7500 Years of Prehistoric Footwear from Arnold Research Cave, Missouri

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Accelerator mass spectrometer dating of an assemblage of fibrous and leather footwear from Arnold Research Cave in central Missouri documents a long sequence of shoe construction by prehistoric Midwestern peoples, beginning perhaps as early as 8300 calendar years before the present (cal years B.P.). An earlier fibrous sandal form dates from 8325 to 7675 cal years B.P., and later fibrous or leather slip-ons span the period from 5575 to 1070 cal years B.P. The assemblage adds to a growing picture of the highly varied nature of prehistoric footwear production in the United States throughout the Holocene.

Fibrous materials and leather used in the construction of prehistoric footwear are perishable and therefore seldom preserved in the archaeological record. One exception is a collection of articles from Arnold Research Cave, a large-mouth solution cavity located in the Missouri River bluffs of southeastern Callaway County, Missouri (*1*). Excavation of the 2- to 2.5-m-thick midden deposit in the cave and the steep talus slope in front of it between 1955 and 1958 (*1*) demonstrated that the cave was used throughout the Holocene. The first suite of radiocarbon dates for the deposit placed the earliest occupation at about 10,000 calendar years before the present (cal years B.P.). The dates seemed reasonable in light of what was then known about the ages of various projectile point styles in the Midwest, but more recent dating of those styles (*2*) suggests that the cave was occupied as early as 11,000 cal years B.P.

Severe mixing of the deposits precluded assignment of the perishable items to any particular time periods (*1*, *3*), and until development of the accelerator mass spectrometer (AMS) method, radiocarbon dating would have resulted in the sacrifice of large pieces of the items. Small samples of material used to construct seven items of footwear were submitted for AMS dating in 1997, and we report those dates here, along with a summary of footwear construction techniques.

Thirty-five specimens were examined, 17 of which are too fragmentary to allow assessment of original shape and function. Sixteen of 18 complete or partially complete specimens are of fibrous construction, and two are primarily of leather. Physical characteristics and textile attributes were examined for all 18 specimens (*4*), which were then categorized according to completeness on the basis of four major components of a shoe—sole, toe, quarter (back), and vamp (*5*). Three of the 18 specimens are complete and have all four components connected to each other so as to make a whole article. Ten specimens are at least 50% complete and have either three or four components, and five specimens are less than 50% complete and have fewer than three components.

Two major types of shoes are present: four sandals and 13 slip-ons; the style of an additional example could not be determined. Sandals often have no sides and are held on the foot by means of straps; slip-ons generally have sides and stay on the foot without the use of straps or fasteners. All specimens showed normal signs of wear, including soil encrustation, frayed fibers, and broken elements. Evidence of padding was found inside four specimens. The majority of fibers identified are from *Eryngium yuccifolium* (rattlesnake master).

The seven dated footwear specimens (Table 1) represent the greatest variety in materials, styles, and construction techniques. Specimen 2 (Fig. 1A), the oldest radiocarbon-dated specimen, is a nearly complete sandal that measures 25.3 cm long. The sole is warp-faced interlacing. The vamp is not interworked and is made from the lengthwise elements. The toe is pointed, and the round-cupped sling heel is formed from twisted lengthwise elements. The sandal also has a pad or lining. The tie system consists of side loops and a braided cord that criss-crosses through the loops and over the foot and is secured at the ankle. Two AMS dates were run, the second as a check on the first. The first sample dates to 8325 to 8100 cal years B.P. and the second dates to 7895 to 7675 cal years B.

Specimen 5 (Fig. 1B) is a nearly complete slip-on measuring 24.5 cm long; the vamp is missing. The sole, sides, and toe are plain interlacing that approaches being weft-faced. The toe is round, and the heel is round-cupped and formed by twisted lengthwise elements. A row of two-strand Z-twist twining and a row of what appears to be a form of looping were used to secure the lengthwise elements at the heel. One row of four-strand Z-twist twining is found at the beginning of what probably was a vamp. The specimen dates to 5575 to 5300 cal years B.P.

Specimen 3 (Fig. 1C) is a complete slip-on that measures 29.0 cm long. It is similar to a specimen from an Ozark Mountains rock shelter in Arkansas that was illustrated and described (*6*) as an overshoe. The sole was produced by a combination of two-strand, S- and Z-twist twining at the heel and 1/1 interlacing at the middle and toe. The toe is round. The high vamp is two-strand, S- and Z-twist spaced twining and appears to have been secured to each side of the heel at the instep. The specimen has no sides; the heel was formed by twisting the lengthwise elements from the sole, thus producing a round-cupped sling style. The specimen dates to 4985 to 4840 cal years B.P.

Specimen 7 (Fig. 2A) is a partially complete slip-on. The sole and sides are 1/1-

Table 1. Summary of dated footwear from Arnold Research Cave, Missouri.

Specimen number	Style	Beta Analytic lab number	Age (radiocarbon years B.P.)*	Calibration curve intercepts (years B.P.)†	Dendrocalibrated 2σ age range (years B.P.)‡
2	Sandal	β103270	7420 ± 50	8155	8325 to 8100
		β108745	6990 ± 40	7770	7895 to 7675
5	Slip-on	β103271	4680 ± 50	5445	5575 to 5300
				5395	
				5330	
3	Slip-on	β103269	4340 ± 40	4865	4985 to 4840
7	Slip-on	β108743	4320 ± 40	4860	4975 to 4835
1	Slip-on	β103268	3990 ± 40	4430	4535 to 4390
4	Slip-on	β108744	1210 ± 40	1095	1245 to 1000
21	Slip-on	β103272	1040 ± 70	945	1070 to 780

*Uncalibrated conventional ^{14}C age of specimens, in ^{14}C years B.P. ($\pm 1\sigma$). †Intercepts between the conventional ^{14}C age and the dendro-calibrated calendar time scale, in calendar years B.P. (*17*). ‡Two-sigma dendrocalibrated age range for specimens, in calendar years B.P.

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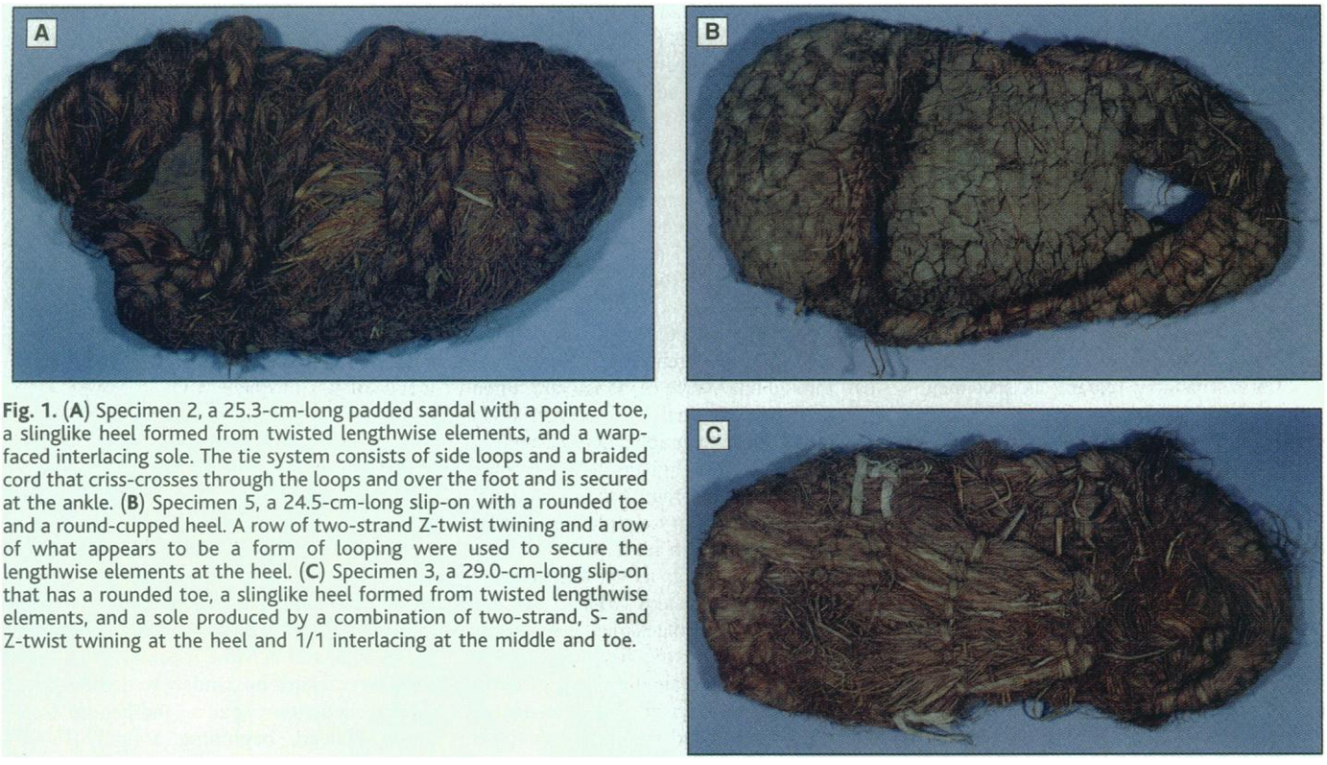

Fig. 1. (**A**) Specimen 2, a 25.3-cm-long padded sandal with a pointed toe, a slinglike heel formed from twisted lengthwise elements, and a warp-faced interlacing sole. The tie system consists of side loops and a braided cord that criss-crosses through the loops and over the foot and is secured at the ankle. (**B**) Specimen 5, a 24.5-cm-long slip-on with a rounded toe and a round-cupped heel. A row of two-strand Z-twist twining and a row of what appears to be a form of looping were used to secure the lengthwise elements at the heel. (**C**) Specimen 3, a 29.0-cm-long slip-on that has a rounded toe, a slinglike heel formed from twisted lengthwise elements, and a sole produced by a combination of two-strand, S- and Z-twist twining at the heel and 1/1 interlacing at the middle and toe.

balanced interlacing. The toe is round; the tip of the heel is missing, but it appears that the interlacing continued at the heel and would have formed a round-cupped heel. The vamp was produced from two rows of two-strand and one row of three-strand Z-twist twining. The vamp appears to have been secured to each side by the last twining element. The specimen dates to 4975 to 4835 cal years B.P.

Specimen 1 (Fig. 2B), a 30-cm-long slip-on, is the most complete and best preserved of the fibrous footwear. The sole and sides are warp-faced interlacing. The toe is round, and the vamp was produced by spaced, two-strand Z-twist twining. The ends of lengthwise elements in the vamp were finished by being turned and secured with the last twining row. The heel form is round-cupped. Two-plied Z-twist cordage that crosses over the instep may have secured the slip-on to the foot. The specimen dates to 4535 to 4390 cal years B.P.

Specimen 4 (Fig. 2C) is the only example

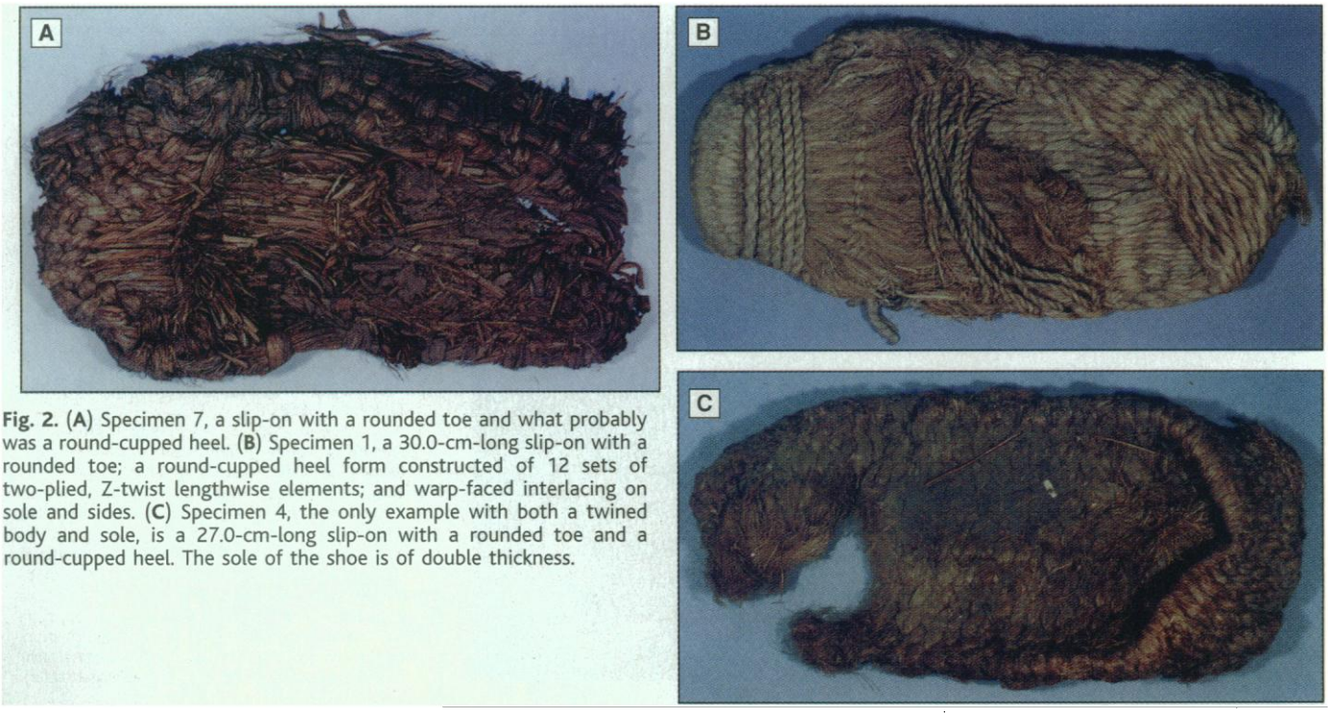

Fig. 2. (**A**) Specimen 7, a slip-on with a rounded toe and what probably was a round-cupped heel. (**B**) Specimen 1, a 30.0-cm-long slip-on with a rounded toe; a round-cupped heel form constructed of 12 sets of two-plied, Z-twist lengthwise elements; and warp-faced interlacing on sole and sides. (**C**) Specimen 4, the only example with both a twined body and sole, is a 27.0-cm-long slip-on with a rounded toe and a round-cupped heel. The sole of the shoe is of double thickness.

with both a twined body and sole. It is a nearly complete slip-on that measures 27.0 cm long. The textile structure is compact two-strand, S-twist weft twining. The heel form is round-cupped and the toe is round. The sole of the shoe appears to be double in thickness. The specimen dates to 1245 to 1000 cal years B.P.

Specimens 21 and 22 (Fig. 3) are examples of leather footwear constructed in the style of a leather moccasin. The leather soles come up to form the sides, quarters (backs), and parts of the vamps. Plied cordage is threaded around the collar of specimen 21, and a fibrous padding remains in specimen 22. Specimen 21 dates to 1070 to 780 cal years B.P.

Two other specimens, neither of which was radiocarbon dated, are noteworthy. Specimen 6 is a nearly complete sandal that has an elaborate tie system consisting of side loops and a strap. The body of the shoe is warp-faced interlacing. At the toe, the lengthwise elements are combined and wrapped into bundles to form a noninterworked vamp. The loops are constructed symmetrically of two-plied Z-twist cordage that is secured on the sides by the crosswise elements. The strap is a two-plied Z-twist cord that comes from the last toe bundle on the right side. It appears that the strap would have criss-crossed through the loops, crossed over the foot, and been tied at the ankle. Specimen 15 is the toe end of a sandal that appears to have had a double-weave construction. Only the top part of the sole remains, but broken elements at the tip of the toe indicate that another structure was present. The sandal is similar in appearance to one recovered from Elk Spring Rockshelter in the Ozark Mountains of Arkansas (*6*).

The production-complexity index (PCI) for textiles (*7*) was used to rate the six radiocarbon-dated fibrous footwear specimens. This measure is an ordinal-scale index based on the number of decisions and amount of labor involved in production of a textile. Numerical values assigned to specific attributes are tallied, with higher numbers indicating more complexity (*8*). PCI values for the six specimens ranged from 20.5 to 12.5. The earliest specimen (2) had a PCI value of 12.5; the next two specimens (5 and 3) had values of 16 and 16.3, respectively; the next two specimens (7 and 1) had values of 12.5 and 20.5, respectively; and the most recent specimen (4) had a value of 13. Although it appears that the complexity of manufacture of footwear does not coincide with age, missing components affected the PCI values. For example, if specimens 7 and 4 had been complete, their PCI values would have been higher than those calculated.

Although the element and fabric structures used to create prehistoric fibrous footwear throughout North America are often similar, styles, materials, and construction techniques varied geographically and temporally. Not surprisingly, given the geographic proximity, footwear from Arnold Research Cave is most similar to examples of undated footwear reported from bluff shelters in the southern Ozark Mountains of southwestern Missouri and northwestern Arkansas. In addition to the two specimens mentioned above reported by Harrington (*6*), he also illustrates a "moccasin with attached legging of deerskin." However, other than in the use of leather, this pieced and stitched specimen is not similar in style or construction to specimens 21 and 22. Scholtz (*9*) classified and described 11 examples of footwear from Ozark rock shelters, some of which have similarities to the footwear from Arnold Research Cave. Numerous examples of footwear have been recovered from Kentucky caves (*10*), including a large number of twined slippers produced with a seam from the point of the toe to the instep, but they differ from the Arnold Research Cave specimens.

Perhaps the most widely published examples of footwear in North America are those from the desert Southwest, especially those of the Anasazi (*11*), and they vary tremendously in style, materials, and technique. There are few similarities with the footwear recovered from Arnold Research Cave. Sandals from the dry rock shelters of West Texas (*12*) are made from agave leaves and also are quite different. Hewitt (*13*) reported 7 whole and 49 fragmented remains of sandals from Cowboy Cave and Walters Cave in Colorado. These specimens include open-twined and plain-weave examples, some of which have grass padding, but they, too, differ stylistically from the Arnold Research Cave footwear.

Although few examples of prehistoric footwear reported from the United States have been directly dated, one early exception is a pair of slip-ons from Fort Rock Cave in south-central Oregon. These were described by Bedwell (*14*) as "sandals" made of shredded sagebrush bark and exhibiting round toes, round-flat heels, interlaced soles, and spaced-twined vamps. One of the pieces was directly dated to 9003 ± 350 cal years B.P. (uncalibrated) (*15*). The stratigraphic position of the sandals suggests considerable antiquity, but the date was derived by means of the early solid-carbon method, leaving the precision of the assay open to question. The twined vamps on the Fort Rock Cave shoes are similar stylistically to the vamps on Missouri specimens 3, 5, and 7. More recently, Geib (*16*) used direct dates on sandals to demonstrate a long occupation span in the central Colorado Plateau, beginning around 10,000 years ago. He reports a variety of sandal forms, though none directly parallels the Missouri examples.

Specimens from Arnold Research Cave extend our knowledge of the production and use of footwear by prehistoric peoples in one part of the Midwest across a roughly 7500-year period. The specimens indicate that at least two basic footwear forms—sandals and slip-ons—were produced in central Missouri between roughly 8325 and 780 cal years B.P. Further, the Missouri specimens add to a growing picture of the highly varied nature of prehistoric footwear production in the United States.

Fig. 3. Specimen 22, a 17.1-cm-long piece of leather footwear constructed in moccasin style. The leather sole comes up to form the sides, back, and vamp. Perforations extend around the top of the shoe, through which cordage would have passed. The inside of the shoe is lined with grass.

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17. The Pretoria calibration procedure program by Beta Analytic, Inc. was used.
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Dissociative Recombination of HD^+ in Selected Vibrational Quantum States

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Rate coefficients for dissociative recombination of HD^+ in selected vibrational states have been measured by a combination of two molecular fragment imaging methods by using the heavy-ion storage ring technique. Recombination fragment imaging yields state-to-state reaction rates. These rates are converted to rate coefficients by using vibrational level populations of the stored ion beam, derived from nuclear coordinate distributions measured on extracted ions. The results show strongly increasing rate coefficients for high vibrational excitation, where additional dissociation routes open up, in agreement with a theoretical calculation. Very low rate coefficients are found for certain, isolated vibrational states.

The last 20 years have seen tremendous progress in our understanding of elementary chemical reactions. Molecular-beam experiments have provided very detailed information about the dynamics of inelastic and reactive collisions (*1*). Supersonic expansion, which leads to a strong reduction of the temperature relevant for the molecular level population, has been widely exploited to analyze neutral molecules in their vibrational ground state. Much greater experimental difficulties are encountered in producing molecules and molecular ions in well-defined excited states, and studies of their collision dynamics, important in such areas as high-temperature combustion media or atmospheric processes under nonequilibrium conditions (*2*), are scarce.

Dissociative recombination (DR) (*3*) of molecular ions with free electrons is an elementary reactive collision that is highly sensitive to vibrational excitation. In many partly ionized gas-phase environments, the process removes charged particles and produces neutral fragments carrying considerable kinetic energy and often also internal excitation. The process is therefore very important in astrophysics and planetary science; for example, the DR of O_2^+ molecules is responsible for the production of the so-called green-light emission (airglow) in Earth's ionosphere (*4, 5*).

The detailed understanding of the DR process has suffered from the lack of knowledge about the internal excitation of laboratory molecular ion beams, which has made comparison between experimental results and theory difficult (*6*). Techniques have been developed during the last 5 years that use molecular ions in heavy-ion storage rings, which relax to their vibrational ground state within several seconds of storage time. Cross sections of DR were measured with this method for a variety of important species after relaxation to the vibrational ground state (*7*). These measurements with vibrationally cold molecular ions revealed structures in the DR cross section that resulted from unexpected recombination mechanisms (*8, 9*); in combination with two- and three-dimensional molecular fragment imaging techniques (*10*), the contributions for well-defined final quantum states of the fragments could be measured. Advanced theoretical calculations yielded good agreement with the data for ions in the vibrational ground state (*11*).

For the experimental approach used here the storage ring technique was extended to yield reaction rate coefficients for vibrationally excited molecular ions during their relaxation. The fragment imaging method allows us to determine relative reaction rates for molecular ions in excited states with vibrational quantum numbers v ranging from 0 to 7; by the simultaneous identification of the final fragment levels, it basically yields state-to-state reaction rates. This powerful technique is combined with an independent method for measuring the vibrational state distribution in the stored, relaxing beam, which uses Coulomb explosion imaging (CEI) (*12, 13*) of molecular ions extracted from the ring; the measured recombination rates for the different initial states can thus be converted into rate coefficients, which can be directly compared with theory.

A reaction well suited for initiating these studies is the DR of HD^+ with low-energy electrons (experimental energy spread ~10 meV). HD^+ is the simplest molecular ion subject to vibrational relaxation by infrared emission. Its DR with low-energy electrons can be depicted as

$$HD^+(v) + e^- \rightarrow \begin{matrix} H(1s) + D(nl) \\ \text{or} \\ H(nl) + D(1s) \end{matrix} \quad (1)$$

where nl denotes the orbital of the electron in the atomic fragments. Starting with the capture of an electron by the molecular ion, a rearrangement of the whole electronic cloud leads to a transfer of kinetic energy to the

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