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 ^{14}C ages correspond with periods of more effective moisture according to paleoecological and treeline data in the range, whereas Pleistocene ages are penecontemporaneous 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, collembola, midge larvae, and a wingless midge (Kohshima, 1984); snow worms were present in Pleistocene glaciers (Tynen, 1970). In and

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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 ecosytem is striking, ranging from glacial margin carabid and staphylinid beetles (Elias, 1991) to the many species that fallout and live in ice (Catranis 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 (Elias and Toolin, 1990; Elias, 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; Elias, 1994) and to date glacial recession (Elias 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; Östmark, 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; Nishiizumi 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 also may 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 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 ^{14}C 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 ^{14}C 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 ^{14}C 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 ^{14}C constraints on the moraines (Fullerton, 1986; Clark et al., 1995) and a couple of ^{14}C 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 ^{14}C 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 ^{14}C age control.

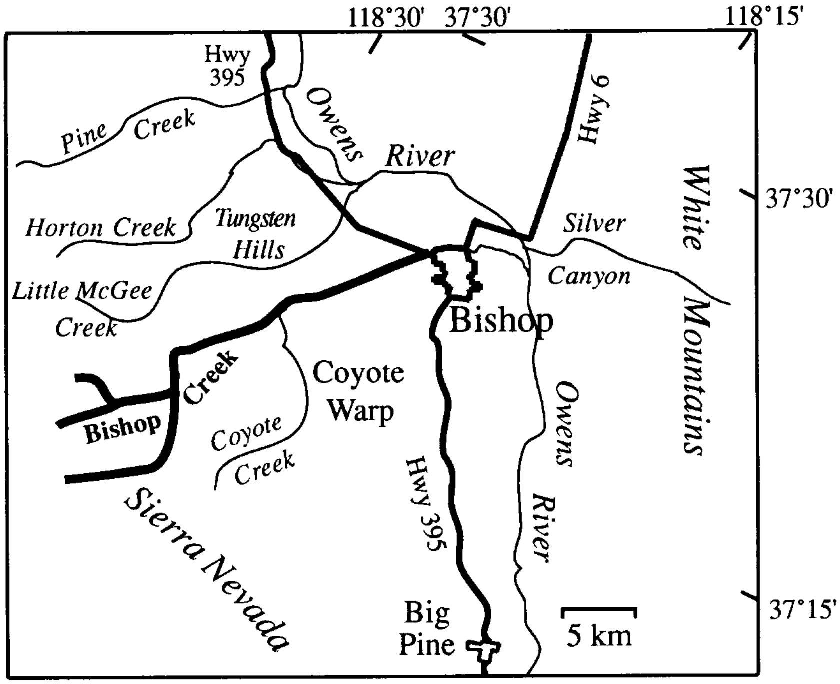

Fig. 1. Location of the Bishop Creek drainage basin in the eastern Sierra Nevada, California.

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 obliterative 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 also are 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

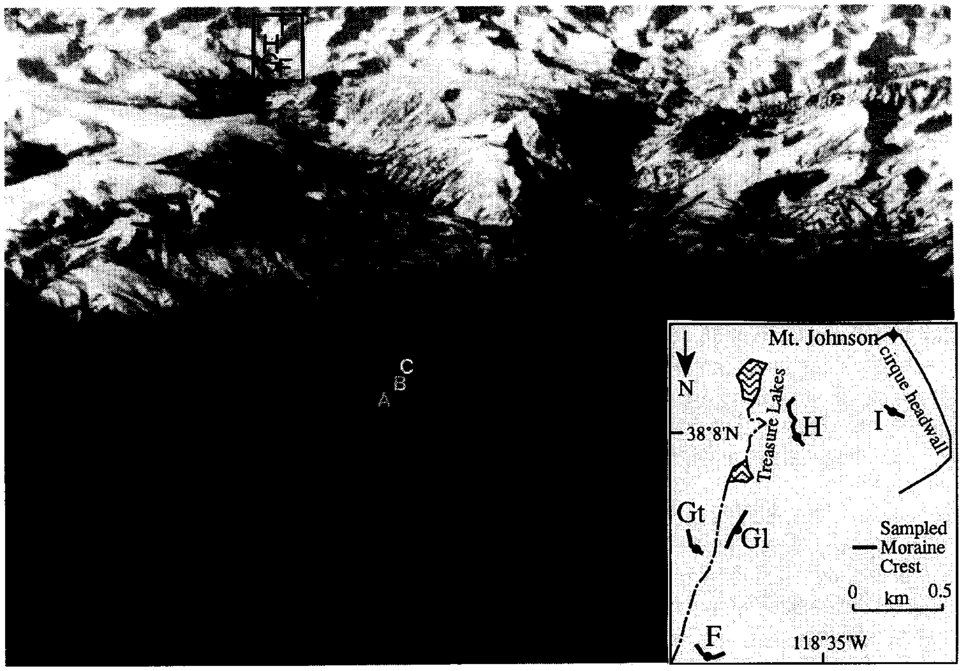

Fig. 2. Oblique aerial photograph looking west toward moraines of the Bishop Creek glacial system, eastern Sierra Nevada, California (center: 37° 15′ N; 118° 35′ W). Letters correspond to Table 1.

(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 synchroneity 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 that 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

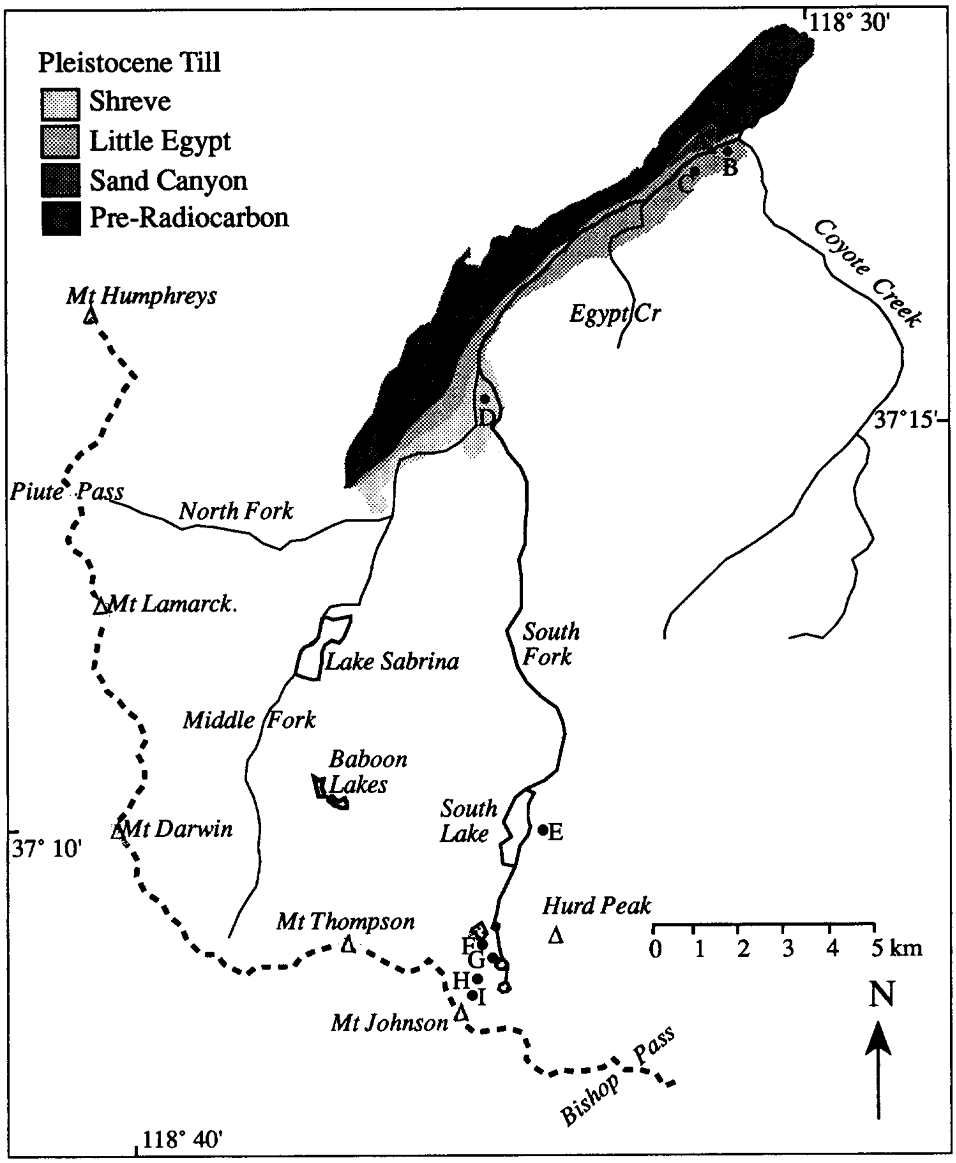

Fig. 3. Location of collection sites in the Bishop Creek drainage basin.

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,

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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 spectometry (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 (Österberg 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 ^{14}C 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 ^{14}C 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 ^{14}C 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 ^{14}C 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[a]

Climatic episode	Possible Sierra correlations	Bishop Creek Stage[b]	Elevation	^{14}C Age[c]	Comments
Little Ice Age	Matthes	Mt. Johnson I[I] (terminal)	3610 m	140 ± 50 (Beta 67935)	Sampled from inner loop
Little Ice Age	Matthes	Mt. Johnson II[H]	3440 m	600 ± 60 (CAMS 12413)	Sampled from outer loop
Neoglacial	Recess Peak	Hurd Peak[G]	3430 m 3410 m	1330 ± 60 (CAMS 11532) 1460 ± 60 (TO1628)	Lateral Terminal
Neoglacial	Recess Peak	Treasure Lakes[F] (terminal)	3290 m	100 ± 60 (CAMS 12412) 2530 ± 60 (CAMS 12411) 2660 ± 60 (CAMS 12410)	
Younger Dryas?	Hilgard?	South Lake[E] (eroded till)	3100 m	7351 ± 83 (NZA 3887) 7753 ± 74 (NZA 3885) 10,618 ± 89 (NZA 3886)	Original surface not preserved
Heinrich Event H1	Tioga	Shreve[D] (lateral)	2425 m	13,870 ± 60 (CAMS 12047) 15,750 ± 70 (CAMS 11535)	Terminal at 2350 m
Heinrich Event H2	Tioga	Little Egypt[C] (recessional)	1980 m	19,600 ± 140 (NZA 3888) 20,540 ± 210 (NZA 3889) 20,660 ± 200 (NZA 3910)	Only moraine with a few trees (*Pinus jeffreyi*)
Heinrich Event H2A	Tioga	Little Egypt Max[B] (lateral)	1920 m	23,590 ± 170 (Beta 67105)	Terminal not preserved
Heinrich Event H4	Tenaya	Sand Canyon[A] (terminal)	1890m	31,900 ± 480 (Beta 67103) 35,420 ± 470 (CAMS 11533) 36,600 ± 560 (CAMS 11534)	Equivalent to Bateman (1965), older Tioga

[a]Including possible correlations with global climatic episodes (Bryson, 1993; Broecker, 1994) and Sierra nomenclature (Sharp and Birman, 1963; Burke and Birkeland, 1983; Fullerton, 1986).
[b]Letters correspond to locations in Figures 2 and 3.
[c]Beta 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 ^{36}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

Till[a]	^{14}C ages aeolian biome (see Table 1)	^{14}C ages on weathering rind organics	^{36}Cl ages	Wood
Mt. Johnson I[I] (terminal)	50–100 B.P.			160 ± 60 (Beta 67091)[b]
Mt. Johnson II[H] (terminal)	~600 B.P.			560 ± 80 (Beta 67098)[b]
Hurd Peak[G] (lateral & terminal)	1250–1600 B.P.			
Treasure Lakes[F] (terminal)	2500–2700 B.P.			
South Lake[E] (eroded till)	7200–10,700 B.P.	10,700 B.P.		
Shreve[D] (lateral)	13,800–15,800 B.P.	14,360 ± 70 (CAMS-15931)		
Little Egypt[C] (recessional)	19,600–20,900 B.P.	19,660 ± 190 (AA 6899)	15,300[c]	
Little Egypt Max[B] (lateral)	~23,600 B.P.	24,480 ± 210 (AA 6917) 23,590 ± 230[d] (NZA 2363) 25,830 ± 270[d] (NZA 2362)	17,100[c]	
Sand Canyon[A] (terminal)	35,000–38,000 B.P.	37.700 ± 740 (NZA 2276)		

[a]Letters correspond to locations in Figures 2 and 3.
[b]Beta Analytic Inc. lab numbers measured by conventional decay counting; all others measured by accelerator mass spectrometry.
[c]Maximum boulder ages, from Zreda et al. (1994).
[d]Measurements on the same boulder.

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

The youngest arthropods yielded ^{14}C 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 ^{14}C 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 organics encapsulated in 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., $^{26}Al/^{10}Be$) 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 (Schidlowskiy, 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 (Burchill 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, 1957), or at Glacier Peak (Beget, 1984), 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 Holocene Results

The Holocene ^{14}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}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}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 7030 ± 130 ^{14}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}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}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}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 (Schidlowskiy, 1983) in the roof pendant (Bateman, 1965), or magmatic CO_2 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 numerical 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 immediately 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 (Röthlisberger, 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 ^{14}C ages in Table 1.

Speculative Correlations with Heinrich Events

If Pleistocene ^{14}C results in Tables 1 and 2 are accurate, the radiocarbon ages are penecontemporaneous with H1, H2, H2a, and H4 Heinrich Events (Bond et al., 1993; Broecker, 1994; Mayewskiy et al., 1994). The ^{14}C 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 glaciations 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.

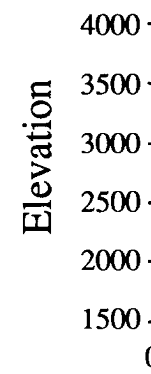

Fig. 4. ^{14}C ag
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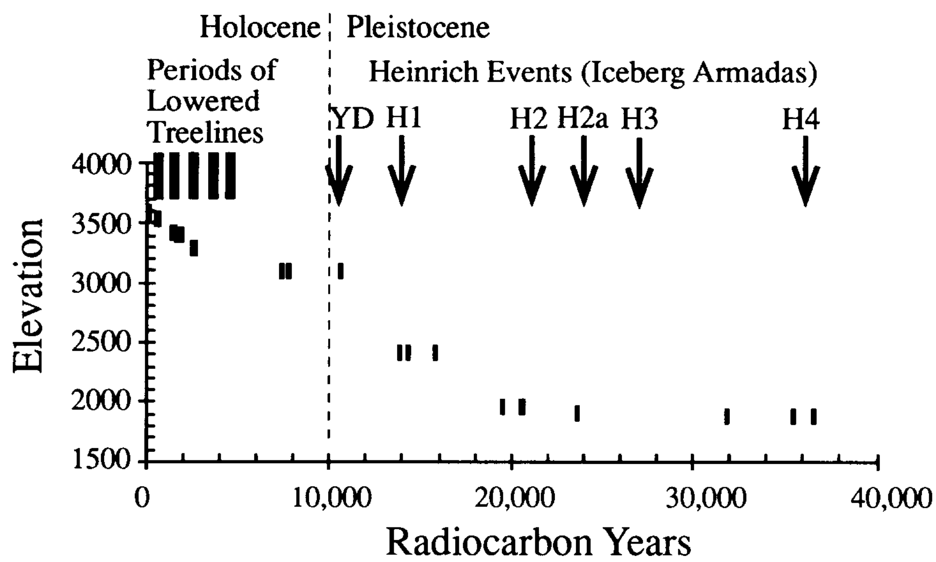

Fig. 4. ^{14}C ages of aeolian biome till matrix material at Bishop Creek (from Table 1), plotted against Heinrich Events (cf. Bond et al., 1993; Broecker, 1994; Mayewskiy et al., 1994) and periods of lower tree line (from Scuderi, 1994).

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 conterminous 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 ^{14}C ages until a number of issues are resolved. Some of the organic matter potentially could pre-date till deposition; in other words, the organics 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 also are uncertainties surrounding the correct chemical pretreatment for the ^{14}C 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.

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