THE ADOPTION OF THE BOW AND ARROW: A MODEL BASED ON EXPERIMENTAL PERFORMANCE CHARACTERISTICS

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The timing of the arrival of the bow and arrow in the New World and reasons for its adoption have long been discussed by archaeologists. It typically has been assumed that the bow and arrow provided mechanical and physical advantages over the atlatl and dart, particularly in long-range killing power. This experimental study examines the effectiveness of traditional bows and arrows to deliver lethal wounds to prey species of different sizes. The results suggest that the bow and arrow was effective in hunting prey species such as antelope and deer but ineffective in bringing down larger animals unless changes in hunting strategies were adopted. In contrast, the atlatl and dart would have excelled in large game hunting. It is proposed that the adoption of the bow and arrow and the abandonment of the atlatl and dart were conditioned by their distinct performance advantages and changes in the game species targeted over time.

El momento de llegada del arco y flecha y los motivos por su adopción en el Nuevo Mundo han sido temas de discusión por mucho tiempo entre arqueólogos. Típicamente, se ha asumido que el arco y la flecha dieron ventajas mecánicas y físicas sobre el propulsor y el dardo particularmente en términos de la capacidad de matar o "killing power" a largo alcance. Este estudio experimental examina la eficacia de los arcos y las flechas tradicionales para herir mortalmente a presas de distintos tamaños. Los resultados sugieren que el arco y flecha tradicional habría sido eficaz en la caza de presas de mediano tamaño, como ser el ciervo y el antílope, pero ineficaz para derribar presas más grandes, a no ser que se adoptaran cambios en las estrategias de caza. Al contrario, el propulsor y el dardo seran más eficazes en la caza de presas de largo tamano como el bison. En base a estos hallazgos, se propone que el arco y la flecha eventualmente podrían haber reemplazado al propulsor y al dardo porque eran más efectivos para especies de presas de mediano porte y por el decremento eventual de especies más grandes.

During the past few decades, several researchers have devised methods to differentiate dart and arrow points to accurately establish the age of the bow and arrow weapon system in the New World (Shott 1993, 1997; Thomas 1978). Although some disagreements remain about the antiquity of the bow and arrow (Ames et al. 2010; Amick 1994; Bradbury 1997; Sliva 1999), recent reviews suggest that until at least 3000 B.C., the dominant weapon technology for New World hunter-gatherers was the atlatl and dart (Blitz 1988; Nassaney and Pyle 1999). Sometime between 3000–1600 B.C., the bow and arrow appeared in the Canadian Arctic (Anderson 1984:84; Dumond 1978:47–51). From the Arctic, it spread to the east and south, reaching the Southeast perhaps as early as A.D. 500 and the Southwest by A.D. 600 (Blitz 1988; Justice 1995, 2002a, 2002b; Nassaney and Pyle 1999:253–257). In some regions, the new technology appears to have overtaken the atlatl and dart relatively rapidly, while in others, the adoption of the bow and arrow may have lagged behind (Nassaney and Pyle 1999:253–259; Simms 2008:209). Yet elsewhere, the two weapon systems may have been part of a single arsenal for quite some time (Aikens 1970; Chatters et al. 1995; Logan 2010; Shott 1996; Webster 1980).

Bradbury (1997), Christenson (1986), Hughes (1998), Laralde (1990), Simms (2008), and others have considered the advantages of the bow and arrow compared to the atlatl-propelled dart. Some advantages relate to the ease of learning and using the weapon, the context of use (woodlands), and the stealth it provided. In addition, due to its higher velocity and greater effective range, the bow and

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American Antiquity 78(3), 2013, pp. 553–569
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https://doi.org/10.7183/0002-7316.78.3.553 Published online by Cambridge University Press

arrow is seen as more efficient than the atlatl and dart (Blitz 1988). The general perception is that as the distance between prey and hunter increases, the accuracy of the bow and arrow and the velocity of the projectile provide a significant advantage over the atlatl and dart (Blitz 1988:134).

This experimental study examines these assumptions particularly as they relate to the hunting of prey species of different body sizes. In this usage, effectiveness refers to the capacity of the weapon to deliver a lethal shot from the typical hunting distance. The discussion is divided into five principal sections. First, kinetic energy (KE) and momentum (P) are introduced. In the next section, the recommended ranges needed to hunt prey species of different sizes are established. The third section presents a compilation of the performance characteristics of traditional bows and arrows. Using ballistics experimentation, the fourth section defines the range of prey species that could have been effectively hunted using traditional bows and arrows. Building on the experimental results, the fifth and final section presents a model of the adoption of the bow and arrow.

Assessing Weapon Effectiveness and Penetration

The effectiveness of any weapon system depends on a combination of factors, including the hunter's knowledge of the behavior and anatomy of the prey species (Frison 2004:54; O'Connor 1970), the skill of the hunter to deliver the arrow to the vital spot, the technical characteristics of the weapon, and the performance of the projectile once it reaches the target. This discussion is limited to the characteristics of the weaponry.

The bow and arrow have to perform two tasks: 1) deliver the projectile to the target and 2) cause a lethal wound. Projectile speed is a key ingredient in accomplishing the first task. Many modern bow hunters achieve arrow flight speeds in excess of 90 meters per second (m/s) (Silks 2011a, b). To develop such speeds, bows have become more powerful and arrows have become lighter.

High arrow speed contributes to the weapon's effectiveness by improving aim, lessening prey flight opportunity, and increasing the kinetic energy delivered by the arrow. Faster arrow speed results in a flatter flight trajectory, and therefore it increases the chance of accurrately compensating for the drop of the arrow during its flight to the prey. Accurate shots are critical, given that the kill zone (hearth and lungs) on a pronghorn antelope is no more than 23 cm in diameter and that of a large deer is only 30.5 cm (O'Connor 1970), less than half the size of a bison's kill zone (approximately 71 cm in diameter).

Based on wariness and flight tendency, hunters categorize game animals into relatively laid-back (e.g., moose, mountain goats), wary (elk, sheep, caribou, bear), and jumpy (turkey, pronghorn, white–tail, and mule deer) species (Timney 2007). Once the hunter releases the bowstring and the arrow is in flight, the prey has only a fraction of a second to react and move out of the way. The faster the arrow, the less time the animal has to take evasive action.

Once the projectile reaches the prey, other factors become significant in ensuring a lethal outcome. Among these are the morphology (e.g., length of the cutting edges, width of the head) of the arrow tip (Ashby 2000), its sharpness (Friis-Hansen 1990), resistance to fracture, and the diameter of the arrow or foreshaft (Ashby 2000). More important, however, the one factor that is critical in the potential of the projectile to inflict a lethal wound is its penetration. Friis-Hansen (1990) suggests that a projectile has to penetrate roughly to the middle of the chest cavity of the prey to achieve a lethal wound. By this measure, a projectile would need to penetrate approximately 19 cm into the chest of a pronghorn antelope, 25 cm into a large deer (O'Connor 1970), and approximately 58 cm into a bison.

The kinetic energy (KE) and momentum (P) of an arrow in flight explain its penetration. When a projectile is in flight, it has kinetic energy. This energy represents the amount of work the projectile can do as a result of its motion. After it strikes, the energy that transfers to the target represents the force of impact. The kinetic energy (KE) of a projectile is calculated by multiplying one-half of its mass by its velocity squared ($1/2mv^2$). Mass is equal to the weight of the object (in pounds) divided by the pull of gravity (9.814 m/s/s). The unit of measurement for kinetic energy is foot/pounds (ft-lbs). Velocity significantly influences kinetic energy, while the mass of the object in motion exerts less effect (Hrdlicka 2003).

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Many bow enthusiasts argue, however, that while kinetic energy determines how hard a projectile strikes, momentum determines how far that projectile penetrates the target. Momentum (P) is the tendency of an object in motion to stay in motion. Measured in slug–feet per second (slug-ft/s), it represents the force of an object's forward movement. The momentum of a projectile is calculated by multiplying its mass with its velocity (P = mv). The calculation of momentum places equal value on the projectile's mass and its velocity.

Recommended Kinetic Energy and Momentum Ranges for Bow Hunting

Since the mid-twentieth century, most North American bow hunters have targeted antelope, deer, fish, and birds. More recently, they have extended their range to large and very large game animals such as grizzly bear and elk in North America, and Cape buffalo and other very large game in parts of Africa.

Based on these experiences, hunters and governing regulatory agencies have defined the recommended kinetic energy and momentum ranges for small to very large game species. Table 1 shows the kinetic energy values needed to cause lethal wounds in small, medium, large, and very large species as recommended by Easton Archery (http://www.eastonarchery.com/store/kinetic_calculator), one of the leading manufacturers of bow hunting equipment.

Table 2 shows the minimum recommended kinetic energy and momentum values in four African countries (Botswana, Namibia, South Africa, and Zimbabwe) that allow bow hunting of a range of species. The author calculated the momentum values using arrow weight and arrow speed recommendations provided in each country's regulations (see www.africahunting.com).

The species of animals included within each size category vary widely. In addition, the recommended minimum kinetic energy and momentum values also vary both by prey size (i.e., weight) and country. To standardize these apparent inconsistencies, the weight ranges of adult males of the species were used to regroup the prey species (see Table 3). In addition, elephants, hippopotami, giraffe, and rhinoceroses are excluded from the very large prey species in the revised list.

The medium prey group includes pronghorn antelope, white–tailed deer, mule deer, and Desert bighorn sheep. The adult males of these species weigh between 33–136 kg and typically exceed 50 kg. The large prey group includes caribou, Rocky Mountain bighorn sheep, black bear, wildebeest, and Roan antelope, among others. The adult males of these species weigh between 73 and 300 kg and typically weigh more than 100 kg. The very large-bodied prey class includes elk, moose, Cape buffalo, and American bison. The adult males of these species weigh from 227 to 1000 kg and typically exceed 400 kg.

Table 1. Minimum Recommended Kinetic Energy Values for North American Game.

Game Size	Prey Species	Recommended KE Range (ft-lbs)
Small	Rabbit, Groundhog, Turkey	< 25
Medium	White–Tailed Deer, Antelope	25–41
Large	Elk, Moose	42–65
Very Large	Bison, Grizzly Bear	> 65

Using these revised game size categories, Table 4 presents the recommended kinetic energy and momentum values for small to very large prey. To hunt medium prey effectively, the recommended kinetic energy developed by the bow and arrow needs to fall between 25 and 41 ft-lbs, whereas to hunt large game, the kinetic energy required has to be between 42 and 65 ft-lbs. To be effective against very large prey, the recommended kinetic energy of the arrow needs to exceed 65 ft-lbs. Momentum requirements exhibit similar incremental changes with increased prey body size. These values are used as the yardstick against which to measure the effectiveness of traditional weapon systems.

Defining the Characteristics of Traditional Bow and Arrow Weaponry

To develop an experimental program, it was necessary to first establish the draw weight of traditional bows, the weight of typical arrows, and the average shooting range employed by hunters. The ethnographic literature is replete with anecdotes regarding the strength of Native American bows (Kelly 1932:144; Mason 1894:678; Ray 1886:833). Unfortunately, such observations do

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Table 2. Minimum Recommended Kinetic Energy and Momentum for African Game by Size.

Country/ Momentum	Game Size Category			
	Small	Medium	Large Game	Very Large
Namibia	Springbok, Impala, Blesbok, Gray Duiker, Steenbok, Ostrich, Caracal, Black–Faced Impala, Red Lechwe, Damara Dik–Dik, Klipspringer, Black–Backed Jackal, Game Birds	Warthog, Cheetah, Nyala, Chacma Baboon	Greater Kudu, Cape Eland, Oryx/ Gemsbok, Red Hartebeest, Blue Wildebeest, Black Wildebeest, Hartmann's Zebra, Burchell's Zebra, Giraffe, Sable Antelope, Roan Antelope, Waterbuck, Tsessebe	
KE (ft–lbs)	25	40	65	
Momentum (slug–ft/s)*	.29	.38	.51	
South Africa	Warthog, Nyala, Springbok, Impala, Blesbok, Duiker, Steenbok, Ostrich, Caracal, Black–Backed Jackal, Game Birds	Kudu, Eland, Oryx /Gemsbok, Hartebeest, Wildebeest, Zebra, Giraffe, Sable Antelope, Roan Antelope, Waterbuck, Tsessebe	Elephant, Rhinoceros, Hippopotamus, Cape Buffalo	
KE (ft/lbs)	40	70	80	
Momentum (slug–ft/s)	.38	.58	.70	
Botswana	Warthog, Nyala, Springbok, Impala, Blesbok, Duiker, Steenbok, Ostrich, Caracal, Black–Backed Jackal, Game Birds	Kudu, Eland, Oryx/Gemsbok, Hartebeest, Wildebeest, Zebra, Giraffe, Sable Antelope, Roan Antelope, Waterbuck, Tsessebe	Elephant, Rhinoceros, Hippopotamus, Cape Buffalo	
KE (ft/lbs)	40	70	80	
Momentum (slug–ft/s)	.38	.58	.70	
Zimbabwe	Warthog, Impala, Reedbuck, Sitatunga, Duiker, Steenbok, Jackal, Game Birds	Leopard, Crocodile, Kudu, Oryx / Gemsbok, Hartebeest, Wildebeest, Zebra, Nyala, Sable Antelope, Waterbuck, Tsessebe	Lion, Giraffe, Eland	Elephant, Hippopotamus, Cape Buffalo
KE (ft–lbs)	56	70	77	80
Momentum (slug–ft/s)	.49	.62	.69	.70

*Momentum figures calculated by author based on arrow weight and speed recommendations provided for prey in each country.

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Table 3. Game Hunted with the Bow and Arrow Arranged by Weight.

Relative Size	Species	Male Adult Weight Range (kg)	Mean of Range (kg)
Very Large	American Bison	422–998	710
	Eland	440–907	673.5
	Cape Buffalo	424–907	665.5
	Moose	385–717	551
	Grizzly Bear	227–771	499
	Zebra	250–408	340.5
	Elk	213–431	322
	Musk Oxen	227–408	317.5
Large	Roan Antelope	224–299	261.5
	Greater Kudu	120–357	238.5
	Sable Antelope	190–270	230
	Wildebeest	118–269	193.5
	Gemsbok	166–209	187.5
	Waterbok	150–227	188.5
	Hartebeest	120–200	160
	Black Bear	57–227	142
	Tsessebe	107–130	118.5
	Caribou	59–159	109
	Rocky Mountain Bighorn Sheep	73–136	104.5
Medium	Mule Deer	43–136	89.5
	Nyala	54–127	90.5
	Desert Bighorn Sheep	68–91	79.5
	White-Tailed Deer	45–110	77.5
	Blesbok	55–80	67.5
	Impala	53–76	64.5
	Pronghorn Antelope	45–61	53
	Springbok	33–50	41.5
Small	Duiker	18–20.5	19.25
	Steenbok	7–16	11.5
	Wild Turkey	5–11	8
	Groundhog	4–11	7.5
	Jack Rabbit	4–5	4.5
	Cottontail Rabbit	1–1.4	1.2

not allow us to determine bow draw-weight parameters for an experimental program. A small number of useful traditional North American bow draw-weight estimates do exist (Hamilton 1982:41, 139; Pope 1923:335–342).

Ten (59 percent) of the 17 bows have draw weights of between 40 and 50 lbs. An additional three (17 percent) have draw weights that fall below 40 lbs, and the remaining four (23 percent) have draw weights exceeding 50 lbs. Pope identified only one bow, an Arctic specimen, with a draw weight of 80 lbs, as adequate for bison hunting (Pope 1923:338).

From this small sample, it appears that traditional Native American bows have draw weights of 40 to 50 lbs. (see also Cattelain 1997:230; Hughes 1998:362–363). Sinew-backed bows tend to be more powerful (Laubin and Laubin 1980:82), and composite bows (e.g., the Inuit) tend to be the most powerful weapons (Hamilton 1982:71; Pope 1923:338). Modern replicas of archaeological specimens suggest that even more powerful long bows existed prehistorically. For instance, the replica of an Osage Orange (*Maclura pomifera*) bow recovered from the Mound Plantation site (16CD12) in northwestern Louisiana

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Table 4. Recommended Range of Arrow Kinetic Energy and Momentum by Game Size.

Game Size	Prey Characteristics	Prey Species	KE (ft-lbs)	Momentum (slug–ft/s)
Small	Weigh less than 20.5 kg; thin skinned, weak ribs;	Rabbit, Steenbok. Groundhog, Turkey, Duiker	< 25	< .24
Medium	Weigh 33–136 kg; often in excess of 50 kg; thin–moderate skin/rib thickness;	Impala, White–Tailed Deer, Pronghorn Antelope, Nyala, Springbok, Mule Deer	25–41	.24–.38
Large	Weigh 73–300 kg; often in excess of 100 kg; moderate skin/rib thickness	Wildebeest, Greater Kudu, Hartebeest, Gemsbok, Black Bear, Caribou	42–65	.39–.58
Very Large	Weigh 227–998 kg; often in excess of 400 kg; moderate to thick skin and moderate to thick ribs	Cape Buffalo, Eland, American Bison, Grizzly Bear, Moose, Elk, Zebra,	>65	.59+

(Webb and McKinney 1975) had a draw weight of 70 lbs (Schambach 1995:11).

While extensive data exist on historic arrow dimensions (e.g., Allely and Hamm 1999, 2002; Fowler and Matley 1979; Mason 1894; Pope 1923), much less is available on arrow weight. Pope (1923:360, 390–400) provides weights for a small sample of historic arrows. This sample of 17 arrows has a mean weight of 20.3 g, and ranges from 13 to 31.5 g.

To increase the sample, the author examined 121 historic arrows from the Grayson Collection housed at the Museum Support Center of the Anthropology Museum at the University of Missouri in Colombia. Figure 1 is a histogram of the weights of this sample. The mean weight of the arrows in the sample is 23.2 g and only one (0.8 percent) arrow exceeds 40 g in weight. Six (5 percent) of the arrows are lighter than 16 g. Overall, 85 percent of the sample falls between 16 to 28 g in weight, and the bulk of these (89 out of 103) fall between 19–28 g.

Information regarding historic bows primarily refers to the distance that a bow can cast an arrow (Pope 1918, 1923). Maximum cast distance does not reflect the effective distance from which hunters typically discharged their arrows at the prey. Ethnographic data compiled by Churchill (1993:Table 1.4) suggest that the effective range of the bow and arrow is 25.8 m. This figure agrees well with Cattelain's (1997) estimate. He reports that 45 m seems to be the upper limit for precise shots with traditional bows but that the distance for accurate shots does not exceed 25 to 30 m (Cattelain 1997:227).

Experimental Approach

To allow for consistent and repeated bow shots at designated draw weights, a bow-shooting device was designed and built to gauge the effectiveness of the traditional bow and arrow. The device allowed the repeated shooting of a bow at draw weights of 40, 45, and 50 lbs. The standardization of string release was achieved using a mechanical caliper release (Master Hunter, manufactured by The Allen Company, Inc.).

A laminated Browning Wasp recurve bow was used in the experiments. The bow was mounted at the front of the shooting device and a winch was used to draw the bowstring while it was in the release mechanism. When the bowstring reached the desired setting, the release mechanism was secured in place to prevent premature firing.

Both longbows and recurve bows were common during historic times (Allely and Hamm 1999, 2002). While, longbows outnumbered recurve bows in most regions, they were relatively

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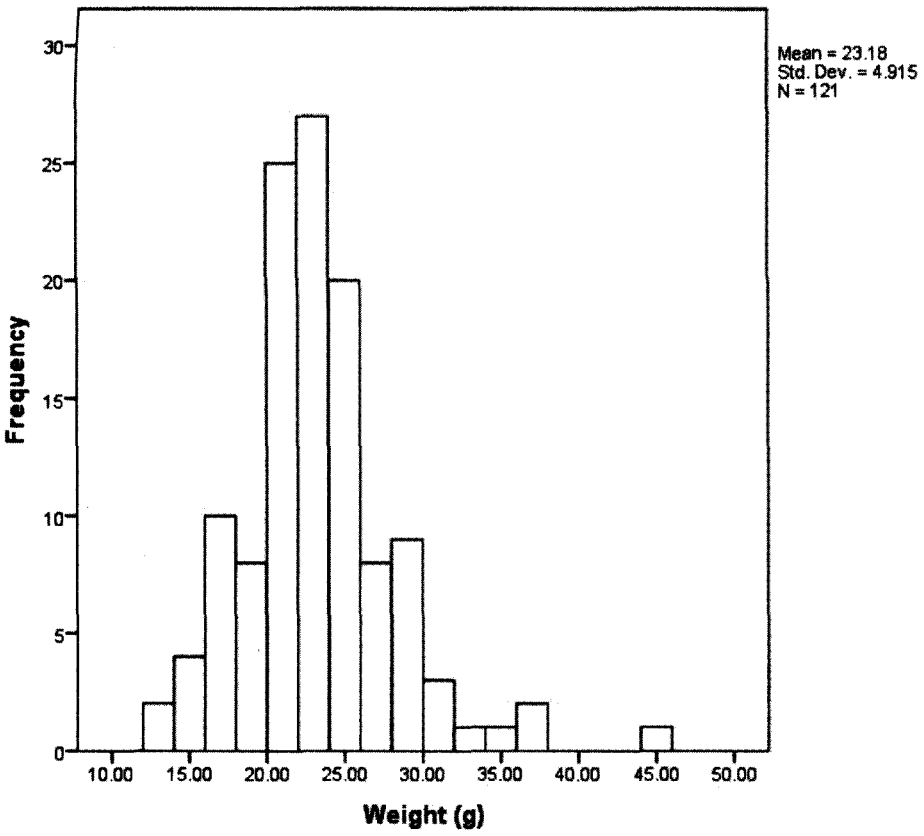


Figure 1. Histogram of arrow weights, Grayson Collection (University of Missouri at Columbia).

common in the northeast (14 of 41 bows) and outnumbered longbows in the Plains (24 of 39 bows). In general, a recurve bow of a given draw weight will shoot faster than a longbow of similar draw weight (Hamm 1992:24–25; Laubin and Laubin 1980:20). Therefore, it may be assumed that the ballistics results obtained during these experiments are at the upper range of performance of longbows of similar draw weights.

To study the influence of projectile weight on effectiveness, three arrows were built using Easton Eclipse X7–2112 aluminum shafts. The lightest arrow weighed 23 g. To increase the weight of the other two, 5 and 10 g metal plugs were inserted into their respective shafts immediately behind the arrow point adapter inserts. The three arrows were identical in length (29 inches), point weight (8.1 g), external morphology, and fletching (three 4-inch-long plastic feathers), although their balance points were slightly different.

The shooting experiments gauged the effectiveness of the weapon system at 20 m downrange from the back of the bow. Arrow speed was measured by a Beta Master Brand Chronometer, set up at 20 m from the bow-shooting device. The speed of the arrow was recorded as it passed above the sensors of the chronometer. A Yellow Jacket foam target served as the backstop. It also helped to gauge penetration as either arrow or draw weight were altered during the experiments. The arrow penetration data is not to be taken as an indicator of actual arrow penetration into animal tissue. Rather, the penetration data reflects relative performance characteristics of arrows of different weights shot at varying draw weights.

Some variability in arrow speed measurements was noted during the experiments. It likely derived from minuscule changes in mechanical release, chronometer operation, and arrow flight stability. To obtain a reading, the arrow had to pass through a rectangular area from 4 to 6 inches above each of the two sensors. When the arrow

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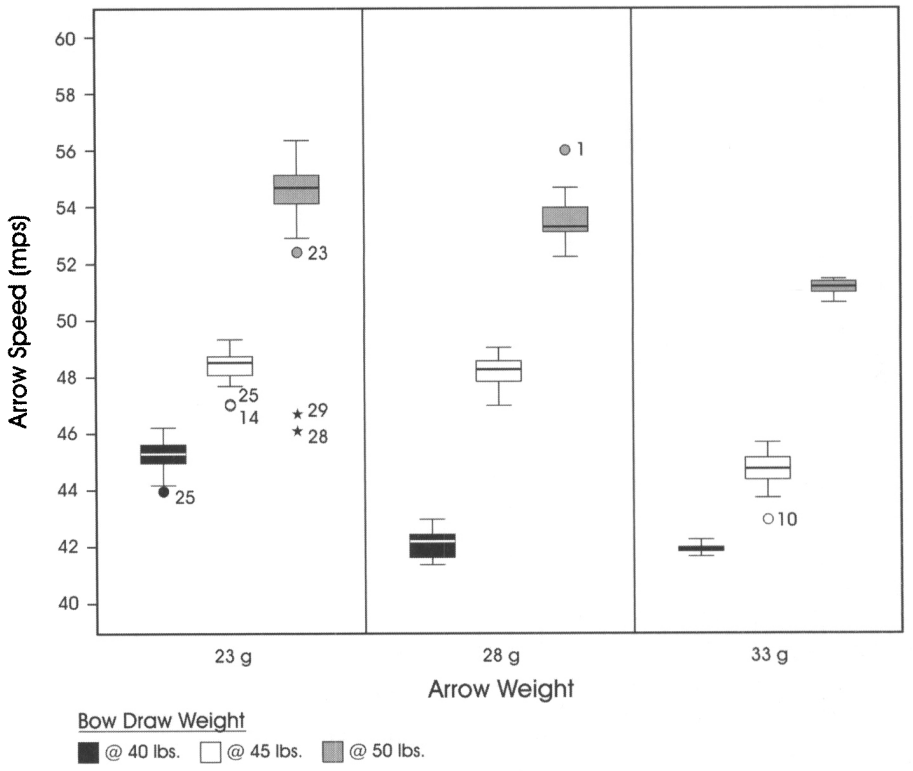


Figure 2. Quartile box plot of arrow speeds for each arrow weight–bow draw weight combination. Extreme values (○) and outliers (•) noted outside of the box.

missed these sensor windows, it was not possible to obtain a velocity reading. In such an instance, the shot was repeated to acquire a reading and only then was the depth of arrow penetration measured as the arrow was extracted from the target. To account for the variability in arrow speed, 30 shots were fired with each of the 3 arrows using each of the 3 draw weight settings. All experiments occurred indoors to reduce the effect of crosswinds on arrow trajectory.

It is recognized that experiments such as the one reported in this study provide a highly controlled setting that is far removed from the field conditions under which traditional weapons were employed and prehistoric hunts were conducted. It is for this reason that the research methodology is composed of two complementary approaches. The kinetic energy and momentum generated by the typical historic bow shooting the typical historic arrow is gauged using controlled experiments. On the other hand, the ranges of kinetic energy and momentum needed to bring down prey species of different sizes is based on years of bow hunting experience. Therefore, this approach combines highly controlled experimentation with the actual experience gained from hunting a variety of prey species across two continents. While the modern bows and arrows are different from pre-industrial weaponry, it is kinetic energy and momentum that are critical to the killing power of the arrow, not whether it is shot out of a state-of-the art compound bow or an Osage Orange longbow.

Experimental Results

Figure 2 shows box plots of arrow speeds for each arrow weight–draw weight combination. For each individual arrow weight, as bow-draw weight in-

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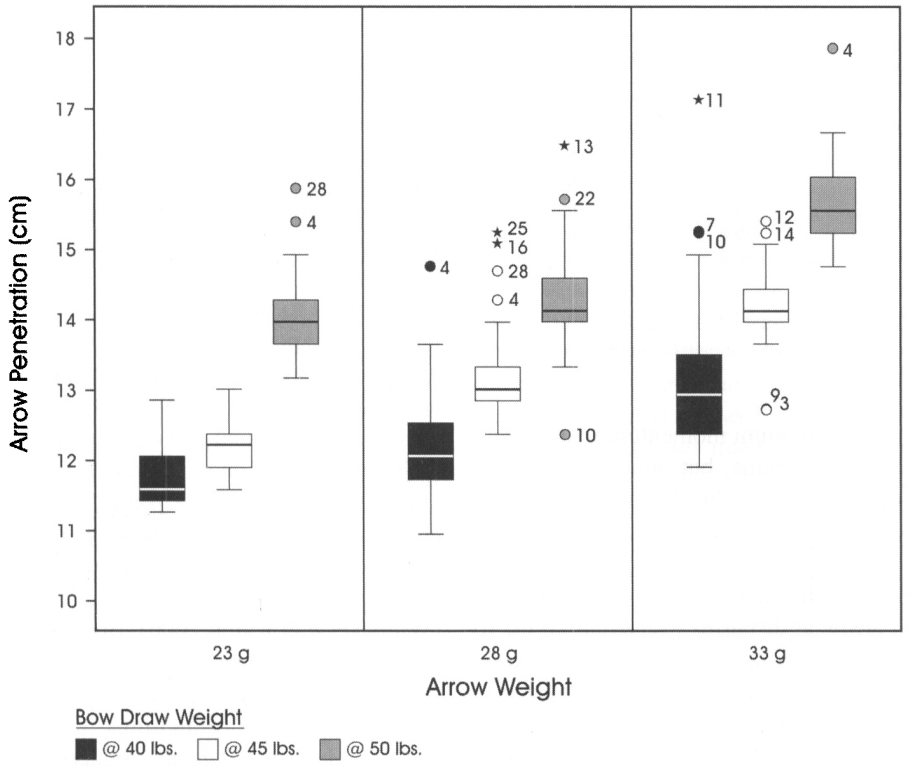


Figure 3. Quartile box plot of arrow penetration for each arrow weight–bow draw weight combination. Extreme values (○) and outliers (•) noted outside of the box.

creased, arrow speed also increased. For instance, the 23 g arrow fired at a draw weight of 40 lbs had a mean speed of 45.5 m/s. In contrast, the same arrow fired at a draw weight of 50 lbs had a mean speed of approximately 54.3 m/s. It is also evident that as arrow weight increased, the speed of the arrows decreased. For instance, the speed of the 33 g arrow fired at a draw weight of 50 lbs was roughly 3 m/s slower than the speed of the 23 g arrow fired at the same draw weight.

The data collected on arrow penetration corroborate the initial expectation that arrow weight has a strong effect on penetration. Figure 3 shows the box plots of penetration for each of the arrow–draw weight combinations. For each individual arrow, as draw weight increased, arrow penetration also increased. In addition, as arrow weight increased, arrow penetration also increased at the same draw weight. For instance, the mean penetration of the 23 g arrow was 11.7 cm, while the 33 g arrow had a mean penetration of 13.2 cm at the same draw weight (40 lbs).

The KE and P values attained by each arrow also were calculated. When one compares the experimental (Table 5) with the recommended values (Table 4), it becomes evident that in terms of kinetic energy, all three arrows fired at the highest draw weight meet the values recommended for medium-bodied species. None of the arrow weight–draw weight combinations meet the recommended values for hunting large and very large species 20 m down-range.

Using momentum to gauge weapon effectiveness (Table 5), it is notable that only the lightest arrow, fired at a 40-lb draw weight, does not reach the minimum recommended momentum for medium-bodied prey. In addition, the heaviest of arrows, shot at the highest draw weight, come

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Table 5. The Kinetic Energy and Momentum Values from Arrow Shooting Experiments.

Arrow Weight/ Draw Weight	Kinetic Energy (ft-lbs)	Momentum (slug–ft/s)
23 g@40 lbs	17.2	0.23
23 g@45 lbs	19.6	**0.25**
23 g@50 lbs	24.4	**0.28**
28 g@40 lbs	18.6	**0.27**
28 g@45 lbs	24.3	**0.31**
28 g@50 lbs	**30.0**	**0.34**
33 g@40 lbs	20.8	**0.31**
33 g@45 lbs	24.7	**0.33**
33 g@50 lbs	**32.4**	**0.38**

*Figures in bold exceed recommended minimum values for medium-bodied prey.

closest to the minimum momentum requirement for hunting large game, but none of the arrow weight–draw weight combinations meets the minimum requirement for hunting very large game, such as bison.

To ascertain the effectiveness of the traditional bow and arrow at distances exceeding 20 m, 10 additional experiments were conducted. In these, the speed of the heaviest arrow was measured as it left the bow and 15 m downrange using two chronometers. Employing the highest draw weight during the experiments, the results showed a decrease in arrow speed of 1.7 m/s over the 15 m distance. Using this rate of deceleration, it is possible to approximate that even shooting at a target 45 m down-range, the 33 g arrow would deliver approximately .35 slug-ft/s of momentum (assuming slightly higher deceleration rates over the second and third 15 m of flight). This figure is well within the range of adequate momentum (see Table 4; .24–.38 slug-ft/s) for bringing down medium-bodied species.

To gauge the effectiveness of the bow at close range, ten more experiments were conducted with the heaviest arrow. In these experiments, the speed of the arrow was measured at 10 m from the bow. The arrow attained a mean speed of 53.1 m/s and generated 34.5 slug-ft/s of kinetic energy and .40 ft-lbs of momentum. Neither of these values is sufficient to be effective against very large prey. Ashby (2000:85) estimates that it would take a long bow with a draw weight of 94 lbs shooting an arrow weighing 50 g with a speed of 53.3 m/s at impact to exceed the minimum momentum necessary to effectively bring down very large game.

Weaponry Performance: A Comparison

The results of these ballistic experiments show that, indeed, the typical historic bow and arrow would have been effective in inflicting a lethal wound to medium prey species even at 45 m downrange. However, the weapon would have been only marginally effective when hunting large-bodied animals at 20 m and would have been ineffective in bringing down very large species, such as bison, even from half this distance.

To begin to understand the factors that may have been responsible for the shift to the bow and arrow, it is useful to assess the performance characteristics of the atlatl and dart. The effective range of the atlatl and dart appears to be between 9–46 m (Churchill and Curran 1991:Table 2). Accuracy may fall rapidly beyond 27 m (Hutchings and Brüchert 1997:892). Practice with the weapon increases targeting ability and success rates particularly during the early years of weapon use (Whittaker and Kamp 2006). Because it weighs more, the kinetic energy and momentum of a dart at impact tends to be relatively high. Based on data reported by Hutchings and Brüchert (1997:Table 1), a 222 g dart produces 100.8 ft-lbs of kinetic energy and 1.75 slug-ft/s of momentum 15 m down-range. Even at 30 m, the kinetic energy (64.9 ft-lbs) and momentum (1.4 slug-ft/s) of the dart would be lethal against very large prey. Therefore, the atlatl dart would have excelled in performance exactly where the bow and arrow was deficient, namely the hunting of large and very large game.

The superior penetration of the atlatl and dart against large game means that it would have performed equally well against medium-sized prey. Therefore, based on penetration power alone, there would be no reason for the adoption of the bow and arrow once it appeared on the horizon. If the atlatl and dart perform exceptionally well once the projectile has reached the target, how does it compare to the bow and arrow when it comes to delivering the projectile to the target?

Few systematic experimental results have been published regarding the speed of atlatl-propelled darts. Furthermore, there is a great deal of variation in both the equipment used and the manner in which the speed of the projectile is measured. Nonetheless, the data suggest that replicated darts

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propelled by atlatl generally reach initial speeds of 19.4 to 23 m/s (Bergman et al. 1988:Table 1; Miller et al. 1986:Figure 1; Raymond 1986:Table 3). Butler (1975:Table 2) computed speeds of 20.45 to 26.9 m/s using atlatls with and without weights. Whitaker and Kamp (2007) reached speeds that ranged between 21.8–24.8 m/s for darts weighing from 75 to 155 g. Hutchings attained speeds of 31.6–50.7 m/s, 15 m downrange using a 222 g dart (Hutchings and Brüchert 1997:Table 1). The highest velocity figure (50.7 m/s) is well outside of the range of the typical replication experiments reported in the literature (see also Hughes 1998:Table I) and may represent an idiosyncratic outlier rather than the norm (Whitaker and Kamp 2006).

Given this overall range in dart speeds and idiosyncratic variability in individual throwing technique and strength, it is impossible to know how representative these speeds may be of prehistoric weapons. However, if we accept that the mean dart speed was approximately 25 m/s, then the projectile's speed would be well below arrow speeds produced by the typical bow. Specifically, the speed of the dart would be about 26.5 m/s slower than the speed of the 33 g arrow fired at a draw weight of 50 lbs. This amounts to a 48.6 percent difference in projectile speed. The virtual doubling of the projectile velocity may have encouraged prehistoric hunters of medium and smaller game to replace the atlatl dart with the bow and arrow.

The higher speed of the arrow, compared to the speed of the dart, would not be of great consequence in hunting large and very large species since the projectile's kinetic energy and momentum would not be sufficiently high to effectively harvest these prey at 20 m. Then again, the slower speed of the atlatl dart also may not be a great disadvantage in hunting very large prey. Bison, slow to frighten, are less likely to react by flight than deer and antelope and have slow initial speed (McDonald 1981; Meagher 1978). The eyesight of bison is inferior to their well-developed sense of smell and hearing on which they depend to detect approaching threats (McHugh 2004 [1972]:148–149). Their internal organs are protected by thick hides and massive rib cages. Heavy projectiles that deliver sufficient momentum to penetrate through the thick hide and ribs are effective against such prey (Frison 2004: 53–61), and the slower flight speed of the darts is not a major disadvantage.

In contrast, it is projectile speed in particular that is needed for hunting the more agile medium-bodied antelope and deer. These species have quick reflexes, rapid flight responses, and great initial speeds. Deer depend on hearing and smell to detect danger (Hiller 1996:32–39). Antelope have excellent eyesight that can detect movement from long distances (O'Connor 1961:69–70). Both species have the ability to react to danger instantaneously (Hiller 1996:32; O'Connor 1961:70). A weapon system that can deliver its projectile to the target twice as fast as its competitor should yield significant advantages by reducing the chances that the projectile will be detected and by shortening reaction time when and if it is detected. In addition, the flatter flight trajectory of the arrow makes aiming easier, a factor that becomes even more significant given the smaller target.

These performance characteristics and prey behavioral traits suggest that the bow and arrow may have been better suited to the procurement of medium-bodied, more agile species, while the slower atlatl dart was more effective for hunting larger prey. A number of other researchers working on the transition in weapons technology have noted the higher kinetic energy generated by the atlatl-propelled dart compared to the bow and arrow (Ellis 1997:45–46; Hitchcock and Bleed 1997:355; Hughes 1998:393–396; Hutchings 1997:136–137; Laralde 1990:160; Yu 2006:206–210).

Based on these results, one would expect that examples of bow hunting large and very large prey would be scarce in the ethnohistoric and archaeological record. On the contrary, however, the recovery of arrow points associated with bone beds indicates that during prehistoric times hunters employed the new weapon technology to procure large and very large (e.g., bison) (Quigg and Peck 1995; Ricklis 1994) animals. Furthermore, the ethnohistoric record confirms the targeting of large and very large species with the bow and arrow (Branch 1962; Schaeffer 1978). Even cross-cultural studies indicate that the bow and arrow is used to procure a wide range of prey, including large and very large species (Churchill and Curran 1991; Hitchcock and Bleed 1997; although see Shott 1993).

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A closer look at some of these examples, however, reveals an interesting underlying pattern. For instance, Churchill's (1993) analysis shows that when hunted with the bow and arrow, animals weighing 200 kg or more tended to be targeted during disadvantage and pursuit hunting. In contrast, the bow hunting of smaller animals occurred during ambush and approach hunting (Churchill 1993:Table 1.6). In his analysis of spear and arrow hunting by Mbuti, Waorani, and Efe groups, Shott (1993:437–438) noted similar patterns. Animals targeted with the bow and arrow were smaller than those targeted with spears, but the majority of the kills were made with the bow and arrow. Hitchcock and Bleed (1997:354) also note that among the Ju/'hoansi and Kua, bow hunting even with poisoned arrows tends to be limited to and is most effective against smaller prey species. In contrast, spear hunting by Tyua males tends to focus on large prey in part because the heavier weapon is more effective against larger-bodied species (Hitchcock and Bleed 1997:356). This is not to say that ethnographic examples of bow hunting very large game without the use of traps and corrals do not exist. They do, but just as in the case of the Ju/'hoansi and Kua, hunters use poisoned arrows to slow down or immobilize the prey (Hitchcock and Bleed 1997:348; Tanaka 1980; Watanabe 1973).

Perhaps the best examples of bow hunting very larger prey species are the communal bison hunts that took place on the Great Plains of North America (Davis and Reeves 1990). During late prehistoric (A.D. 200–1750) and historic times, the communal hunting of bison was done with the bow and arrow, and tended to involve pedestrian or equestrian drives, surrounds, and impounds (Dunbar 1880:329–330; Ewers 1955; Forbis 1962; Grinnell 1962 [1923]; Hanson 1986; Kelly 1932:82–86; Lowie 1982 [1954]:13–14; McHugh 2004 [1972]:81–82; Reeves 1978). These hunting techniques were highly successful in capturing large numbers of animals. The results of the ballistics experiments reported here suggest, however, that the success of these hunts was not due to the bow and arrow. Rather, by reducing the distances between hunter and prey (both in surrounds and equestrian hunting), and, more important, by preventing the escape of the animals (surrounds), these communal hunting techniques made it feasible to use the bow and arrow to dispatch large game. The opportunity to launch multiple arrows at the confined prey compensated for the weakness of the weapon. Stalking of large and very large game also was a viable technique that brought hunters closer to the prey, thereby increasing the effectiveness of the weapon (Arthur 1975:61–64). However, stalking limited the ability of the hunter to fire multiple projectiles, which would have been needed to bring down larger game.

Could these differences in performance characteristics explain the variable rates of adoption of the bow and arrow and the retention of the atlatl and dart across North America? And, what were the conditions that lead to the eventual predominance of the bow and arrow over the atlatl and dart?

A Model of Bow and Arrow Adoption

The bow and arrow performed adequately when it came to the hunting of medium and smaller game. Situational advantages offered by the weapon (Bergman et al. 1988; Christenson 1986; Hughes 1998; Laralde 1990; Shott 1993) coupled with the higher velocity of the arrow compared to the dart may have further increased hunting success. The experimental results suggest, however, that unless changes in hunting strategies accompanied the adoption of the bow and arrow (i.e., surrounds and corralling to allow multiple shots), the weapon would not have been effective against very large prey.

Therefore, a change in weaponry would have had consequences for prehistoric hunters. The bow and arrow could have increased yields of medium and smaller game, but the weapon would not have been viable against very large game unless hunting strategies also were changed. Retaining the atlatl and dart would have meant continued success in large game procurement and continued capacity to hunt smaller game but perhaps at a diminished rate of return compared to hunters equipped with the the bow and arrow. Choosing to retain the atlatl and dart and also adopting the bow and arrow would have allowed hunters to broaden their hunting capacity and retain a flexible subsistence strategy in the face of changing big game densities.

If these consequences of weaponry change are accurate, then the principal factor that would have

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conditioned the actual choice would have been the game animals available for harvest at the time of the appearance of the bow and arrow. The prey choice model predicts (Stephens and Krebs 1986:17–24) that high-ranked prey will be targeted whenever encountered. Since there is a strong relationship between body size and return rates among vertebrates (Broughton 1994), it can be expected that in regions where large prey was available in abundance at the time of the appearance of the bow and arrow, groups would have chosen to retain the atlatl and dart. In contrast, in regions where medium and smaller game animals were the principal prey, hunters would have rapidly shifted to the bow and arrow. The eventual adoption of the bow and arrow by groups that chose to continue using the atlatl and dart would have been encouraged by the decrease in abundance of large prey. The eventual decline in large game animals on the continent would have resulted in the predominance of the bow and arrow weapon system over time.

Using these implications, the following specific expectations are proposed regarding the adoption of the bow and arrow and/or retention of the atlatl and dart: in regions such as the Southeast where the dominant prey consisted of medium-bodied species, the bow and arrow would have displaced the atlatl and dart rather quickly, and therefore the temporal overlap of the two weapon systems would have been short. In contrast, in regions such as the southern fringes of the Great Plains where both medium and very large game were present, the two weapon systems may have coexisted for as long as larger species continued to be targeted. As larger prey species declined in availability, and hunters began selecting medium prey more regularly, the bow and arrow would have replaced the atlatl and dart. Alternatively, the bow and arrow would have been readily adopted by Northern Plains groups that had long traditions of communal bison hunting because the social organization of the hunt would have compensated for the weakness of the weapon against the larger prey.

The comprehensive and systematic assessment of these expectations in the archaeological record is difficult. The period from A.D. 100–800 seems to cover the transition in weaponry across the Southeast and the Southern Plains. Unfortunately, archaeological assemblages with co–occurring arrow and dart points dating to this transitional period are often considered mixed. If not mixed, it is assumed that the presence of dart points in such assemblages represents prehistoric recycling (Meinkoth 2000:255) rather than the contemporary use of the two weapon systems.

The challenge to assessing the model's expectations may not only consist of accurately identifying site and assemblage formation processes, but also overcoming interpretive preconceptions. While the potential that assemblages may be mixed should be critically evaluated, it should not *a priori* be assumed that all archaeological components with dart and arrow points lack associational integrity. Furthermore, weaponry change is a regional phenomenon and as such, it will require regional-scale documentation rather than single-site evidence. Therefore, systematic criteria may need to be established regarding what constitutes acceptable evidence of weaponry contemporaneity in the archaeological record both at the intrasite and regional level.

Inferring artifact use based on artifact morphology also may be a complicating factor. For instance, there are Woodland assemblages with both arrow points and large hafted bifaces in seemingly solid depositional contexts in many sites (Green and Nolan 2000:364; Reeder 2000:188). These hafted bifaces are morphologically similar to Archaic dart points. It is possible, however, that these large bifaces were used as hafted knives rather than dart points during Woodland times. Without the proper use-wear analysis of these artifacts, and their correct functional assignment, the assessment of the model is difficult.

Cave and shelter sites have the best preservation of perishable artifacts. Unfortunately, these same sites also are the most likely to have undergone vertical displacement of materials due to their limited floor areas. While the direct dating of atlatls, dart, and arrow shafts can help reconstruct processes of weaponry change, the number of directly dated weapon components is still pretty limited (Ferg and Peachey 1998; Fields 2005; Moreno 2000). Recent archaeological investigations in glacial melt fields in the Arctic (Hare et al. 2004) have increased the number of dated weaponry components. The data from the Arctic show only minimal temporal overlap between the

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atlatl and dart, and bow and arrow technology (Hare at al. 2004:268). However, as of now, the number of samples, the ages of the components sampled, and their spatial distribution is too limited to allow definitive statements regarding the coexistence of the two weapon systems.

Conclusions

While the experiments reported herein focus on weaponry performance, it is recognized that the replacement of an existing technology with a new one is often dependent on multiple factors such as its fit within the overall organization of technology, existing social relations, and the actual performance characteristics of the respective tools and technology. The experimental results demonstrate that the bow and arrow would not have been adequate to hunt very large game, such as bison, without alterations in hunting strategies. However, the same weapon would have performed well against deer, antelope, and smaller game. As archaeologists, we tend to view the adoption of the bow and arrow as having caused or lead to the abandonment of the atlatl and dart. However, the results of the study suggest that the adoption of new technologies does not necessarily directly lead to the abandonment of existing technologies. Adoption and abandonment of technologies can proceed on distinct causal tracts that may or may not be temporally synchronized. In the case of the bow and arrow, its adoption may have been driven by its greater effectiveness against medium game while the abandonment of the atlatl and dart may have been conditioned by decreases in the density of very large game, such as bison.

Acknowledgments. The ideas expressed in this paper are the product of years of discussions with fellow Texas archaeologists and, in particular, Raymond P. Mauldin, Mike Quigg, and Chris Lintz. I greatly appreciate their insights, points, and counter points over the years. I also want to thank the anonymous reviewers who provided useful comments on an earlier draft of this manuscript. Their comments helped me crystallize what were the key elements of a much lengthier manuscript. Many thanks also to Andrew Bradbury, Brad Logan, Christopher Lintz, Donna Roper, and Susan Vehik for their insightful comments and encouragements to forge on with the manuscript. My thanks as well to Elizabeth Pintar for her assistance with the Spanish abstract, which reads much better as a result of her help. I express my gratitude to the staff of the Museum Support Center at the University of Missouri at Columbia for their generosity and assistance in allowing an alumnus of Ol'Mizzou to return to the old campus. Finally, I would like to express my thanks to my son, Joshua, for the numerous weekends he spent with me shooting arrows and keeping me company.

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Submitted September 24, 2012; Revised February 21, 2013; Accepted February 26, 2013.

https://doi.org/10.7183/0002-7316.78.3.553 Published online by Cambridge University Press