Another cause of the offset may be the production rates of $^{36}$Cl from $^{36}$K, $^{40}$Ca, and $^{35}$Cl, which are in revision (Phillips et al., 1996). It is possible that some contamination by “dead” organics within the unweathered host granodiorite rock (below the weathering rock) could add carbon to the weathering rinds, but concentrations of extractable organics in the host rock were only 1–8% of rind concentrations. Boulder rotation could lower apparent $^{36}$Cl ages, since age calculation assumes that the top of the boulder always was the top; however, boulder movement is infrequent in this part of the Bishop Creek moraines (Bach, 1995). Boulder erosion also could lower $^{36}$Cl ages, but $^{36}$Cl is less sensitive to boulder erosion than other cosmogenic nuclides (e.g., $^{10}$Be) because of its production from $^{35}$Cl (Zreda et al., 1994).

Uncertainties

There are several uncertainties associated with dating aeolian biome remains in a till matrix. Uncertainties are grouped here into factors that could drive ages in an older direction, factors that could make them younger, and other methodological issues.

Like any detrital deposit, organics could pre-date moraine deposition. Airborne fallout contains organics (Ketseridis et al., 1976) that probably were deposited in regolith above the glacier. Organic materials are present on arêtes, horns, and nunataks above a glacier, even in Antarctica (Ryan et al., 1992). Avalanches could have added this older carbon. If the insects’ food chain derived from dead carbon sources, for example those associated with the Long Valley Caldera (Reid et al., 1995), they could be anomalously old. In addition, insects are present within modern alpine glaciers that have yielded radiocarbon ages that are several hundreds of years old (Lockwood et al., 1991; Naftz et al., 1993). It also may be possible that organic matter in the metamorphosed sedimentary (Schidlowsky, 1983) roof pendant (Baseman, 1965) survived pretreatment and contaminated the Pleistocene samples with unidentified organics.

Younger organics could contaminate a sample. Although all but the youngest till samples were collected at depths $>1.5$ m, bioturbation occurs at Bishop Creek (Bach, 1995) and could bring in younger macrofossils. Although great effort was made to avoid pit-side wasting, when sampling is taking place in a deep soil pit it is
difficult to know for sure that material did not fall down from above. The likelihood of bioturbation certainly is greatest for the youngest samples—which were limited to collection from moraine crests. Another source of younger contaminants would be organics that percolate through a soil (Österberg et al., 1993) and adsorb to clay minerals and organic matter (Burnhill et al., 1981; Hedges and Hare, 1987; Murphy et al., 1989). The Pleistocene samples would be less susceptible to bioturbation, because they were collected deeper within the till matrix from excavated road and stream cuts.

There are other methodological uncertainties that could affect the interpretation. For example, the pretreatment procedure was selected to try to avoid younger carbon that might be added with vadose water after moraine deposition, for reasons discussed in the methods section. However, different pretreatments may yield different $^{14}$C ages. Soil chemistry, soil physics, and other soil-forming factors probably also are extremely important in affecting the preservation of organic matter (Marchand, 1974; Ellis, 1980; Baes and Bloom, 1988; Eswaran et al., 1993; Hedges et al., 1993). For example, I tried and failed to find arthropods in till matrix from the Peyto Glacier (Luckman et al., 1993), the Hoh Glacier (Heusser, 1997), or at Glacier Peak (Beget, 1994), perhaps from too much vadose water leaching chitin from till.

Specific examples from Bishop Creek highlight some of these methodological uncertainties:

(1) As explained in the methods section, the younger of each of the duplicate samples for the Hurd Peak moraines was not pretreated with HF. Although the ages overlap at the 1 sigma error, it may be that some younger carbon adsorbed onto clays was added to these samples. This emphasizes uncertainty associated with sample pretreatment.

(2) There is an anomalously young (100 ± 60 yr B.P.) age for the Treasure Lakes till, which probably reflects contamination from younger organics.

(3) The South Lake till has two AMS $^{14}$C ages close to one another, and a third ~3000 $^{14}$C yrs older. This till is not a moraine; it has no moraine form, but is present on an eroding slope. It is likely that the till truly is Pleistocene in age, but has been “contaminated” at different times. The dated organics could be from additions of carbon that post-date till deposition.

(4) AMS ages on organics collected side-by-side on the Shreve moraine differ by ~2000 $^{14}$C yrs. A Little Egypt recessional moraine has two AMS $^{14}$C ages within analytical overlap, but a third is ~1000 $^{14}$C years younger. These differences could be from the detrital carbon having different histories in the drainage basin or before avalanching onto a glacier.

(5) Results on Sand Canyon moraines exemplify a likely problem of contamination of bulk conventional ages with younger material, especially for Pleistocene moraines. The conventional measurement was >4000 $^{14}$C yrs younger than the two $^{14}$C AMS measurements. However, since the radiocarbon content of a 36,000 $^{14}$C B.P. sample is 1%, it would take only an additional ~1% contamination of modern carbon in the bulk sample to make up the observed difference.

Correlation of $^{14}$C and $^{13}$C Results

The Holocene chronology is constrained mainly by the radiocarbon results from these stades. These results were interpreted to be retained for the whole Wisconsin and early Holocene and II moraines, perhaps for younger than ~10,000 yr B.P. (Burbank et al., 1986).

In the Nevada Basin, correlation with licheneous material may help to constrain some of the $^{14}$C dates. For example, 14000 $^{14}$C B.P. Burbank et al. (1986) interpreted the stadial lines in the sheet with young moraine that characterizes the transgression margin of the Carson and montane complexes. The correlations of radiocarbon and cultural data (Burbank et al., 1988; Sneath et al., 1994). The general correlation with the cultural data has been consistent with the interpretation of the radiocarbon time (Stine, 1994). The chronology also is consistent with the relative radiocarbon chronology resolution of the late Wisconsin and early Holocene Age-type events of Stine (1994). (Stine, 1994, p. 1682).

The evidence for the correlation is ambiguous. In the Sierra Nevada, a young moraine thought to be ~13,000 yr B.P. was dated as 8600 yr B.P. (Burbank et al., 1986). A second moraine, the South Lake till, which is ~7000 yr B.P. ago, can be inconsistent with the correlation. For example, paleoecological evidence (Koehler and others, 1989) indicates that...

At first glance, the results of the radiocarbon study (Clark and others, 1994) in the Sierra Nevada suggest that moraine “climate in the Sierra Nevada” can be used to support this interpretation. In an earlier study, Clark and others (1994) argued that the younger moraines on the Sierra Nevada moraine field...

There are several possible explanations for the discrepancy. It may require further study of the reasons for the discrepancy.

(1) Anomalous $^{13}$C signature in wood that accumulated in the floodplain forest on the modern floodplain (Clark and others, 1994).

(2) Early Holocene vegetation. The vegetation may have had a higher $^{13}$C signature than the modern forest and thus may have been...
Correlation of Holocene Results

The Holocene \(^{14}\text{C}\) ages at Bishop Creek fall into time periods consistent with prior studies in the Sierra Nevada. Although the relevance and age of some of these stades, such as Recess Peak, continue to be debated, their names are retained for this discussion. In the Little Ice Age (cf. Grove, 1988), the Mt. Johnson I and II moraines at Bishop Creek could correlate with Matthes moraines that are younger than tephra that is 720 ± 60 \(^{14}\text{C}\) B.P. (Curry, 1971; Wood, 1977; Fullerton, 1986).

In the Neoglacial, the Hurd Peak and Treasure Lakes deposits could correlate with lichenometric age estimates (Curry, 1971; Scuderi, 1987a) and tephras that constrain some Recess Peak deposits in other areas to be between 3000 and 1000 \(^{14}\text{C}\) B.P. (Burbank, 1991). These age assignments also fit periods of lowered timberlines in the southern (Scuderi, 1987b) and central (Anderson, 1990) Sierra Nevada, transgressions at nearby Mono Lake (Stine, 1990), periods when subalpine and montane conifers reached their maximum extent, high water tables in meadows, and cultural adaptations to cooler/moister conditions (Davis et al., 1985; Moratto et al., 1988; Anderson, 1990; Anderson and Smith, 1994; Koehler and Anderson, 1994). The gap in ages between the Hurd Peak and Mt. Johnson II moraines is consistent with a period of drought thought to have occurred during medieval time (Stine, 1994). Taking a more global perspective, the Neoglacial ages in Table 1 are consistent with global compilations (Röthlisberger, 1986) and with high-resolution data emerging from Greenland ice cores revealing that Little Ice Age-type events were “common throughout the Holocene” (Meese et al., 1994, p. 1682).

The evidence for an early Holocene advance (Beget, 1983) in the South Lake till is ambiguous. Elsewhere in the Sierra Nevada, the Hilgard stade (Birman, 1964) is thought to be older than 7100 ± 130 \(^{14}\text{C}\) yr, based on a tree growing on a moraine buried by a landslide (Curry, 1971); there also is a Recess Peak moraine that is >7000 yr BP (Burbank, 1991). For reasons discussed earlier, the available \(^{14}\text{C}\) age on the South Lake till yields an unclear signal. However, an early Holocene advance would be inconsistent with early Holocene aridity (9000-6000 \(^{14}\text{C}\) yr B.P.) recorded by paleoecological analyses in the central and eastern Sierra Nevada (Anderson, 1990; Koehler and Anderson, 1994, 1995).

At first glance, the Holocene results in Tables 1 and 2 contrast with recent claims (Clark and Gillespie, 1994; Clark et al., 1995) that there were no Holocene glaciers in the Sierra Nevada larger than the Matthes (Little Ice Age) glaciers and that the “climate in the Sierra between ~13,000 and 700 yr B.P. was too warm and/or dry to support significant glaciers” (Clark and Gillespie, 1994, p. 164). Most relevant to this study, Clark et al. (1995) report two basal \(^{14}\text{C}\) ages of ~11,000 yr B.P. for the Baboon Lakes on the Middle Fork of Bishop Creek (Fig. 2) at ~3385 m.

There are several potential resolutions to this apparent contradiction that require further evaluation.

(1) Anomalously old carbon could have been a part of the sampled basal carbon from Baboon Lakes, either from volcanically contaminated carbon (cf. Reid et al., 1995), airborne additions (cf. Ketseridis et al., 1976; Ryan et al., 1992), organics in
metamorphosed sedimentary rock (Schidlowsky, 1983) in the roof pendant (Bate-
man, 1965), or magmatic CO₂ that originally was trapped in granitic minerals,
released during mineral weathering, and subsequently incorporated into organic
matter. Although I believe such contributions of old carbon likely are minor, my
intuitive assessment is certainly insufficient for accurate comparisons of numer-
ical ages.

(2) The arthropods extracted from the soil pits (South Lake till and younger)
could post-date moraine deposition from mechanisms such as bioturbation,
incorporating younger arthropods. I think that this is most likely for the South Lake
till, as noted in the aforementioned discussion.

(3) If the lowest Treasure Lakes till (3250 m) had a deglaciation age equivalent to
Baboon Lake (3385 m), radiocarbon ages on the moraine (3290 m) behind the
lowest Treasure lake could reasonably post-date lake excavation by any amount of
time. A glacier easily could have emerged from the steep tributary cirque immedi-
ately to the south, depositing the moraine during the Neoglacial but still not re-
excavating the Pleistocene lake.

(4) The Hurd Peak (3410 m) and Mt. Johnson moraines are higher than the
sampled Baboon Lake (3385 m), and could reasonably post-date lake excavation by
any amount of time.

(5) Taking a broader perspective, the postulated lack of larger-than-Matthes
Holocene moraines in the Sierra Nevada is at odds with a global-scale perspective
on Holocene climate change (Meese et al., 1994) and alpine moraine chronology
(Rothlisberger, 1986). There are many studies of Holocene glacial advances in the
Sierra Nevada (e.g., Matthes, 1939; Birman, 1964; Curry, 1969, 1971; Wood, 1977;
Burke and Birkeland, 1983; Scuderi, 1987a, 1987b; Burbank, 1991) that are generally
consistent with the Neoglacial and Little Ice Age ¹⁴C ages in Table 1.

Speculative Correlations with Heinrich Events

If Pleistocene ¹⁴C results in Tables 1 and 2 are accurate, the radiocarbon ages are
peenecontemporaneous with H1, H2, H2a, and H4 Heinrich Events (Bond et al.,
1993; Broecker, 1994; Mayewsky, 1994). The ¹⁴C ages on aeolian biome
material are plotted in Figure 4 against Heinrich Events and periods of lower tree
line. If this correspondence is real, it suggests that there were multiple pulses
during the last glacial maximum (marine oxygen isotope stage 2), and that these
pulses were in phase with massive iceberg discharges into the North Atlantic. The
occurrence of Heinrich Event-driven climatic changes in the Sierra Nevada is
consistent with a link between Searles Lake and Greenland ice core data (Phillips et
al., 1994), with thoughts that Heinrich Events may correlate with mountain glacia-
tions throughout the western United States (Clark and Bartlein, 1995).

Heinrich Events H3 and a Younger Dryas moraine were not found at Bishop
Creek. Heinrich Event H3 could have been obliterated by a larger Little Egypt
glacier. It is possible that a Younger Dryas glacier was not sampled or was not as
extensive as subsequent Holocene advances, at least in the Treasure Lakes fork of
Bishop Creek that was studied.
CONCLUSION

There is a growing realization that many different types of sediment, formerly thought to be "barren," actually contain particulate organic matter that can be extracted by wet sieving and can provide $^{14}$C ages determined with AMS. For example, enough charcoal for AMS $^{14}$C measurement was obtained by wet sieving piedmont alluvium in southwest Arizona (Pohl, 1995). In a research news report, R. Bonnichsen describes the surprising amount of organic material that turned up in a western Montana archaeological site: "We've found a lot of little fragments of hair, both animal and human, plus bird feathers, a single fish scale, plant matter, beetles—things that we'd never found before because this [sediment] material is normally discarded" (Morell, 1994). It should not be surprising, therefore, that fossils of the aeolian biome (Swan, 1992) can be found in glacial till.

This first test of the reliability of radiocarbon dating remains of the aeolian biome from till matrix yielded mixed signals. On the optimistic side, $^{14}$C ages for moraines at Bishop Creek are in the correct morphostratigraphic order. Holocene ages correlate well with dates from wood samples, and Pleistocene ages correlate with $^{14}$C ages from organics encapsulated in boulder weathering rinds. Aeolian biome remains have yielded the first radiocarbon ages for a Holocene glacial sequence in the contiguous United States, and the most detailed radiocarbon chronology for a Pleistocene glacial sequence in the Sierra Nevada. There also is the potential for combining dating and paleoecology through an analysis of identifiable arthropod fauna (cf. Elias, 1994). Since it is possible to extract dozens of datable samples from a single moraine, histograms of radiocarbon ages could be constructed—and the composite results might clear up some of the ambiguities found here. In
summary, these results demonstrate that aeolian biome remains offer potential for assigning radiocarbon ages to till matrix.

However, considerable caution must be used in interpreting these aeolian biome 14C ages until a number of issues are resolved. Some of the organic matter potentially could pre-date till deposition; in other words, the organicas had a prior history before falling on a glacier. Other organic matter could post-date till deposition—for example, as a result of bioturbation or other pedogenic processes that could mix particulate matter in till. There are also uncertainties surrounding the correct chemical pretreatment for the 14C dating of aeolian remains, and whether vadose water geochemistry might influence preservation and reliable dating. Because of the difficulty in identifying the source of material being dated (both in time and in space by reworking), it is very difficult to attribute cause of differences between ages to pretreatment or antiquity. Identifiable arthropods occur in the youngest tills, and may be appropriate for paleoecological analysis, but extreme topographic gradients and strong mountain-valley winds may make it difficult to extract accurate paleoecological information.

Acknowledgments: This research was supported by NSF EAR-9314927 and sabbatical support from Arizona State University. Thanks to R.S. Anderson, A. Bach, F. Phillips, M. Pohl, R.S. Sharp, an anonymous reviewer for comments, to Scott Elias for identification of arthropods, and to Jeremy and Zachary Dorn for help in digging soil pits and extracting fossil arthropods.

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