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The Ballistics of Archaic North American Atlatls and Darts

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by

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Abstract

Preserved atlatls and darts, commonly of small size, have been found across North America from the Early to Late Archaic. Close replications of these systems were employed in a naturalistic experiment on a fresh hog carcass. The use of high-speed cameras, a radar gun, and a video analysis program to measure dart velocity and view impacts in slow motion allowed a detailed analysis of the results. The experiment captured several details about atlatl and dart ballistics, including killing potential, the effects of point beveling on dart flight and impact, traceable impact damage on bones and stone points, and the effectiveness of various hafting arrangements. The results provide details about the atlatl and dart that will be helpful to the study of ancient hunting cultures.

KEYWORDS atlatl and dart, spear thrower, experimental archaeology, hunting, projectile ballistics

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Numerous other individuals helped with project. Barney Bahrenfus and his family were instrumental in selling a hog at an affordable price, dispatching it humanely, transporting it and allowing the experiment to be carried out on their property. Three experienced atlatlists, Justin Garnett, Patrick Hashman and John Whittaker, put substantial time and effort into participating in the carcass experiment. A total of eleven skilled flint knappers made projectile points for the experiment, some of which were traded or purchased but many were donated. Special thanks to these generous flint knappers.

Special thanks also to atlatlists at the Valley of Fire 2014 event in Nevada who assisted in the velocity studies. Pascal Chauvaux and others shared several slow motion videos of atlatlists in action, which inspired that portion of this project. Mike Evans of the Arkansas Archaeological Survey and B & R Meat Processing near Winslow, Arkansas donated cow and pig bones for the beveled point test; and others at the Arkansas Archaeological Survey helped in numerous ways. Finally, the author’s father, Jerry Pettigrew, and several friends and family members provided assistance in filming and photographing aspects of dart flight and impact, as well as in helping me to understand the math behind calculating ballistics, which is not my strong point. My thanks to all of these individuals, the following project could not have progressed without them.

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1. Introduction

Modern atlatlists may not offer direct evidence of the abilities of ancient hunters, but many have become quite skilled with the weapon and provide insight into its capabilities (Whittaker 2010:212–213). Their observations combined with my own fascination with the atlatl have led to a series of questions regarding atlatl and dart ballistics that I will explore in this thesis. The project began in 2013 with a naturalistic approach that involved experienced atlatlists and replicated atlatl and dart systems. The best approach to study the true killing potential of a projectile system is a *naturalistic* one in which replicated systems are tested against fresh carcasses, since a *controlled* approach that seeks to isolate specific effects removes the many variables present in an actual hunting scenario, and does not produce “real-world” results (Ashby 2005a). Nevertheless, controlled target media can be useful, and in this project initial tests were carried out on various target media including Perma-gel, a type of ballistics gelatin. In July of 2014 four participants took part in an experiment on a fresh hog carcass. The experiment was patterned after previous experiments that pitted atlatls against carcasses (Callahan 1994; Frison 1989; Letourneux and Pétillon 2008; Pétillon et al. 2011). However, a higher degree of detail was captured in this experiment from slow motion footage of darts impacting the carcass, while a video analysis program called Tracker (http://www.cabrillo.edu/~dbrown/tracker/) and a radar gun provided velocity measurements. Shots were marked on the carcass so that damage to stone points could be matched with damage to bone and correlated with velocity. This approach offers an appropriate experimental protocol for naturalistic studies of ancient projectile systems not represented in previous studies.

This thesis addresses one primary question: what are the killing potentials of atlatl and dart systems of various sizes? Simultaneously, several additional effects resulting from a naturalistic experiment with replicated projectiles are considered, including the effects of point beveling on dart flight and impact (see Pettigrew et al. 2015), the results of pronounced or tapered shoulders at the socket ends of Basketmaker darts, the effectiveness of various hafting methods and point designs, and damage and breakage on stone points and impacted bone.

Four experimenters skilled in the use of the atlatl and dart took part in the carcass experiment: Patrick Hashman, John Whittaker, Justin Garnett and the author. All have been making and using atlatls for several years. The most effective way to procure large game with spears, darts and arrows is to cut a wound of sufficient size through vital organs inside the thoracic cavity and cause substantial hemorrhaging (Friis-Hansen 1990). Once done an animal will drop within a short distance of being shot. If not poisoned, a projectile needs a point of sufficient shape and size and must penetrate a sufficient depth to achieve this effect. Consistent velocity data from well-practiced modern atlatlists (Raymond 1986; Whittaker and Kamp 2007) supports the concept that, assuming effective point designs, the mass of the dart is the simplest measure of its killing potential (Hutchings and Brüchert 1997) since velocity does not increase substantially with lighter darts. Preserved atlatl darts from North America are commonly of small size and low mass (Figure 1) in contrast with larger ones from Australia (Cundy 1989), and heavy darts used to produce lethal wounds on fresh elephant carcasses (Frison 1989). Preserved darts have been recovered primarily from western North America where drier conditions have led to better preservation (Hutchings and Brüchert 1997; Pettigrew and Garnett 2014; Pettigrew 2014a, 2012); but also at sites on either side of the Great Plains (Pettigrew 2015). These artifacts range from the Early Archaic (Hester 1974) until the widespread adoption of the bow no later than 1,200 years ago. Admittedly these darts represent a tiny sample of what must have existed in prehistory, and larger point types from North America probably represent the use of larger darts. Based on our experience using replicas of preserved North American systems (e.g. Garnett 2011a; Pettigrew and Garnett 2014; Pettigrew 2014a), we thought they were too light to reliably kill very large game such as American bison (*Bison bison*) through penetration and hemorrhaging, and wanted to test them further.

Figure 1. Justin Garnett holding a replica Broken Roof Cave atlatl with a White Dog Cave dart. The system has good balance right at the handle. Photo by Ken Villars; used with permission.

The effects of point beveling were simultaneously addressed since the experiment took a naturalistic approach using actual point types represented in the archaeological record. The need for a naturalistic study of beveled points was realized following recent research (Lipo et al. 2012) claiming that beveled points could increase accuracy by spinning darts in air. In addition Dr. Ed Ashby, a popular authority on modern bow hunting, claims that beveled broadheads on arrows are more lethal due to their ability to torque and split dense bone, as well as various other effects resulting from rotation through the wound channel (Ashby 2007).

Initial penetration experiments were carried out on Perma-gel to test the killing potential of darts of various sizes. Perma-gel offers a consistent target medium for measuring penetration but proved a poor analogy to flesh for darts and arrows, since only shallow penetration was achieved. Subsequently, several target media were tested for the effects of point beveling on impact, including the Perma-gel, paper and foam targets, melons and lastly fresh pig and cow bones. Because a beveled point needs a target it can slice through and that provides adequate resistance against the bevels to induce rotation (Ashby 2007), cantaloupes of all things actually show rotation of beveled points on atlatl darts (Pettigrew et al. 2015). Of course the question remained whether point beveling would also rotate darts through flesh. The need for a fresh carcass was recognized to substantiate the results of both the killing potential of replicated North American systems and point beveling.

The projectile kit for the carcass experiment involved five atlatls and eight dart mainshafts representing three classes of dart weight. Two atlatls and three darts were replicas of artifacts from White Dog Cave (Guernsey 1931) and Broken Roof Cave (Guernsey and Kidder 1921; Garnett 2011a) in northeastern Arizona, and represented the smallest weight class (Figures 1 and 2a, b). Two cane darts were slightly heavier and were used with beveled points and also foreshafts based on artifacts found under Ozark bluffs in Arkansas and Missouri (Pettigrew 2015). Two more darts were not based on specific artifacts and represented the heaviest class. A reproduction Catawba bow (Figure 3) (Allely and Hamm 1999:80) and two arrow mainshafts were included to provide a comparative sample of shots using archery equipment. A total of 92 projectile points (89 of which were successfully hafted, and 29 were used) were obtained from skilled flint knappers and hafted to foreshafts using ancient and modern methods. The foreshafts were then mated to various mainshafts. A series of measurements of each projectile provides a detailed data set that can be tied back to each shot (see Appendix A for a summary of the results).

Tip cross-sectional area (TCSA) and tip cross-sectional perimeter (TCSP) are measurements used to determine the force necessary for a projectile point to penetrate a lethal depth. This can give some idea of the weapon systems that may have been used with specific

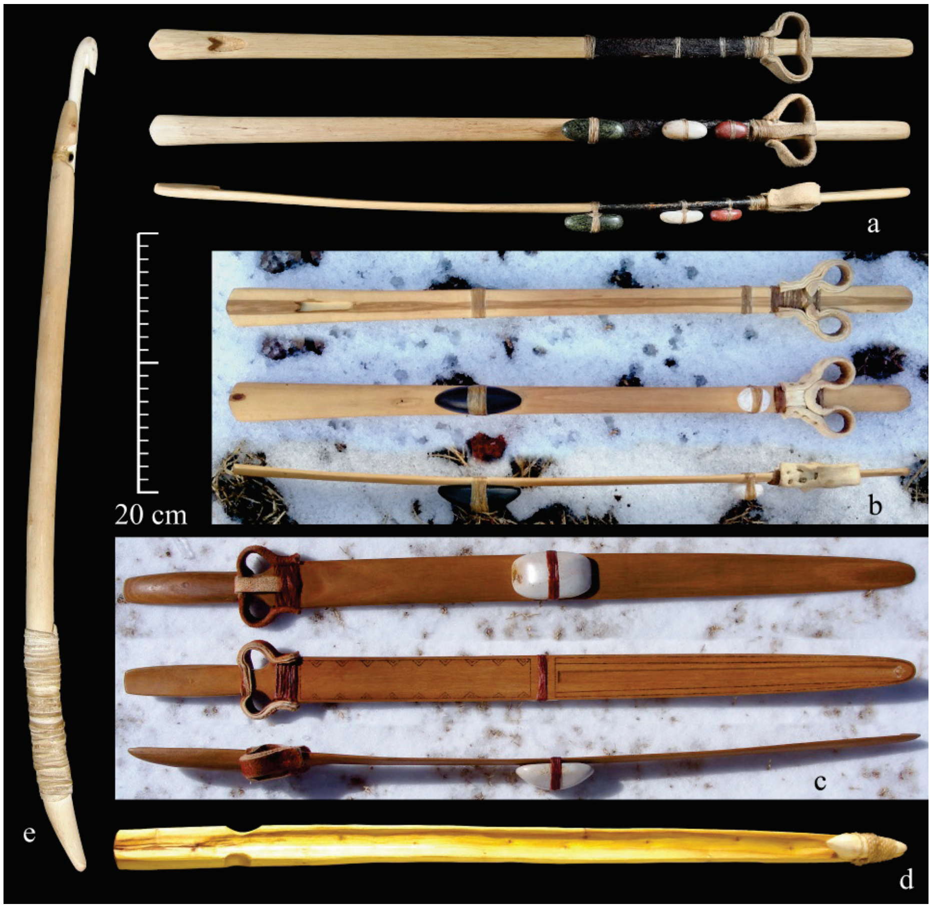

Figure 2. Atlatls used in the carcass experiment; a) White Dog Cave replica [made by the author], b) Broken Roof Cave replica [Justin Garnett], c) Great Basin inspired [the author], d) Clovis atlatl [John Whittaker], e) Magdalenian spearthrower [Pascal Chauvaux].

point types (Hughes 1998; Sahle et al. 2013; Shea 2006; Sisk and Shea 2011; Wilkins et al. 2012). However, due to the variety of point sizes used with various projectiles in this study, points range beyond ethnographic and archaeological samples and merge with TCSA/P plots for spear tips in previous studies (Shea 2006; Sisk and Shea 2011). The TCSA/P values compared with penetration depth also correlate poorly for the same reason, and this may indicate that a degree of caution is necessary when using these measurements.

Figure 3. The author with a reproduction Catawba bow and cane arrow. Photo by Jerry Pettigrew; used with permission.

The results of this project show that when paired with consistent and reliable velocity data from skilled atlatlists (Raymond 1986; Whittaker and Kamp 2007), preserved North American atlatl systems do not meet the suggested momentum or kinetic energy recommended for modern bow hunting of very large animals such as American bison (Tomka 2013); although preserved atlatl and dart components have been found in context with bison remains at Spring Creek Cave in Wyoming (Frison 1965; Pettigrew and Garnett 2014), and small corner-notched points typical of these systems have been found at bison kill sites (Frison 2004; Kornfeld et al. 2010:Figure 4.34). This is even the case when velocities for these systems are calculated at 30 m/s; above our highest recording. Preserved North American atlatls and darts are actually comparable with later ethnographic bows and arrows in kinetic energy and momentum (Tomka 2013). This may reflect a similar focus on small to medium game during the Archaic, as well as tactics to get close to bison, or the use of poisoned foreshafts or specialized weaponry that is less visible in the archaeological record.

While point beveling does not spin a dart in air it can cause rotation through solid media like flesh. Whether this makes a dart more lethal is still unclear. If so, this could function as an addition to the unifacial resharpening theory. Resharpening remains the most likely reason for most beveling since unifacial resharpening saves material (Sollberger 1971) and the archetypes of most beveled points start out with non-beveled edges (e.g. Frison 2014:149; Kay 2012; Morse 1997). Additionally, various hafting arrangements held up better or worse after being shot into the carcass. Corner notched points that are tied in may not have been designed for retrievability, since the experimental points of this type were often lost in the carcass.

1.1 Basics of terminology and function

Atlatl comes from the Nahuatl language and could be a combination of words meaning "to throw" and "water", referring to the weapon's common use in duck hunting on Mexican lakes (Nuttall 1891). *Atlatl* is a common term for the weapon in the literature from North America. Although it is also referred to as *spearthrower*, this is a more common term in Europe. The projectile is commonly referred to as a *dart*, though some (e.g. Callahan 1994) prefer to use *spear*, since one may be tempted to think of the much smaller dartboard darts. However, atlatl darts are typically different than spears, being lighter, flexible and often fletched. This is especially the case considering the small darts from North America. To maintain both consistency and a clear distinction between the weapons, *atlatl* and *dart* are used here, while *spear* refers strictly to the thrusting weapon and *javelins* to spears that are thrown by hand.

Darts have a *spine,* which refers to the shaft's resistance against bending (see Klopsteg 1943). The spine must be tuned to the atlatl and thrower for the proper flex to maintain a straight trajectory. This flexure compensates for the deviations from the trajectory in the rotational motion of the throw (Figure 4) (Cotterell and Kamminga 1989; Cundy 1989:60–69). Previously, it has been common to think of both the atlatl and dart as storing energy in their flexure that adds to the dart's propulsion (Baugh 2003; Cotterell and Kamminga 1989; Cushing 1895; Perkins and

Leininger 1989a, 1989b, 1990), however, the atlatl is not an energy storage device (Pettigrew 2013, 2014b; Whittaker and Maginniss 2006), but functions purely as a lever addition to the human body (Whittaker 2010, 2014).

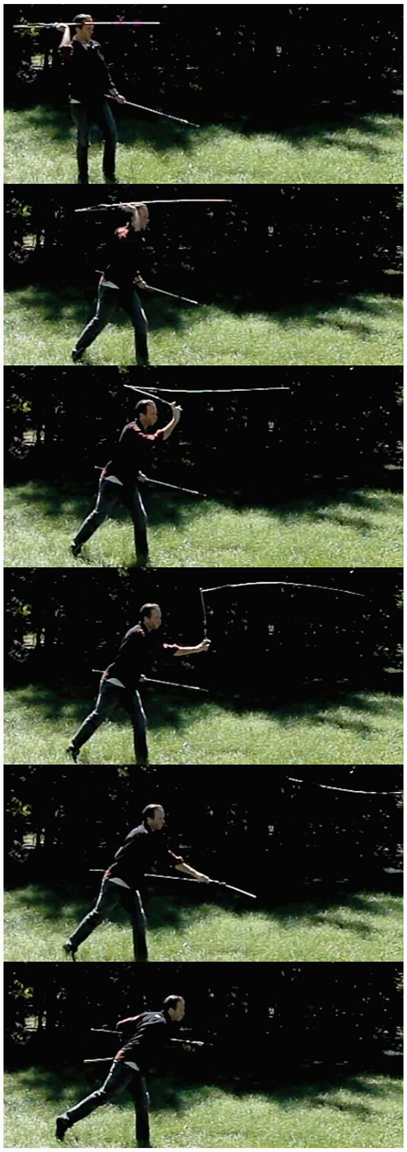

Figure 4. Stills of the author in a full throwing sequence with the White Dog Cave atlatl and dart (Pettigrew 2015:Figure 5).

Velocities reported here may be lower than one would expect. Professional baseball pitchers can throw over 45 m/s (100 mph), but an atlatl requires a different throwing form. The dart must be aimed at the target in ready stance and then cast smoothly towards it (Figure 4, Video 1). Even well-practiced javelin throwers could not immediately adapt to the atlatl (Hutchings and Brüchert 1997). This should not detract from the atlatl's credibility. The weapon is capable of lethal shots even on very large prey, and operates primarily through reducing the skill level necessary to throw accurately and with sufficient power. Onlookers are generally quite impressed with the level of power and distance that can be achieved with an atlatl.

Through slow motion video darts can be seen to oscillate dramatically from transverse wave vibrations traveling back and forth through the shaft as a result of compression from the tail during launch (Figure 5, Video 1). Less commonly, *spine* refers to a shaft's weak side, or the side the shaft prefers to bend toward when compressed (further use of *spine* in this context will be noted). Darts with significant enough spines often spin alternately during oscillation to quickly realign the spine with the new direction of flex. Spinning is not correlated with the plane of oscillation, and can stop or change direction during flight. Some atlatlists' throwing motions can place directional spin, or a "crank-shaft" rotational effect on a dart (Video 1). This appears to result from a push or pull of the tail of the dart—lateral to the line of the trajectory—by the atlatlist in the final moments of the throw. These factors often combine to give darts highly dynamic flight characteristics.

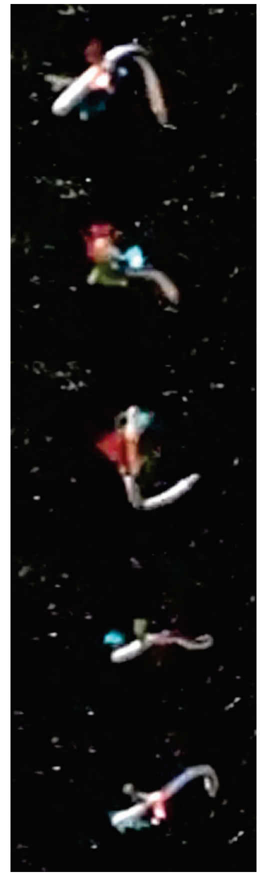

Figure 5. Stills from a video filmed at 300 fps of a White Dog Cave dart in flight. Oscillation is a result of waves traveling back and forth through the dart.

1.2 Calculating ballistics

Kinetic energy (KE) and momentum (P), are calculated from a projectile's mass (m) and velocity (v), and can be used as simple measures of a projectile's ability to penetrate.

$$P = m * v$$

$$KE = \frac{1}{2} m * v^2$$

When English measurements of weight are used such as pounds (lbf), a gravitational constant (32.174 f/s/s or 9.814 m/s/s) must be factored out to convert to a unit of mass (lbm or slug). Mass is an inherent property of an object, while in physics terms weight has an acceleration value due to gravity (G). Unlike pounds, grams are units of mass and are not divided by G before calculating KE and P. Previous literature on arrow ballistics has primarily dealt with English units, such as KE in *foot-pounds* (ft-lbs) and P in the slightly outdated *slug feet per second* (slg-ft/s). For this project, values were initially calculated in International System (SI) units and converted to English ones for comparison with the literature. Projectiles were measured in grams, velocity was taken in meters per second (m/s), KE was calculated in joules (J) and P in kilogram meters per second (kg-m/s). Conversion from J to ft/lbs for KE was automatically calculated in Microsoft Excel, while kg-m/s was multiplied by 0.224859 to get P in slug-ft/s. These conversions are particularly important for comparing atlatl dart P and KE to recommended values for arrows in hunting animals of four different size ranges (Tomka 2013).

Tip cross-sectional area (TCSA) and tip cross-sectional perimeter (TCSP) values were calculated from point max width and max thickness. Equations came from Sisk and Shea (2011) who recommend using TCSP for triangular cross-sectional points. However, their study deals primarily with unifacial points. Experimental points in this study were bifacially worked, so the rhomboidal equation for TCSP was used.

$$TCSA = \frac{Width * Thickness}{2}$$

$$TCSP\ (rhomboid) = 4 * \sqrt{\left(\frac{Width}{2}\right)^2 + \left(\frac{Thickness}{2}\right)^2}$$

The last two important measurements are arrived at through a review of Friis-Hansen's (1990) calculations of the efficiency of a cutting point. The *wound surface area* is the ratio of TCSP and the penetration depth for a particular point and shot, and measures the lethality of a shot into the thoracic cavity of an animal. The *cutting index* represents the point's efficiency in cutting a wound that induces sufficient hemorrhaging, and is calculated by dividing the *perimeter ratio* (TCSP/foreshaft circumference) by the *area ratio* (TCSA/foreshaft cross-sectional area).

1.3 Previous studies

Experimental archaeology is an effective approach to understanding the past. Experiments with close replicas of ancient tools can provide more informed interpretations of those tools, and produce byproducts that are readily found in the archaeological record (Coles 1979; Ferguson 2010). This type of information can give detailed insights into the activities of ancient people. The method for using ancient tools may have varied, so it is important that our experiments are both rigorous and approached with a mindset that is open.

This project further tests a notion formalized by Hill in 1948:

> "It is unfortunate that only light weight atlatls comprised the small number of ancient examples which have been found to date, the sole exceptions being a few short, stout specimens from the Arctic Zone. We can only surmise, therefore, that atlatls and darts for big thick-skinned game were heavier and larger than those which have been found in a preserved state, and which were probably utility types for general use" (Hill 1948:40).

The method to test this hypothesis was inspired by several previous experiments that pitted atlatls and darts against carcasses. Frison (1989) used replica Clovis points mounted on very heavy darts to produce lethal wounds in his seminal experiments on African elephants. From his previous experience reproducing an atlatl he found at Spring Creek Cave (Frison 2004), he understood that very heavy darts would be needed. Callahan's (1994) experiment on an elephant carcass was also informative, although dart weights were not reported and the carcass was not fresh. This experiment did suggest that a shoulder at the mainshaft socket would halt penetration. These experiments were primarily concerned with penetrating ability, and were not so organized as carcass experiments carried out in Europe (Cattelain 1997; Letourneux and Pétillon 2008; Pétillon et al. 2011), which better documented damage to points and bone.

While these experiments took a naturalistic approach, some carcass experiments have taken a controlled approach by using calibrated crossbows as consistent firing mechanisms (e.g. Hunzicker 2008; Knecht 1991; Shea et al. 2001; Wilkins et al. 2012) rather than the original weaponry. In absence of direct insight into the abilities of ancient hunters, the naturalistic approach relies on experimenters who must be skilled in their use (Hutchings and Brüchert 1997; Raymond 1986; Whittaker and Kamp 2007) and able to produce consistent and comparable results. The controlled approach using a non-human firing mechanism, however, also has to assume that certain aspects of energy output and impact are adequate analogies to ancient use (Shea 1997:99; Shea et al. 2001:810). These approaches are often employed for different reasons. The controlled method is useful for constructing samples of points and bone that were damaged from impacts at consistent values of P and KE for comparison with original artifacts. This comes with the sacrifice of realism, since ancient projectiles were not launched under controlled laboratory conditions, but came in various weights and impacted their targets at various angles and velocities (Ashby 2005a). The naturalistic method is most often used to study replicas of the projectile technology itself in the hands of skilled users and under realistic conditions. However, consistency in variables such as velocity and projectile flight to pair with each shot is lost, resulting in less certainty when interpreting patterns of damage.

The calibrated crossbow experiments have primarily focused on more rigid thrusting spears and javelins (but see Hunzicker 2008). Considering the dynamic flight of darts observed in slow motion (Video 1), a crossbow as a mechanism for studying atlatls would not create accurate characteristics of dart flight or impact. This is important for a number of reasons. Darts oscillate dramatically in flight and if the dart is flexed on impact additional shaft drag in the wound channel results, which decreases penetration (Ashby 2005b:4; Hughes 1998).

Additionally, darts were seen to continue to vibrate after impact—more so if the shafts were flexed on impact or struck at a skewed angle. Shaft vibration could result in additional damage to points and bone, and additional effects could occur in the wound channel. These characteristics are important for understanding realistic killing potential. At least one experimenter (Cain 2011) has built a launching machine that mimics the human arm and launches darts with atlatls under controlled conditions. However, an atlatl functions as a lever addition to the entire body, with the legs, torso and arm playing a role (Figure 4) (Cundy 1989; Whittaker 2010, 2014). Therefore, it would be difficult to produce a synthetic throwing mechanism that would reliably mimic the dynamic flight characteristics of darts thrown by humans for naturalistic studies on carcasses.

As in this project, Raymond's (1986) study included both radar measurements and video flimed at 150 frames per second (fps) to examine the throwing motion and calculate velocities using replica Basketmaker atlatls. His recorded velocity of 21 m/s (Raymond 1986:Table 5) is the same as several shots from this experiment with a replica Basketmaker atlatl and darts (Appendix A). Others (Bergman et al. 1988; Hutchings and Brüchert 1997) have used still cameras to record velocity. However, their findings are inconsistent and probably range above realistic values (Whittaker and Kamp 2007). Although calculating velocity using the dart's mass and flight distance when thrown for distance is not recommended due to a lack of consideration for aerodynamic effects (Hutchings and Brüchert 1997:891), the velocity measurements recorded by Hughes (1998:Table 1) using this method for a number of previous experiments are comparable with our own.

Other work has been done with high-speed video cameras to study atlatl function; however, little of it has been reported in a reliable context. Four experimenters previously obtained high-speed cameras and shared their videos on the internet. Most notably Pascal

Chauvaux of Belgium used a Casio EX-F1 to film several European throwers using various setups. These videos were eye opening, and helped me initially to understand the function of the atlatl and dart. Later David Colter of England also obtained a Casio EX-F1 and provided more video, including of himself with a replica White Dog Cave atlatl and dart that I sent him specifically for the occasion. Following their work I obtained the same camera, which is still the highest quality high speed camera available at a reasonable price. John Whittaker used a different camera filming various throwers in 120 frames per second (fps) for his own atlatl studies, and lastly Jim Winn of Nevada obtained a different camera and posted only a few video segments of himself throwing very long darts. The combination of these videos resulted in slow-motion footage that showed consistent, albeit complex, characteristics of atlatl function and dart flight between various throwers.

Still photography used to examine mechanics of the throw may have led to a misunderstanding of the atlatl and dart as a spring-energy storage device. Photos often only capture a few steps in the launching sequence, when the dart first starts flexing down, then up as the wrist engages, and then down again after it has left the spur. This may have assisted the concept of the dart launching off the spur when it straightens out at the end of the throw (Perkins and Leininger 1989b, 1989a, 1990). The vital phase at the very end showing the dart being bent down by the atlatl just before its departure was not made apparent until Whittaker and Maginniss' (2006) experiment using a flexible atlatl and dart in a dark room with a strobe light and long exposure photographs. High speed videos have since added to this argument (Pettigrew 2013, 2014b), and we now know the atlatl functions purely as a lever addition to the thrower's body (Cundy 1989; Whittaker 2010, 2014) and can view the dynamic characteristics of darts in flight.

1.4 Artifacts and replications

Experiments with replications of preserved North American atlatl and dart systems have been carried out by myself (Pettigrew and Garnett 2014, 2015; Pettigrew 2008, 2009, 2012, 2014a, 2015) and by numerous others (Cushing 1895; Garnett 2011a, 2011b; Hill 1948; Howard 1974; Hunter 1992; LaRue 2010; Pepper 1902; Raymond 1986; Spencer 1974; Whittaker 2011). Atlatls and darts provide a good example of the necessity for close attention to detail when replicating artifacts. Bias from the replicator, lack of proper material, lack of familiarity with the technology, or lack of skill in execution can create substantial misinterpretations. Acceptable margins exist in which alternative materials or slight mistakes in construction may not affect functionality, but it often takes experience to know them. The most common mistake is to assume that an atlatl system can be improved upon in one way or another. However, the best insights come from exactitude in replication and forcing oneself to adapt to the characteristics of the original. Although many atlatls are capable of launching a wide range of darts (Hutchings and Brüchert 1997), experience shows that the most accurate interpretations of ancient systems are made when replica atlatls are properly matched with the darts they are intended to launch (Pettigrew and Garnett 2015). For this reason, the most accurate replications are of complete systems where matching atlatls and darts are preserved. Unfortunately this is a rare case in the archaeological record.

White Dog Cave (WDC) in northeastern Arizona (Guernsey and Kidder 1921; Pettigrew and Garnett 2015) is notable for housing two whole atlatls and three whole darts. The darts are short and light. Including a 12 cm foreshaft, they are approximately 152 cm (60 in) in length and 9.7 mm (3/8 in) diameter at the tail to 15 mm (19/32 in) at the socket. Close replications reveal a system that was obviously refined over generations by people who relied on the weapon daily.

The short willow (probably coyote willow [*Salix exigua*]; Justin Garnett, personal communication, 2013) darts fly exceptionally well with low oscillation (Pettigrew 2008), and have also been found to pair well with a replica of the Broken Roof Cave atlatl (Figure 2b) (Garnett 2011a), which was found not far from WDC.

Figure 6. Examples of corner notched points made by John Whittaker for the experiment. These are based on types represented in Basketmaker and other Late Archaic assemblages in Western states.

When complete darts are not present, fragmentary remains (Pettigrew et al. 2015; Pettigrew and Garnett 2014) or aspects of preserved atlatls can still give some indication of the complete system, especially in regards to approximate dart size. On atlatls this is represented principally in effective balance of the atlatl with the dart (e.g. Figure 1), which can indicate approximate mass of the dart (Pettigrew 2012, 2014a). This is especially the case when loose gripping techniques are used, as has been found to work best with the WDC and Broken Roof Cave atlatls (Figure 1). Additionally, many atlatls from North America are simply too slender to be used with heavy darts (Hunter 1992). Based on these observations, the WDC darts have been found to be a good representation of the size and weight of other atlatl systems in North America. These darts constituted the primary test subject in the carcass experiment and were paired with close reproductions of foreshafts from Basketmaker and other western assemblages (e.g. Cosgrove 1947:Figure 70; Guernsey and

Kidder 1921:Plate 34; Frison 2004:Figure 54d), that are composed of small corner notched points (Figure 6) lashed into square notches with sinew (Figure 7).

In addition to the WDC equipment, the design and diameters of foreshafts from Ozark bluffs also influenced the projectile kit for the carcass experiment. Several foreshafts [two in particular (Harrington 1924:Plate 2b; Henning 1966:Figure 9e)] have long socket tangs suggesting they were made for hollow river cane (*Arundinaria gigantea*) dart shafts. The diameters of these foreshafts [both reported as 0.5 inches (Harrington 1960; Shippee 1966:23)] could be used to give some indication of mainshaft distal diameter. However, differences in millimeters can make a difference in dart spine and weight, and these specimens should be measured more accurately. More foreshafts from Ozark bluffs (Pettigrew 2015) are slightly smaller diameter and pair well with light weight cane darts. Two cane darts were used in the experiment that were based on these foreshafts and weighed slightly more than the WDC darts. In addition to the influence of

Figure 7. Examples of foreshafts fitted into experimental WDC darts; a-b,) dart 1, exhibiting a shoulder at the socket, c) dart 2, exhibiting a tapered socket; a) point # 87, b) point #36, c) point #90.

foreshaft size, some of the Ozark foreshafts retain points hafted with bark, and points were also found with bark hafting remnants around their bases (Pettigrew 2015). Some foreshafts used in the experiment were also made to represent these artifacts (e.g. Figure 8).

Figure 8. Experimental point # 70 was hafted into a split notch with bark lashings. Left) views of both faces and one side of the foreshaft before use. Bottom right) views of both faces of the point and two views of the foreshaft notch after the carcass experiment. Upper right) the result of a shot (# 48) into the carcass—the strand of bark coming out of the wound channel is still attached to the point. The bark remaining around the foreshaft and base of the point after removal from the carcass during butchering is comparable with artifacts excavated from Ozark Bluffs.

2. Methods

2.1 Target media: Perma-gel and carcasses

Perma-gel (http://www.perma-gel.com/) is a medium similar to ballistics gel, but that can be reformed when heated and reused. Both of these gels were developed to test modern firearms. Perma-gel was chosen for its consistency and reusability to test penetration of various dart weights fitted with consistent tips and thrown with the same atlatl. Foreshafts were composed of 0.5 inch diameter oak dowels tipped with 160 grain metal archery field points. These foreshafts were 35 cm long and mounted to four dart mainshafts of various material, length and weight. Because it is highly resistive, Perma-gel proved to be a poor analogy to a body for low velocity piercing projectiles. The darts exhibited very shallow penetration, with high speed video from the side showing darts bouncing back approximately half the length of the actual depth (Figure 9). Sharp metal broadheads were also tried with the same shallow penetration. A few shots were tried with cane arrows from the Catawba bow, which had comparable penetration to the heavy dart, around 10 cm, but these also had lower diameter trailing shafts of 0.375 inches. In short these projectiles were not so dissimilar from ones that would later penetrate deeply into the hog carcass to warrant such shallow penetration. Perma-gel is a consistent medium, however, and the results clearly reflect dart weight (Table 1).

Table 1. Penetration results of shots into Perma-gel using three darts of variable mass but fitted with consistent tips.

	Mean (cm)	**Min**	**Max**	**S. Dev.**	***n*.**
WDC (92 g)	6.7	6.4	7.3	0.2	19
Cane (117 g)	7.5	6.5	8.3	0.5	18
Heavy ash (244 g)	10.4	8.9	11.3	0.5	18

Aside from a live body, a carcass must be fresh to provide the best evaluation of a projectile's true lethality (Ashby 2005a:17). A fresh carcass was needed for the experiment, with initial throws occurring as soon after the animal's death as possible. Therefore, easy access to the animal was necessary, and it would need to be in a location close to a suitable place to carry out the experiment. The most obvious choice was a domestic or semi-domestic animal, however, obtaining one with little funding was not easy. Barney Barhenfus, an organic hog farmer in Iowa, sold an approximately 100 kg (220 lb) male Berkshire hog at a reasonable price. He also put the animal down humanely, and transported the carcass with a tractor to a suitable location on his property for the experiment to be carried out. To coincide with Tomka's (2013) study, this hog fell in the range of medium to large prey.

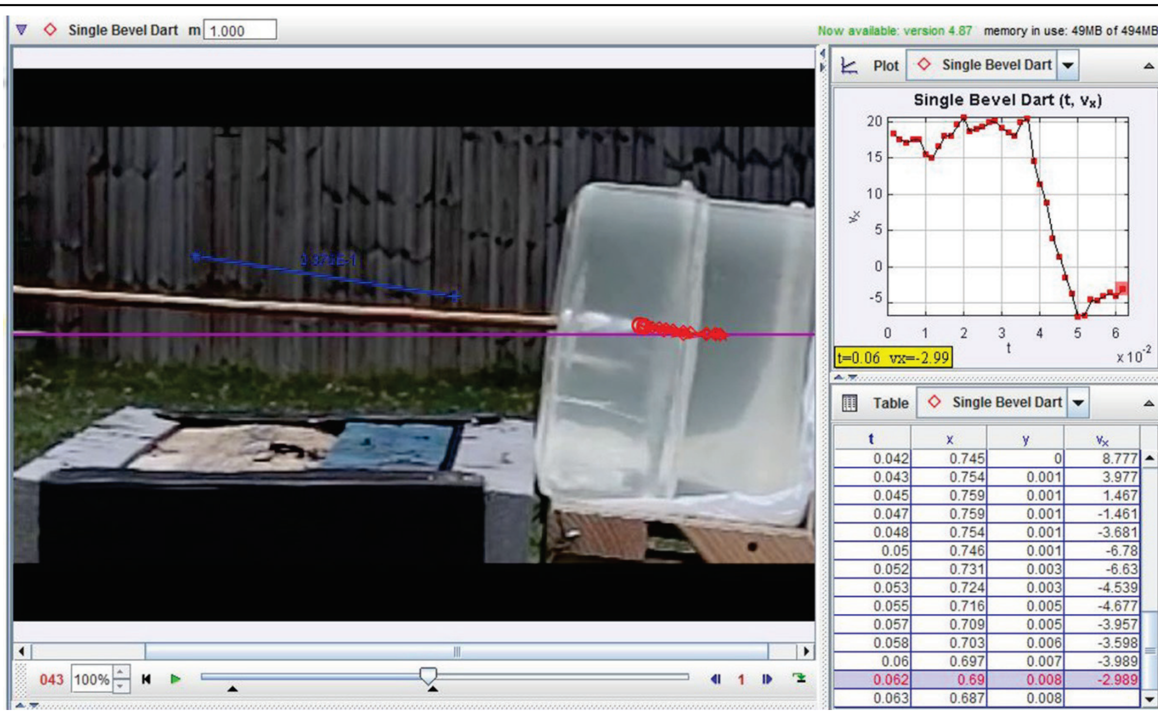

Figure 9. A screen clipping from Tracker showing the shallow penetration of a dart into Perma-gel. Red points in front of the dart indicate the distance of rebound.

2.2 Slow-motion video analysis

Two high speed digital cameras were used for the experiment; a Casio EX-F1 and a Casio EX-ZR1000. Both are fairly affordable cameras that do not film in quality comparable to much more expensive “commercial” high-speed cameras. However, with sufficient light the EX-F1 films clear pictures in 512 X 384 pixel resolution at 300 fps, and 432 X 192 pixels at 600 fps, and was successfully used throughout the project to study many aspects of dart flight and impact. The ZR-1000 is a smaller camera with lower film resolution at high speeds, however, filming at 240 fps with 512 X 384 pixel resolution was judged high enough quality to function as the velocity camera for the carcass experiment. On the day of the experiment we welcomed a clear sky and bright sun to offer the best conditions for the video. The EX-F1 produces the best slow motion video with fast shutter speed to obtain the sharpest image per frame, and high aperture values to let in the most light, even though with high aperture comes less depth to the field of focus. Additionally, better video typically results from the shutter speed set slightly higher than the recommended value in the camera’s view finder, producing a darker image but with a clearer view of the dart, which has a tendency to be bright in contrast to the background.

All mainshafts were marked with two opposing stripes in black electrical tape and fletches of three different colors to study flight and impact in slow motion (Figure 10). The tape gave strong contrast and was found to be easier to apply and alter than paint. Whippings of artificial sinew helped hold the tape in place. An attempt was made on all shafts to place one black stripe and the red fletch on the outer side of the dart’s spine (the weak side on which the shaft prefers to bend). The spine can affect dart flight characteristics by causing the shaft to spin alternately during oscillation, or to rotate while flexed on that side in the case of a rotational emphasis from the thrower. Marking the spine can therefore be useful in understanding flight characteristics. A bright red mark was also placed at the socket end of each dart to the right of the black stripe marking the spine. The foreshafts were matched to this mark (Figure 7), allowing for observation of the projectile point's orientation on impact.

The Tracker program was found to work best with a highly visible object moving across a solid background with good contrast and film resolution. The program uses a scale placed in the video and the camera's film speed to provide velocity and other data for points tracked across the screen. I discovered that slight changes in the measurement could change the calculated velocity fairly dramatically, and the best location for the scale is on the projectile itself. A 20 cm marking in red tape was placed on each shaft 50 cm back from the socket where it would be visible after the dart struck the carcass and slowed enough to provide a clear picture for an accurate measurement (Figures 10 and 11). A white sheet was placed on the opposite side of the carcass from the velocity camera for a clear view of the projectile passing in front of it. The tip of the dark projectile point was tracked across this backdrop.

Figure 10. Dart shafts were marked with tri-colored fletches, stripes, and a 20 cm scale for video analysis. Shown here is shot # 64, which hit high and penetrated through the back.

Prior to the carcass experiment, the Tracker program was also used to measure the displacement of the tip of an oscillating dart in flight (Pettigrew et al. 2015), which for the particular system studied was around 6 cm. This effect was discovered after a large margin of error in velocity when tracking the tail of the dart was noticed to follow a pattern that corresponded with the oscillation. Displacement at the tail of the same setup was 15 cm. Three measurements taken at the tail, center of gravity (the central balance point, see Cundy 1989), and tip of the same dart found the tip to be the most stable and consistent for velocity measurements.

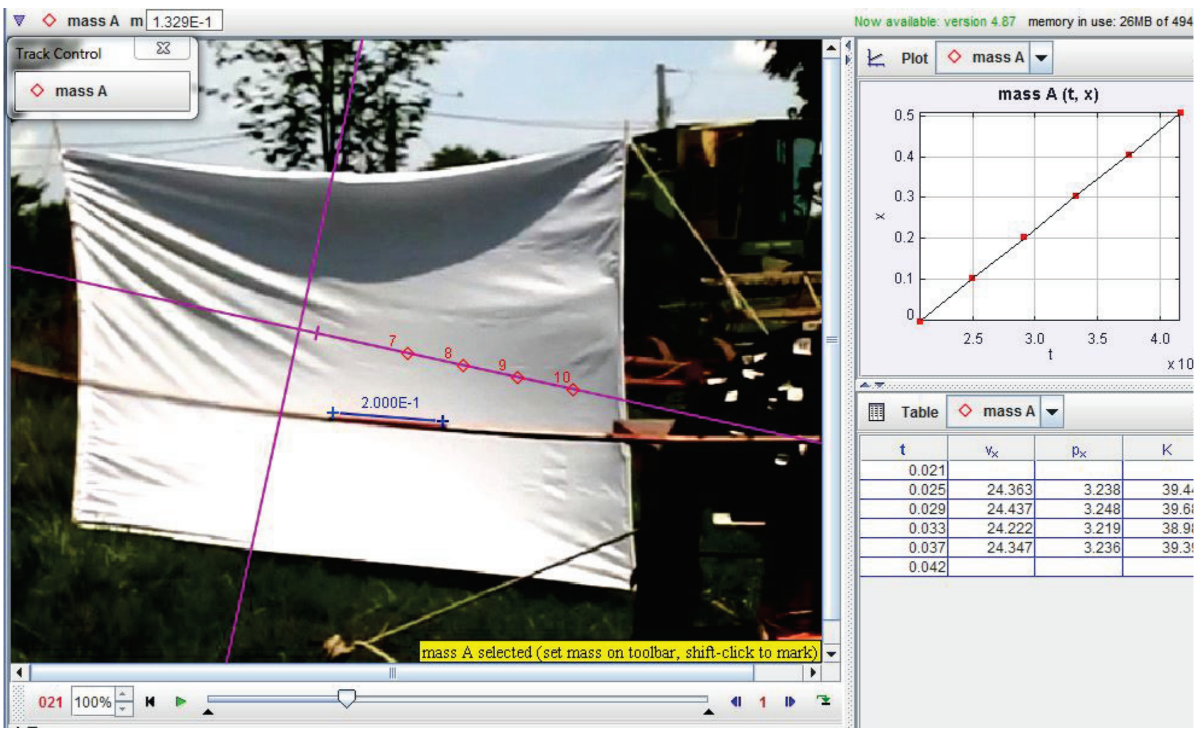

Figure 11. A screen clipping from the Tracker program during analysis of a video from the velocity camera. The 20 cm scales on the dart shafts were used to scale the videos after the dart struck the carcass and slowed enough for the scale to be visible.

The method of using slow motion footage to analyze flight and impact characteristics allowed for a detailed look back at the results of each shot. This is especially effective concerning damage to bone and stone points, since aspects of the dart's angle, the point's orientation and the exact placement of the shot can be seen in detail. Other aspects of the dart's flight and impact, such as shaft vibrations and the result of a pronounced shoulder at the socket joint are also visible, as well as vibrations in the carcass from impact. Additionally, slow motion footage paired with the Tracker program is an effective tool for understanding atlatl and dart function in general, and one that is available to most researchers since the Tracker program can be downloaded for free (although the best results were obtained using the EX-F1, which was purchased used on eBay for about $800). These methods are encouraging for future studies of ancient projectile technologies.

2.3 Velocity measurements

A proper discussion of the killing potential of various dart weights hinges on accurate measurements of dart velocity. The EX-F1 was paired with the Tracker program and used to measure the velocities from eight different atlatlists, many of whom were well practiced with the atlatl and have been throwing for several years. These trials were carried out to measure the velocities of throws at both the atlatlist's typical power when shooting for accuracy, and as hard as he/she could throw while still maintaining control (Table 2). Measurements were taken for a span of approximately 3 m and began as soon as the dart left the atlatl in those tests. A Bushnell "Velocity" hand-held radar gun used in a previous study to measure dart velocity (Whittaker and Kamp 2007) was added to the carcass experiment to provide cross-comparable data and as a backup if the velocity camera faltered. The velocity camera was found to be more reliable than radar in this experiment, since the radar does not always capture a reading; however, the radar readings were more consistent, and this was due to the lower resolution of the EX-ZR1000 (discussed further in section 4.1).

Table 2. Typical and hard throws from several atlatlists. An asterix indicates a mean of velocities taken from the carcass experiment. Whittaker's velocity was taken with a heavy cane dart and is lower than his average (see Whittaker and Kamp 2007).

Atlatlist	Average Throw		Hard Throw	
	m/s	mph	m/s	mph
Justin Garnett	22.6*	51*		
Pat Hashman	26.1*	58*		
Chris Henry	24.6	55	25.8	58
Bob Kitch	23.8	53	24.3	54
Gina Lunn	16.7	37	17	38
Jesse Martin	23.8	53	26.2	59
Michael Hermann	22.7	51	24.7	55
Devin Pettigrew	22.3	50	28.7	64
Unknown	24.6	55	28	63
John Whittaker	21*	47*		

2.4 Carcass experiment protocol

The hog carcass was bled at the suggestion of the other experimenters who warned of foul results in the meat otherwise, and cleaned with a scrub brush and hose. Mr. Barhenfus then transported it to a trestle composed of a heavy board lain over two sawhorses. Ropes were attached to the legs and staked out to keep the heavy carcass on the trestle, and a board was propped against the side opposite the thrower for added support (Figure 12). The initial throw was made by Garnett soon after. The experiment took the span of an entire day to setup, run, butcher the carcass and package the meat.

The organization of the experiment is shown in Figure 12. The throwing line was set at 12 m, which past experience by us and others (Cattelain 1997) has shown to be a reliable distance for accurate atlatl shots. We made most throws from this distance with the exception of six shots at the end when the distance was reduced in an attempt to hit the scapula with a beveled point. Each shot was filmed with the two high speed cameras; the EX-F1 filming the impact of the dart at 300 fps and the ZR-1000 filming from the side close to the carcass at 240 fps for velocity on impact.

Sixty-six shots were made, 42 of which were good impacts to the carcass. The shot order (Appendix A) was designed to address the primary questions in order of importance; 1) the killing potential of the various dart weight classes, with the small Late Archaic darts under particular scrutiny, and 2) the effects of point beveling. The initial set of throws was made with the replica Basketmaker gear while the carcass was freshest. Following sets tested beveled points attached to cane darts, heavier darts, assorted foreshafts and arrows.

Figure 12. The setup of the experiment showing the method used to support the hog carcass.

Several variables were recorded for each shot on a shot record form (Appendix B) to include penetration depth, impact location, point damage and the impacted medium that caused it. The shot marking technique utilized small numbered flags of masking tape attached to bamboo skewers that could be trimmed to match the approximate penetration depth and inserted into the wound channel (Figure 13). The intention was to track each shot to effects in bone and flesh that would be visible during butchering and after cleaning the bones.

Figure 13. Shot markers made of bamboo skewers and tape flags were effective for tracing the results of particular shots during butchering.

The projectile gear was thoroughly photographed prior to the experiment. In addition, photographs were taken during the experiment of the carcass after each successful shot, of the projectile point if damage occurred, and of the experiment in general. The experiment setup required no less than four participants: job 1 - thrower, job 2 - photographer and radar gun operator, job 3 - shot recorder and flight camera operator, and job 4 - velocity camera operator, who also measured penetration depth and inserted shot markers. All four experimenters were familiar with the atlatl and could switch between jobs as needed, so that four different experimenters made throws into the carcass. I hoped this would solve the problem of bias in the results toward an individual thrower. However, atlatlists become accustomed to particular atlatl systems and quickly switching between systems and making effective shots can be challenging, especially during the pressure and narrow time frame of an experiment. All successful throws with the WDC darts were thus made by Garnett, while I made the majority of throws using the cane darts, and Whittaker and Hashman took on jobs 2 and 4 respectively and were content to make one successful throw apiece.

2.5 Experimental projectile kit

2.5.1 Atlatls

Variations in an atlatl's design when paired with the parameters of the dart and body of the thrower are important variables when considering atlatl function, but that was not the focus of this project. Rather the focus rested on the dart's velocity on impact and its depth of penetration. The atlatls themselves only needed to operate comfortably for at least one thrower and be effective with at least one dart type. Five atlatls (Figure 2) were used in the experiment, two of which were close replicas of Basketmaker atlatls from northeastern Arizona (Figure 2a, b) and were used exclusively with darts based on those found at WDC. The other atlatls were custom made and based on general styles, and matched with darts based on the experimenters' knowledge of effective operational parameters in atlatl gear—the result of each experimenter using the atlatl for several years.

2.5.2 Dart mainshafts

Eight dart mainshafts were prepared for the experiment to represent three different classes of mass ranging from 74 to 182 g (Table 3). The three additional darts comprised two backup WDC and cane shafts, and an additional Basketmaker mainshaft with a variation in the socket area. These socket variations were designed to test the hard shoulder that is represented on some Basketmaker darts between the socket edge and a foreshaft of lesser diameter (Dart 1; Figure 7a, b), while others have slightly tapered sockets (Dart 2; Figure 7c) (Chuck Larue, personal communication, 2014). The light willow (*Salix exigua*) WDC darts, and the light and mid-weight cane (*Arundinaria gigantea*) darts were designed to represent the known weights represented in the archaeological record in North America, while a heavier cane mainshaft and a green ash (*Fraxinus pennsylvanica*) shoot mainshaft were intended to provide a comparison with heavier weights that were probably present in North America for hunting large animals. Modern glue and artificial sinew whippings were used to support sockets and attach fletchings on all mainshafts. Coatings of Titebond III wood glue reduces fraying of artificial sinew, and was used to coat all whippings. These materials do not appear to alter the functionality of a dart shaft compared to ancient methods, but they are typically more resilient.

Table 3. Primary parameters of mainshafts used in the experiment. *Total Mass* is mean mass of the complete projectiles including foreshafts.

Category	**Shaft** #	**Type**	**Material**	**Prox. Diam.** mm	**Dist. Diam.** mm	**Length** cm	**Mass** g	**Total Mass** g
Light (WDC)	1	shouldered socket	willow	8.8	13.7	140	74.2	88
	2	tapered socket	willow	8.9	13.7	140	74.3	88
Medium	4		cane	8.4	12.6	157.1	76.7	108
	5		cane	8.6	13.8	175	93.8	133
Heavy	7		cane	10.2	15.9	196	150.1	200
	3		ash	11.1	14.2	188.2	181.5	225
Arrows	A1	arrow	cane	7.1	7.9	75	21	27
	A2	arrow	cane	6.95	9.3	75.3	20.9	33

2.5.3 Foreshafts

A total of 93 stone points were obtained in preparation for the experiment and 90 were hafted to foreshafts, 29 of which made it into the experiment. The points were dyed with methyl violet so that flaking from impact would be visible. They were then hafted using four methods: 1) binding in a square notch with sinew, 2) gluing into a square notch with pine pitch and providing a supportive sinew wrapping, 3) binding into a split notch with bark, and 4) gluing into a sawn notch with modern adhesives and artificial sinew.

Several corner notched points were bound into square notches with sinew in reproduction of hafting methods represented with Basketmaker type equipment from the West. The majority were sharp, thin points made by John Whittaker (Figures 6 and 7), and were good representations of corner notched points used with Basketmaker and other Late Archaic systems. The technique for creating the square notch has been well illustrated by the discovery of foreshafts in various stages of production (Cosgrove 1947:Figure 70; Frison 1965). This technique involves two pairs of cuts at opposing ends of the proposed notch. Following each upper cut the wood is bent until an inner split occurs. The lower pair of cuts then weakens the wood in between these splits so it can be broken out, forming a square notch and a discarded tenon. This proved an effective method for the swift production of foreshaft blanks in willow (*Salix sp.*), chokecherry (*Prunus virginiana*) and green oak (*Quercus sp.*).

Slightly side-notched or stemmed experimental points were glued into square notches with pitch mastic and given a supportive wrapping of sinew. Some corner notched points were wedged into a split in the foreshaft and bound in with the inner bark of elm (*Ulmus sp.*) following the method represented in foreshafts and points with binding remnants from the Ozarks (Figure 8). This produces a haft that stands up well to head-on pressure but offers little resistance to lateral or reverse pressure. The best method is to whittle down the sides of the foreshaft and start the split with a thin blade, then soak the foreshaft in water before making some initial wraps with the bark, shoving the point into the split and binding around its base.

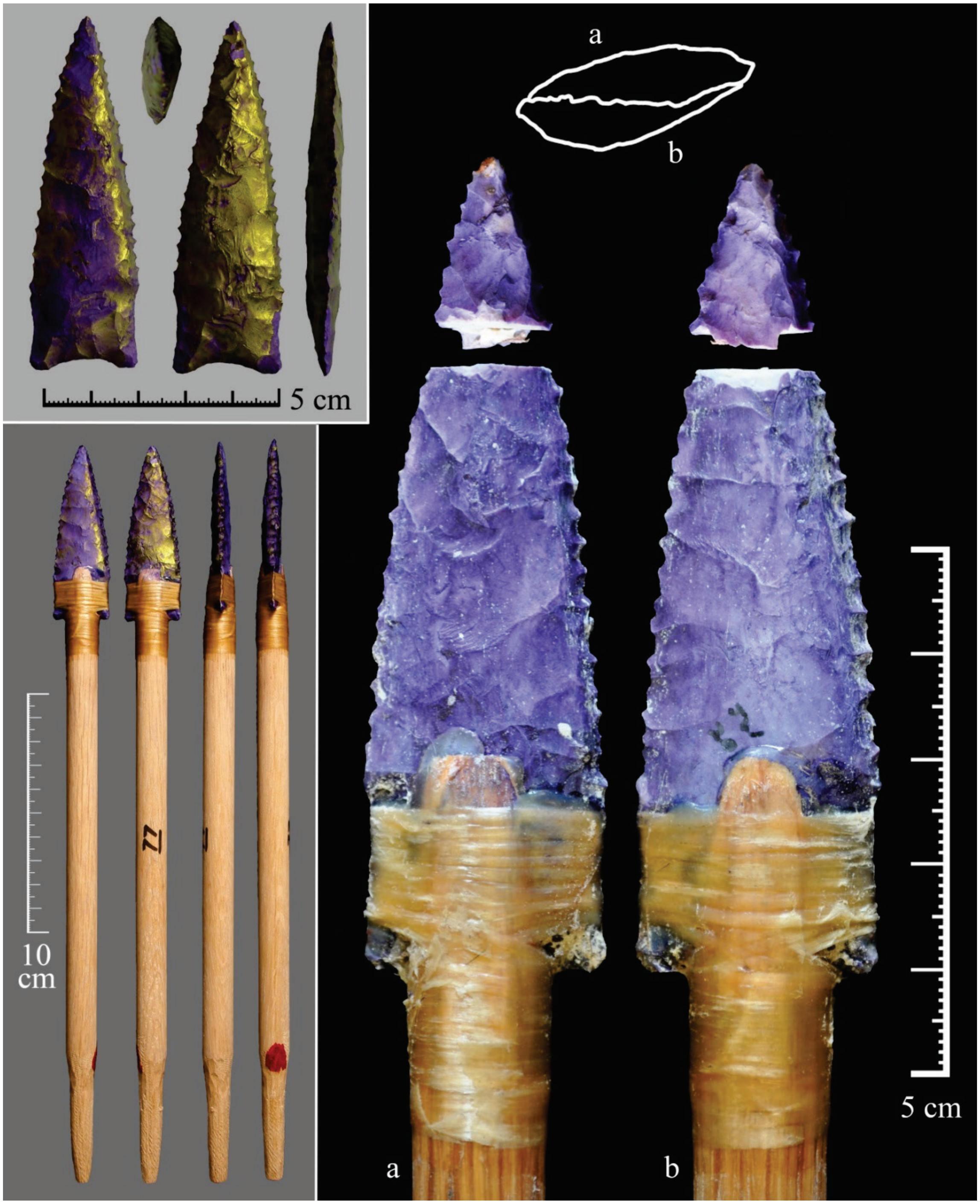

Figure 14. Experimental point # 77, a beveled point mounted to a 1/2 inch diameter oak dowel using modern adhesive and artificial sinew. Upper left) four views of the point prior to hafting, including one view looking down the beveled point from the tip. Lower left) four views of the complete foreshaft prior to the carcass experiment. Right) views of both faces of the point after the experiment. The tip snap occurred after impacting rib # 6 (Figure 21b). The point's orientation on impact is shown at top right.

Wet wood is more pliable and can mold around the base of the point, however, green wood shrinks as it dries and the binding will loosen. This does not seem to occur as much with dried and resoaked wood.

Figure 15. An experimental beveled point fitted into the socket of a cane dart.

Gluing points into sawn notches in oak dowels with hot melt glue and making supportive whippings with artificial sinew represents the fourth hafting method. As with the mainshafts, the whippings were then covered with two coats of Titebond III wood glue to produce a strong and smooth haft (Figures 14 and 15). This method was used on nine beveled points for reliability in multiple throws, since the idea of the bevel experiment was to test the effects of point beveling in a carcass, and not the effectiveness of a traditional hafting technique.

Two different techniques of socketing foreshafts into mainshafts were used. The long socket tangs on foreshafts in the Ozark assemblage (Figure 8) have a taper at the top for insertion into a naturally hollow cane mainshaft that is reamed out at the socket (Pettigrew 2015). This reaming thins the socket to allow give so that with a supportive wrapping, the foreshaft can be wedged tightly into the socket. The taper above the socket tang also produces a stronger foreshaft than one with a sharp 90 degree shoulder, which in mine and another's experience (Frison 1989:770) causes the tang to break off regularly and leave an annoying plug in the socket. The other socketing technique is represented in Basketmaker equipment and involves drilling an approximately 1 inch deep socket in the willow mainshaft with a stone drill. The forehaft is inserted only a short distance, but holds more firmly when the socket tang is roughened in a spiral fashion and also wetted with saliva before inserting with a twist (Frison 1989:770; LaRue 2010:20). This method can produce a reliable fit for a few throws, but loosens fairly easily. It's tricky to make consistent sockets between dart mainshafts so that foreshafts can be easily interchanged, especially when drilling sockets into wood, so each foreshaft was assigned to a specific dart and adapted to fit. Once a straight fit was found a red mark was placed on the foreshafts in line with the red mark on the socket of the dart (Figures 7 and 15).

2.5.4 Archery equipment

In addition to the atlatl equipment, a black locust (*Robinia pseudoacacia*) bow made by the author that is closely based on two Catawba bows (Allely and Hamm 1999:80) was included in the experimental arsenal (Figure 3). This bow has been used to successfully harvest two white tailed deer, and sends a 28 g river cane arrow at about 45 m/s (100 mph). Two river cane arrows (Table 2) were made with a spiral two feather fletching represented in some traditional archery kits from eastern North America (e.g. Allely and Hamm 1999:20, 84). Nine of the 92 projectile points were assigned to arrows, and four were used in the experiment. Of these four, three were at the upper end of arrow point size and designed to add more samples for future microwear studies of the transition from atlatl to bow (Figure 16).

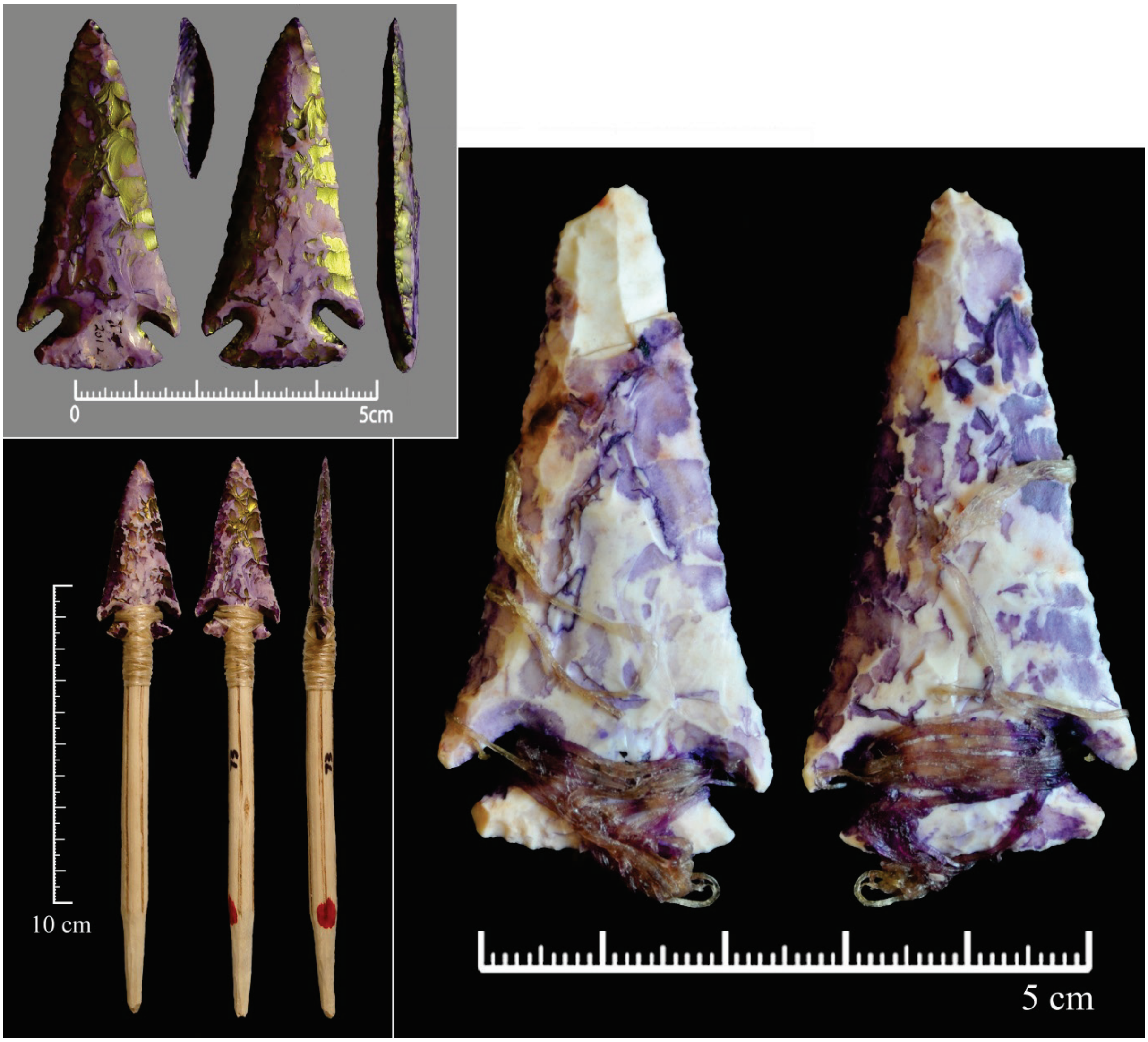

Figure 16. A large arrow point (#73) that received tip damage after contacting the spinous process of a thoracic vertebra (Figure 25) (shot #55). Upper right) four views of the point prior to hafting. Lower right) three views of the complete foreshaft prior to the carcass experiment. Right) views of both faces of the point after the carcass experiment.

3. Results

3.1 Killing Potential of various atlatl systems

This project and a previous trial with the same radar gun (Whittaker and Kamp 2007) recorded dart velocities ranging between 18 m/s (40 mph) and 28 m/s (63 mph). These values are consistent with two previous studies (Hughes 1998; Raymond 1986). Unsurprisingly the results of the initial velocity tests show an increase in velocity with harder throws (Table 1). However, the difference between an atlatlist's typical and harder throw may not be significant, and reliable velocities have yet to be taken above 28.7 m/s (64 mph), even from skilled and powerful throwers. This highest velocity of 28.7 m/s resulted from throws that were as hard as the author could manage with the WDC system. These velocity ranges are informative when paired with the weights of ancient systems. In Tables 4 and 5 a comparison is provided between the killing potential of darts of various mass and velocities, and recommended KE and P for bow hunters to hunt game of various sizes. To make a proper comparison it is necessary to look at both KE and P simultaneously. For instance, darts that have similar killing potential to a certain class of arrows typically carry lower KE but higher P, since they are moving slower than arrows but are much higher in mass. Therefore an undefined value in between KE and P actually provides the comparison.

When throwing for accuracy with the WDC darts, our typical velocities are around 21 m/s (47 mph), which results in killing potential adequate for hunting small to medium sized game. Even when the velocity of a WDC dart is artificially "boosted" to 30 m/s, just above our highest yet recorded velocity, it still does not meet the requirements for killing very large game, but is adequate for medium to large game. Rather, an easier way to raise the KE and P of an atlatl dart for hunting very large game is to increase its mass.

Table 4. The kinetic energy (KE) and momentum (P) of experimental darts and arrows at average and boosted velocity (V). All are from this study (Table 2), except Frison's elephant dart (Frison 1989). Mass includes foreshafts.

Classes of Projectile weight and V	**Mass** (g)	***V*** (m/s)	***KE*** (j)	***P*** (kg-m/s)	***V*** (mph)	***P*** (slg-ft/s)	***KE*** (ft-lbs)
WDC (boosted V)	90	30	41	2.7	67	0.61	30
WDC (higher V)	90	25	28	2.3	56	0.51	21
WDC (average)	90	21	20	1.9	47	0.42	15
Cane Dart (average)	112	25	35	2.8	56	0.63	26
Frison's heavy elephant dart	465	20	93	9.3	44.7	2.09	69
Cane arrow from Cat Bow	34	45	34	1.5	100.6	0.34	25

Table 5. Recommended kinetic energy (*KE*) and momentum (*P*) for modern bow hunters in hunting animals of four different size ranges (Tomka 2013:Table 4). Reproduced by permission of the Society for American Archaeology from *American Antiquity* 78(3) 2015.

Game Size	***Prey Size***	***Prey Species***	***P*** (slg-ft/s)	***KE*** (ft-lbs)
Small	Weigh less than 20.5 kg; thin skinned, weak ribs;	Rabbit, Steenbok, Groundhog, Turkey, Duiker	<.24	<25
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	.24-.38	25-41
Large	Weigh 73-300 kg; often in excess of 100 kg; moderate skin/rib thickness	Wildebeest, Greater Kudu, Hartebeest, Gemsbok, Black Bear, Caribou	.39-.58	42-65
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	.59+	>65

It should be noted that all point/foreshaft combinations used in the experiment met the qualifications for fair to excellent points in the cutting index established by Friis-Hansen (1990); 1.5 to 1.9 being "fair", and over 2 being "excellent" (Appendix A). Other aspects of the projectiles could have affected penetrating ability, including the aerodynamic profile of the point (Ashby 2005a; Hughes 1998) and of the haft (Howard 1995). Unfortunately the girth of the hog carcass was not measured prior to the experiment, but its girth is estimated at 35 cm based on a photo taken looking down the length of the carcass and including a scaled dart shaft protruding from the back (Figure 10). No shot punched entirely through the center of the carcass, though shot #24 with a cane dart penetrated 32.4 cm and probably put a nick in the interior of the opposite rib cage (Figure 17). A thick layer of fat and skin added to the hog's girth, and this should be considered when interpreting penetration depth.

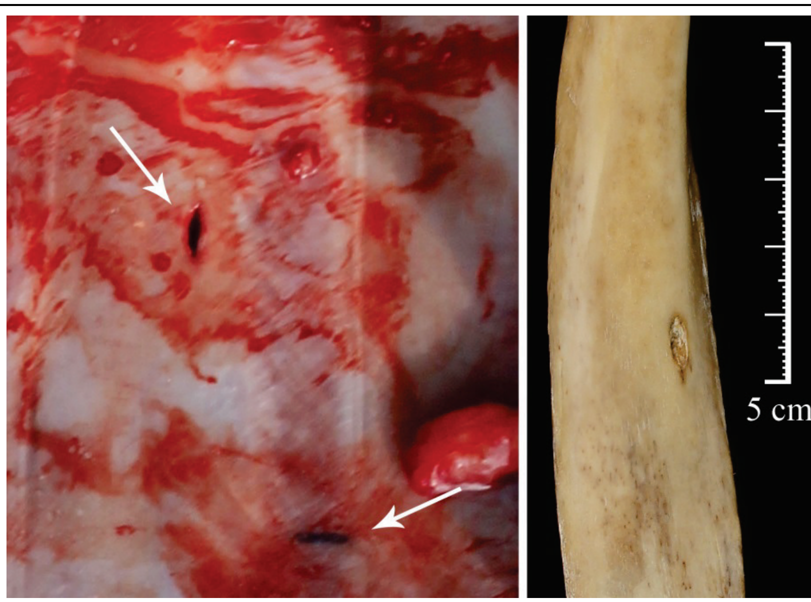

Figure 17. Some shots went through the chest cavity and put nicks in the opposite rib cage, however, no shots punched entirely through the middle of the carcass.

The wound surface area of a shot can be used as a base line for determining lethality. Since the hog in this experiment is similar to reindeer and red deer in the depth of the thoracic cavity (30 and 35 cm respectively), a wound surface area of 75 cm^2 into the thoracic cavity (Friis-Hansen 1990:Table 1) can be used as an estimate for a lethal shot on the hog (Appendix A).

Due to the variation in shot placement, point profiles, and the variable resistance that points met in bone, muscle and skin, penetration results cannot be expected to be consistent. However, two graphs (Figures 18 and 19) compare the results of projectile masses and their KE and P values to penetration depth. Three groups were plotted representing the three different weight classes. Despite low R-squared values for the light and mid-weight cane groups a correlation between higher KE and P and deeper penetration is definitely visible. The mid-weight cane darts are effective projectiles that averaged deeper penetration than the lighter WDC darts, while the heaviest class averaged lower penetration than expected for reasons that will be discussed. In short, the experimenters were more familiar with both the cane and WDC darts than with the heavy darts, and fewer shots were taken with the heavy darts due to time constraints.

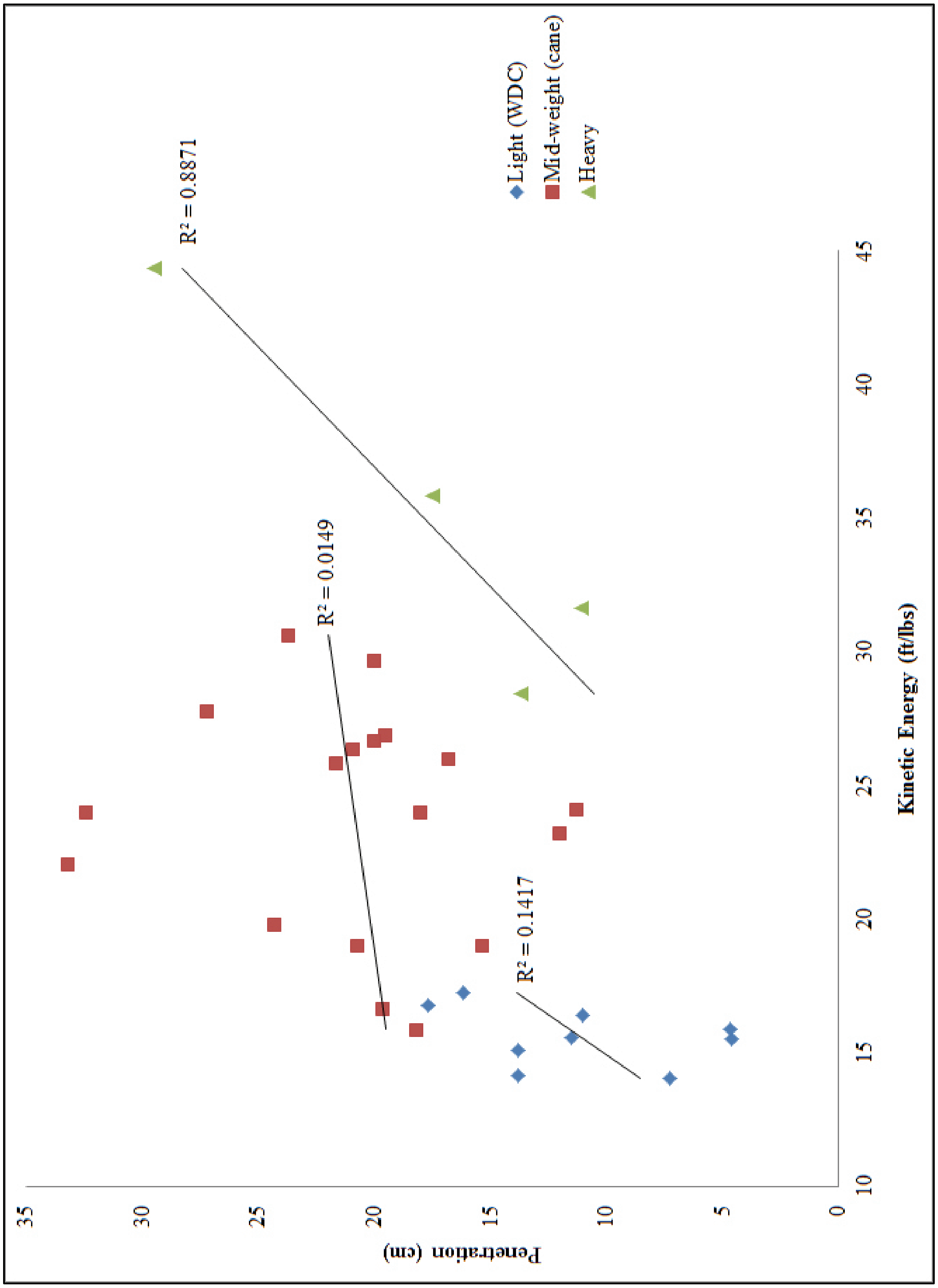

Figure 18. Kinetic energy and penetration of shots into the carcass grouped by dart weight class. The second highest penetration recorded for the mid-weight (cane) class is attributed to a shot that hit high and came out the other side of the upper back (shot # 64, Figure 10), but the highest penetration struck the center of the carcass (shot # 24).

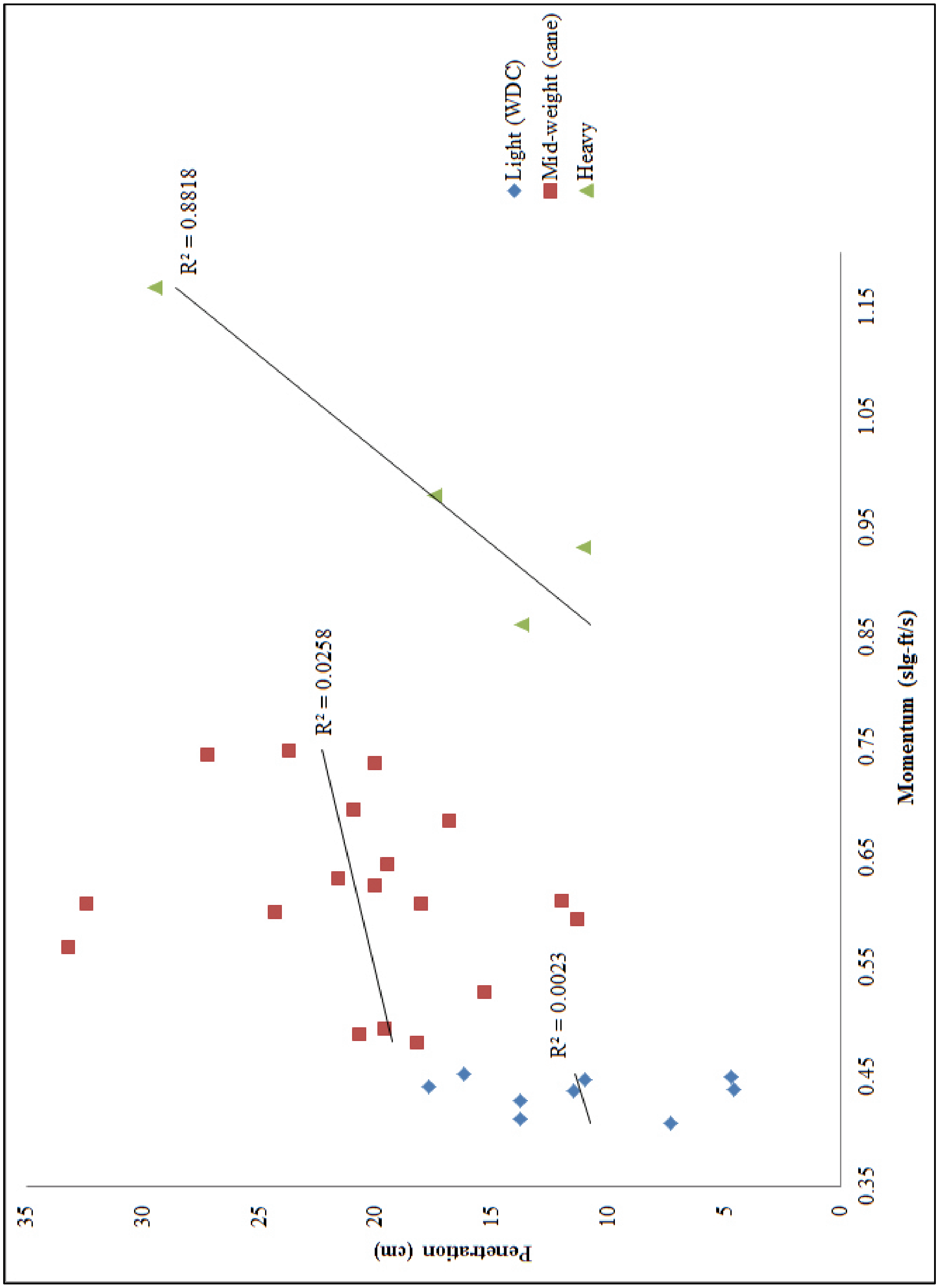

Figure 19. Momentum and penetration of shots into the carcass grouped by dart weight class.

3.1.1 Basketmaker (WDC)

The average penetration depth was 12 cm for 10 hits to the carcass with the WDC darts. Two shots (#s 4 and 7) struck the thoracic cavity and would probably have killed the hog fairly quickly. Other shots may have been lethal eventually but struck behind the thoracic cavity or had shallow penetration. One shot (#5) included a replica of a foreshaft found at Spring Creek Cave in Wyoming (Figure 20) (Frison 1965:fig. 7c) with a very sharp point and foreshaft of chokecherry. This dart stopped at only 7 cm after striking the fourth rib, nicking it (Figure 21a), and breaking the point. The wound surface area was 41 cm^2. Another shot (# 20) likely struck a rib and stopped at 5 cm. Although the darts are capable of producing lethal wounds when they hit vital organs between ribs, the overall results were not inspiring for hog hunting with Basketmaker equipment.

To match at least one experimenter's findings (Callahan 1994), the WDC dart with a hard shoulder at the socket and a smaller diameter foreshaft (Figure 7a) did not penetrate past the socket (shot #s 16 and 17), while one of three shots (# 4) with the tapered socket (Figure 7c) penetrated 17 cm—about 5 cm past the socket. This suggests that Basketmaker darts with shouldered sockets may have been designed to stop at the socket and only penetrate the length of the foreshaft, which is often quite short. This may have been a tactic to increase the longevity of mainshafts, since Basketmaker foreshafts disengage from the socket fairly easily, and the mainshaft would fall away from a running animal rather than being broken as the animal dove through brush. The long skinny forehshafts such as those common to the Great Basin (Aikens 1970; Hattori and Tuohy 1982) may penetrate deeper on average.

Figure 20. Point #37 was mounted to a choke cherry foreshaft and made to replicate a foreshaft found at Spring Creek Cave, WY (Frison 2004:Figure 54a). This foreshaft penetrated only 7 cm into the carcass after contacting rib # 11 (Figure 23a). Upper left) four views of the point prior to hafting. Lower left) four views of the complete foreshaft prior to the carcass experiment. Lower right) both faces of the point and a view of a flake driven off after being thrown into the carcass. Upper right) the point's orientation on impact.

3.1.2 Light and mid-weight cane

All but three throws (#s 49-51) with the light and mid-weight cane mainshafts were made with beveled points. The average penetration of 17 throws from 12 m was 20.6 cm, while four

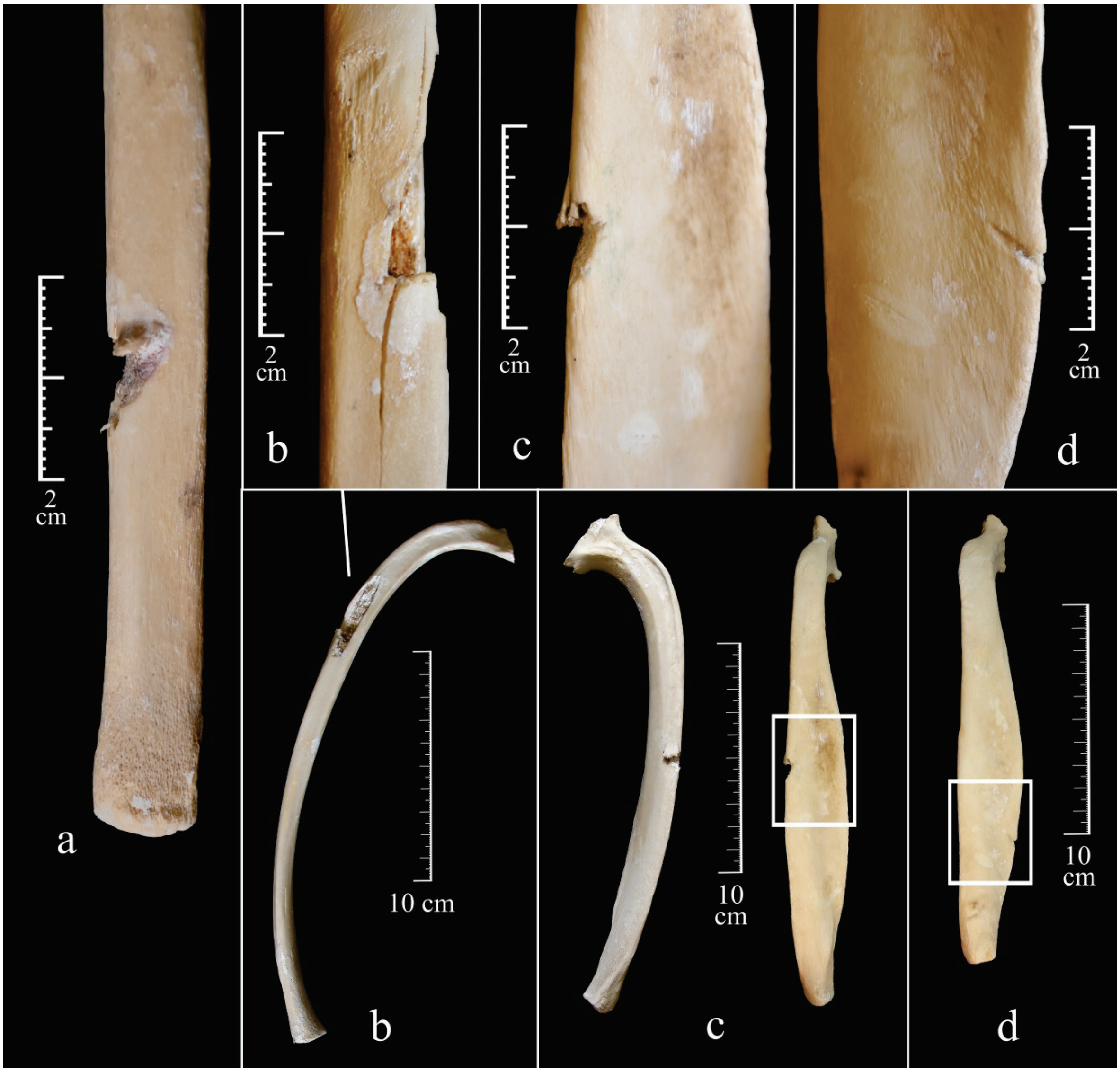

Figure 21. Examples of damage to ribs; a) rib #11 [shot #5], b) rib #6 [shot #26], c) rib #4 [shot #7], d) rib #3 [shot #29].

effective throws from close range in the scapula attempt averaged 17.4 cm. In contrast to the WDC darts, these darts exhibited the ability to punch through ribs (Figure 21b) and some shots stopped only after contacting the opposite side of the rib cage (Figure 17). This is not surprising, since inner organs offer less resistance than bone, skin and muscle. The darts were not carrying enough KE or P to punch through the other side but did produce more than adequate penetration for lethality, with an average wound surface area of 123 cm^2. Garnett's final shot (# 66) sent a beveled point through the scapula and into the spine, from which it could not be retracted (Figures 22 and 23). In my own experience bow hunting, shots that impact the spinal column are often fatal. However, according to Ashby (2007) the primary cause of increased penetration with beveled metal broadheads on arrows is due to torqueing and splitting of dense bone when it is encountered, and the subsequent reduction in trailing shaft drag. However, this beveled stone point (# 59, Figure 22) encountered two hog scapulae in the project and did not produce splits (Figure 23) (Pettigrew et al. 2015). One beveled point (Figure 14) struck rib #6 and split off a large splinter (Figure 21b) but this is not a reliable analogy to the splits produced in ribs by thinner metal broadheads (Ashby 2007). Point beveling probably did not contribute to the increased penetration of the cane darts, but rather mass and average velocity was higher, producing higher KE and P values (Figures 18 and 19). Several aspects of the projectiles' profiles may have also led to slight improvements in penetration; including the aerodynamic profiles of the points and hafts, and the smoother transition of the oak dowel foreshafts to the mainshafts (Figure 15).

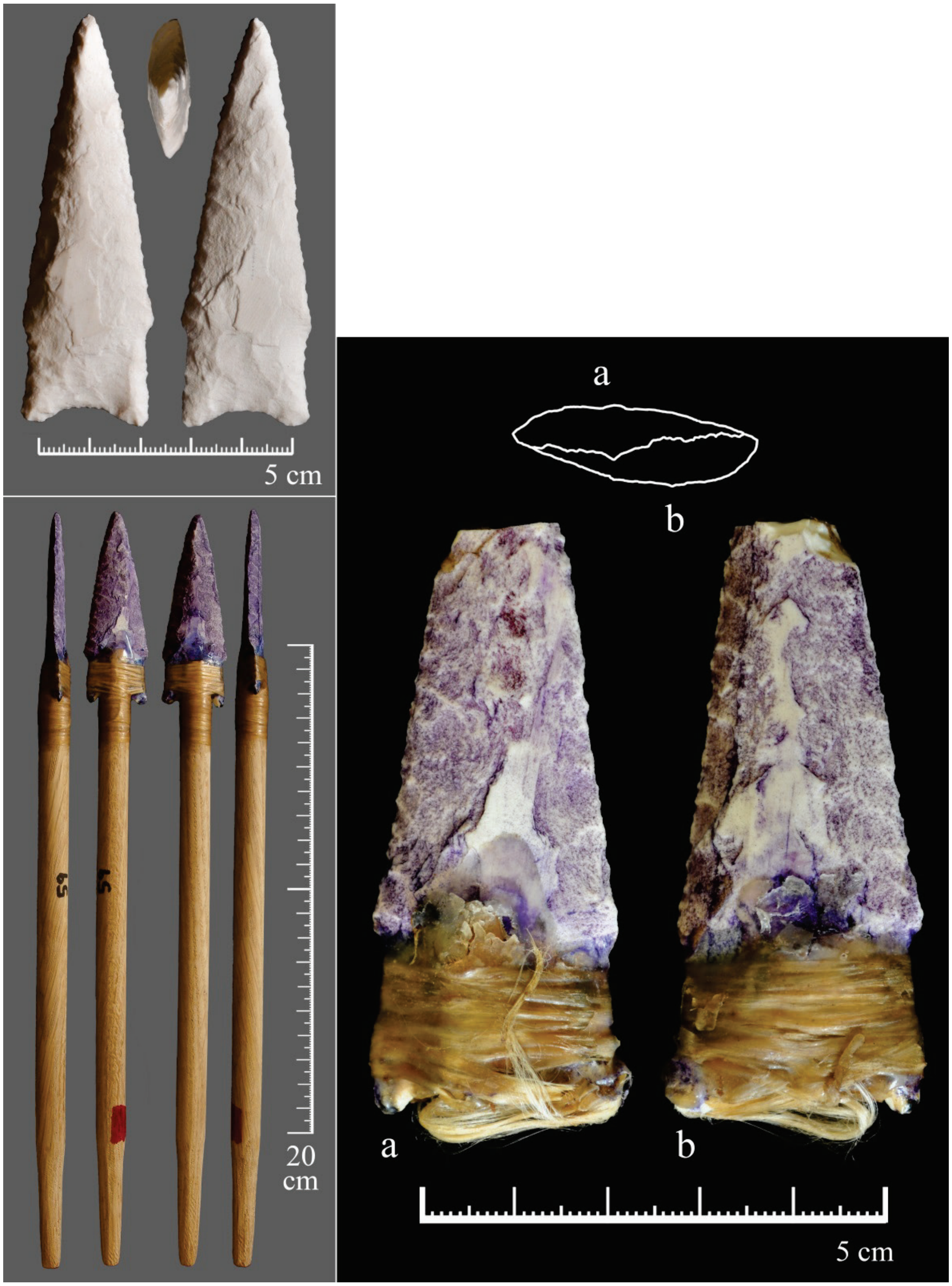

Figure 22. Experimental point # 59, a beveled point that punched through the scapula on shot # 66 (Figure 25), and then lodged in the spine. The foreshaft could not be removed and was left in the carcass. The lateral tip snap occurred when the carcass fell off the trestle and onto the protruding foreshaft during transportation for butchering. Upper left) three views of the point prior to hafting. Lower left) four views of the complete foreshaft prior to the carcass experiment. Lower right) both faces of the point after being retrieved during butchering. Upper right) the point's orientation on impact.

Figure 23. The result of a beveled point (# 59) punching through the scapula (shot # 66).

1.1.1 Heavy darts

Due to time constraints, only eight throws were made with the heavy ash and cane darts, and only four resulted in hits to the carcass. These results should not be allowed to skew the KE and P data compared to penetration (Figures 18 and 19), given the small sample size, shot placement variation and other issues. Only one shot (# 44) with the heaviest shaft, the ash dart, was an adequate hit to the carcass. However, the flight video reveals that the dart's flight was skewed, with its tail closer to the ground than the tip. The next shot resulted in the foreshaft breaking off and leaving a plug in the socket, at which point this dart was abandoned to save time. The three throws with the heavy cane shaft averaged only 14.1 cm penetration, but may have been skewed due to shot placement (shot #s 48 and 54) and contact with bone (shot # 46). One throw with this dart was not factored into the penetration depth (shot # 47), that was made with a heavy Clovis point replica that impacted the humerus and broke off the tip in the bone (Figure 24). Despite the high momentum this wound would probably have resulted in nothing more than a limp for a healthy hog.

1.1.1 Arrows

Six shots with the Catawba bow and cane arrows resulted in five impacts to the carcass that averaged 15.6 cm penetration. Unfortunately batteries ran out on the velocity camera just prior, and the radar gun did not capture readings. However, this bow shoots arrows of this weight consistently around 45 m/s. In construction, the arrows were based on previous shafts that flew well off the bow, and were tested with 110 and 125 grain metal field points. However, arrow spines are finicky and must be well tuned to match the bow. Due to differential tip weight some shots (#s 58, 59 and 60) showed a slight tail down effect, which reduced penetration depth. The best penetration (shot # 57) was achieved with straight arrow flight.

All of the arrow points were hafted into square notches with sinew and two of the four survived for two shots. The primary goal of the archery test was to provide comparative data for impact and hafting wear on stone points that could be either large arrow or small dart points. In support of previous studies that have focused on interpreting shaft diameter from the basal characteristics of points (Corliss 1972; but see Corliss 1980; but see Thomas 1978), I found the large arrow points awkward to haft to foreshafts that matched the arrows. Rather than just width

Figure 24. The result of a heavy Clovis point (# 93) impacting the humerus with high momentum (shot # 47).

of the bases as focused on by Corliss (1972), the thickness of the points' bases made them difficult to securely attach in the notches of small diameter shafts, and extra steps were required to ensure they were secure. All three would have worked well as small dart points. Obviously, however, points of this size can be hafted to arrows, and arrows of different material or stronger spines for stronger bows can be of larger diameter. A degree of overlap must be recognized to exist between arrow and dart diameters and point sizes.

1.1.2 Point tip cross-sectional area/perimeter (TCSA/P)

Point tip cross-sectional area (TCSA) and point tip cross-sectional perimeter (TCSP) are calculated from the maximum width and thickness of a point. Samples of TCSA/P measurements from the points of archaeological, ethnographic and experimental spears, darts and arrows help researchers make determinations about which weapon technologies are likely represented when only stone points remain (Hughes 1998; Sahle et al. 2013; Shea 2006; Sisk and Shea 2011; Wilkins et al. 2012). This is because, theoretically, lower TCSA/P values should be attributable to smaller projectiles, and also make a projectile capable of penetrating deeper since a lower surface area means less resistance will be met. Marginal differences exist between the cros-sectional area of a point (TCSA) and its cross-sectional perimeter (TCSP). The latter is slightly more applicable to points that slice a hole in a target, but analytically the two measurements are very similar (Sisk and Shea 2011).

Shea's (2006) study used measurements by Shott (1997) and Thomas (1978) of points found still hafted to dart foreshafts to calculate a TCSA range for darts. Using hafted points ensures that points erroneously assumed to be dart points don't make it into the sample. However, this also means a limited sample size. Owing to better preservation of perishable components in dry conditions, both of these samples (Shott 1997; Thomas 1978) were composed primarily of foreshafts found in the American Southwest. With the exception of one from Arkansas and one from Australia (Shott 1997), the majority were from Basketmaker II period sites including WDC and Broken Roof Cave. This study shows that the Basketmaker and other preserved Late Archaic equipment is of fairly small size and weight, and points with higher

TCSA can be effective on larger darts. The comparative sample of thrusting spear tips used by Shea (2006) was not from archaeological remains but came from an experimental weapons kit (Shea et al. 2001).

Lacking a larger sample of ancient hafted dart points, the experimental kit in this project could add further data to the TCSA/P study. Table 6 provides TCSA values from this and Shea's (2006:Table 1) study for comparison. Several of the experimental points were well above the mean in Shea's (2006) dart sample, and were within the value range for the experimental thrusting spear tips. The mean TCSA of the Basketmaker dart points in this project is close to the mean from Shea's (2006) study, which makes sense given that those points came primarily from Basketmaker assemblages, providing another indication of the accuracy of the experimental Basketmaker points made by Whittaker and others for this project. The mean for points used with the light and mid-weight cane darts in this project is higher, since the points used with the cane darts were larger, but still functioned perfectly well with those darts. Two points (#s 83 and 84) are exceptional examples (Appendix C). Point # 83 has a TCSA of 197 mm—at the upper end of Shea's (2006) experimental spear tip values—and was used effectively with a mid-weight

Table 6. TCSA (mm) values from Shea's (2006) study, and a total of 89 points used in this project. "WDC" indicates points made for the replica Basketmaker darts.

	Shea 2006			This study					
	Arrows	**Darts**	**Spears**	**Arrows**	**Whittaker WDC**	**All WDC**	**Cane darts**	**Heavy darts**	**All darts**
Mean	33	58	168	51	63	69	106	125	97
S. Dev.	20	18	89	28	9	15	30	58	43
Min	8	20	50	19	45	45	66	66	45
Max	146	94	392	93	75	120	197	294	294
n.	118	40	28	12	19	29	27	21	77

cane dart to penetrate 27 cm into the thoracic cavity of the hog (shot # 43), producing an exceptionally high wound surface area of 304 cm^2. A similar point (#84) did not penetrate well on one shot, (#40) possibly because its “ears” (barbs that taper outward quickly) caught on the skin, although it struck a fleshy area at the back of the shoulder and may have also contacted bone. The next shot with this point (#41) penetrated 24 cm and produced a wound surface area of 231 cm^2 (Figure 25). These were the highest wound surface areas recorded in the experiment.

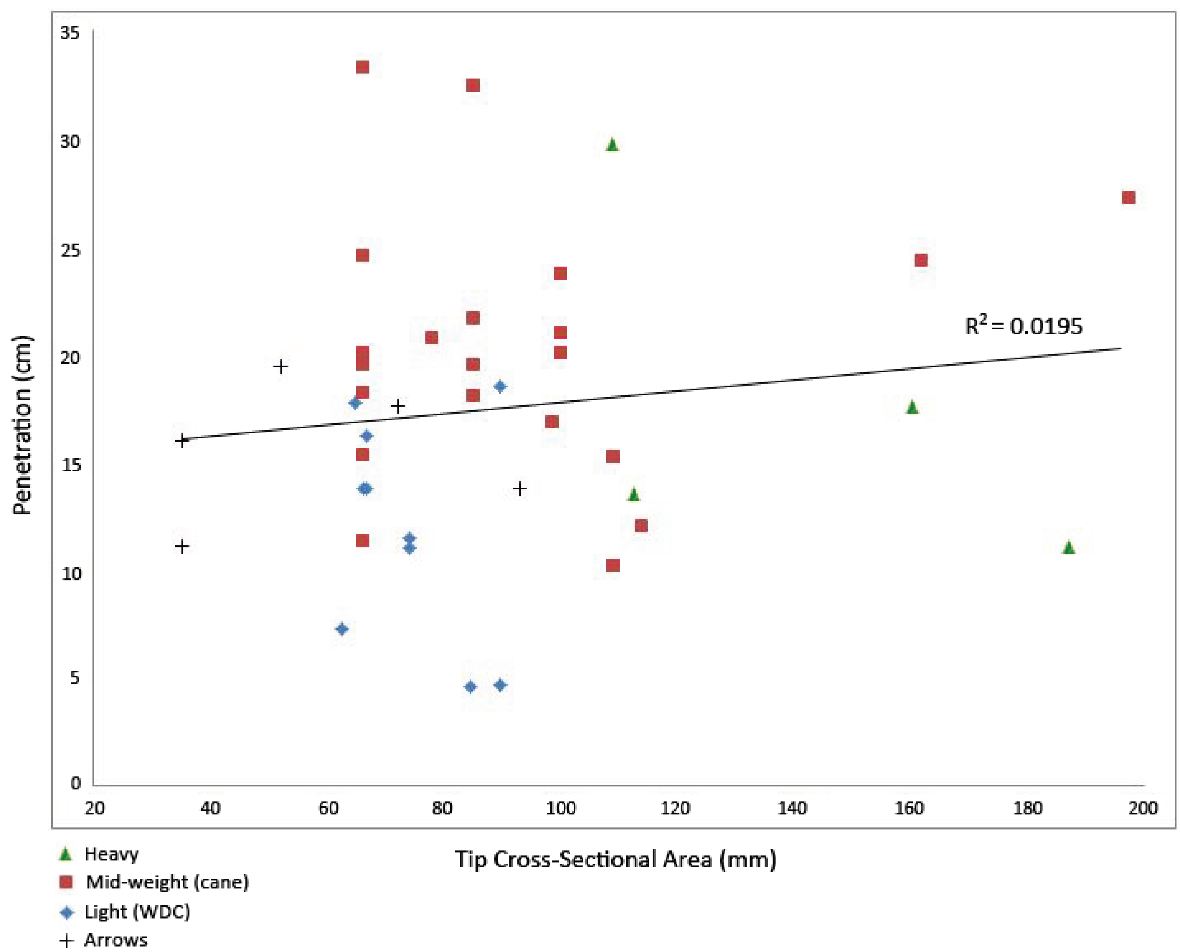

Figure 25. TCSA compared with penetration for individual shots into the carcass. Outliers for cane darts on the far right represent point #s 83 and 84.

Only one arrow point (# 92) was within the TCSA/P value range for arrows used in Shea's (2006) study. The rest were higher. However, the other experimental arrow points were larger than what the author considers effective points for arrow shafts of this size, primarily due to basal thickness and the greater effort required to haft them effectively rather than their maximum width and thickness. The arrows actually flew better with the heavier points with higher TCSA given that their spines were adjusted for 125 grain metal field points.

Figure 25 provides a comparison of the TCSA values for the experimental points of each projectile class and their penetration depths into the carcass. A very low r^2 value of 0.0195 for the regression line indicates a poor correlation. TCSP compared to penetration produced a very similar graph but with an even lower r^2 value of 0.0036 for the regression line. All points were hafted and matched with the various shafts prior to calculating TCSA/P, so the measurements did not factor into the resulting TCSA/P means attributed to each weight class.

These discrepancies from the archaeological and ethnographic samples are significant because they demonstrate that larger points with higher TCSA/P can still function on darts and arrows, and produce lethal wounds. Typically stone points are the only remnants of weapon systems, while preserved perishable components are only found under limited circumstances. Using only archaeological and ethnographic samples with attached perishable components may yield samples too small from which to build accurate determinations. The weight of the point is the primary factor that affects proper flight and in both darts and arrows heavier points with higher TCSA/P can be adjusted for by using shafts with stronger spines. This is especially the case with arrows, which need to be well tuned to the bow in order to bend around the handle properly without striking it—an effect known as the *archer's paradox* (Klopsteg 1943). However, a greater range of point weights on atlatl darts can be adapted to by adjustments in the atlatlist's throwing form. For killing potential TCSA/P does affect the projectile's ability to penetrate, yet larger points penetrated better than expected in the experiment and produced wounds with large surface areas.

1.2 Hafting effectiveness

The replicated hafting methods proved highly effective, however, in most cases the traditional hafts did not last more than two shots into the carcass. Several shots resulted in the point being lost in the carcass and retrieved after butchering. Points bound into split notches with bark come out of the haft with only slight reverse pressure, and both points (#s 70 and 48) were lost in the carcass after the first throw. A remnant of the bark wrapping stayed around the point bases, and in one case around the foreshaft (Figure 8), mimicking what was found under Ozark bluffs (Pettigrew 2015). The method of binding with sinew in a square notch was found to be somewhat more reliable for point retrieval, with four points (#s 36, 42, 87, and 92) holding up for two throws into the carcass. However, the sinew quickly loosens after exposure to the fluids in the carcass, and several of these points also stayed in the carcass. Two points (#s 93 and 27) that impacted the carcass were glued into a square notch with mastic and the foreshaft bound with sinew. The tip of the Clovis point replica broke after impacting the humerus. The other was a stemmed point, still solid in its haft after penetrating the jowl, though the experiment proceeded without a second throw to save time. All but two of the beveled points (#s 84 and 88) hafted with modern materials were solid in their hafts for multiple throws. One of these points (# 84) stayed in the carcass and was the only point not retrieved after butchering, probably being lost somewhere in the gut pile. Although it can't be said with certainty that contracting stem points that are glued in are definitely more easily retrieved, since most of the experimental points hafted in this manner were done so with modern glue, we can see that notched points that are tied in are effective at penetrating but may not have been designed with retrievability in mind. This may be important when interpreting point morphology through time. There are good indications that early hunters who often used stemmed or lanceolate points were trying to retrieve and reuse their projectiles whenever possible (Kay 1996, 2012). Later notched points were made with less precision and appear to be more numerous.

1.3 Butchering

Following the shot experiment, the carcass was moved by Mr. Barhenfus with a tractor to a location nearby for butchering. The carcass fell off the trestle on the first attempt to lift it, which broke the foreshaft and snapped the tip of the beveled point (#59) that had punched through the scapula and lodged in the spine. The carcass was gutted with a steel knife while hanging from the tractor bucket, then lain on a tarp for butchering with stone flakes and three beveled knives hafted with pitch and sinew to wooden handles (Figure 26). This was intended to provide samples of butchering use-wear on stone tools, and to test the effectiveness of beveled knives in butchering, since the most common theory to explain Archaic point beveling is unifacial resharpening following use as knives (Sollberger 1971).

Sharp flakes worked best for slicing through the hog's thick skin, while the beveled knives were effective at slicing through a thick layer of fat under the skin, and cutting through meat. No differences were noticed between the beveled knives and bifacial stone knives. The beveled knife is simply turned so that the edge is perpendicular to the cut. After the carcass had been skinned and quartered, to save time only sections of the skeleton thought to receive impact damage were kept. A section of the spinal column and the ribs were removed with a metal saw, and final processing was completed with steel knives. Most meat on the carcass was surprisingly still in good condition and of excellent quality, though wound channels had to be trimmed due to the slight toxicity of methyl violet.

Figure 26. Experimental butchering tools—hafted beveled knives and flakes.

1.4 Impact damage

The faunal remains reveal several broken and chipped ribs and thoracic vertebrae (Figures 21 and 27), the hole punched through the scapula by the beveled point (Figure 24), and the tip of the replica Clovis point lodged in the humerus (Figure 24). It was discovered after cleaning that the section of spinal column unfortunately did not include the vertebra with the tip of the beveled point (# 59). Due to a shortage of time during butchering it was decided that only notable damage to bone should be recorded for various shots. A marking system was not found that would remain on the bones during the cleaning process, however, based on notes taken during butchering and the impact video of each shot most damage to bone could be traced back to individual shots (Figure 28).

Of the 29 points used in the experiment 13 received macroscopic damage from contact with various objects (point #s 21, 37, 42, 54, 59, 73, 76, 77, 78, 83, 86, 88, 93). Of these, nine received damage from impacting bone (#s 37, 42, 59, 73, 76, 77, 78, 88, 93), three from hitting the concrete base of an old house behind the carcass (#s 54, 76, 86), one from the wood of the house wall (# 78), one from the board on which the carcass lay (# 21), and one from objects in the ground (# 83). Damage from striking bone resulted in edge wear characterized by edge flaking or abrasion, longitudinal flaking from the tip, or the tip snapping off lattitudinally, while striking the concrete house base resulted in crushing of the tip with longitudinal flaking. Both strikes to wood resulted in a tip snap, while the point that landed in the ground received longitudinal flaking from the tip (see Appendix C for additional images of damaged points). It is reasonable to suspect that impacts to denser bone that what was found in the hog at KE and P values high enough to hunt large animals would result in more substantial breakage to points than what was seen in this experiment.

Figure 27. Thoracic vertebrae that received extensive damage from four different shots that landed close together.

4. Discussion

High speed film has proven highly productive to understanding how the atlatl and dart operates. Darts can be seen to oscillate from transverse waves and often spin alternately. Additional spinning or rotation while remaining flexed can result from the motions of some throws. The Tracker program revealed an approximately 6 cm displacement in the tip of one dart as a result of oscillation, while the tail oscillated approximately 15 cm. Although oscillation eventually attenuates down range, accurate shots are taken at fairly close ranges (Cattelain 1997:219–219), and this indicates an inherent limit to the accuracy of the dart, which could be more pronounced in some systems. Shafts that increase in diameter distally are more stable in the front than non-tapered shafts, which can oscillate equally between the point and tail.

However, this is not the primary factor impairing atlatl accuracy. In the transition from javelins, to atlatls and darts, to bows and arrows the most significant improvement is in ease of use, since none of these projectiles are significantly more powerful than the former, but are easier to launch in a controlled manner and travel faster with flatter trajectories, and are therefore easier to aim (see Cundy 1989; Hughes 1998). The bow offers a major improvement by storing consistent energy in its limbs, so that aiming the arrow and releasing it properly are the primary components of accuracy. Although the atlatl is capable of a high degree of accuracy, consistency can be difficult to achieve since the atlatlist must not only aim the dart but coordinate the body properly to throw accurately. This equates to, in the author's experience, the necessity for a level of concentration when using the atlatl that can be challenging to arrive at and maintain.

Accuracy of darts and arrows hinges on proper spine, or the shaft's resistance to bending. In arrows, this is due to the archer's paradox—the necessity that the shaft bends around the

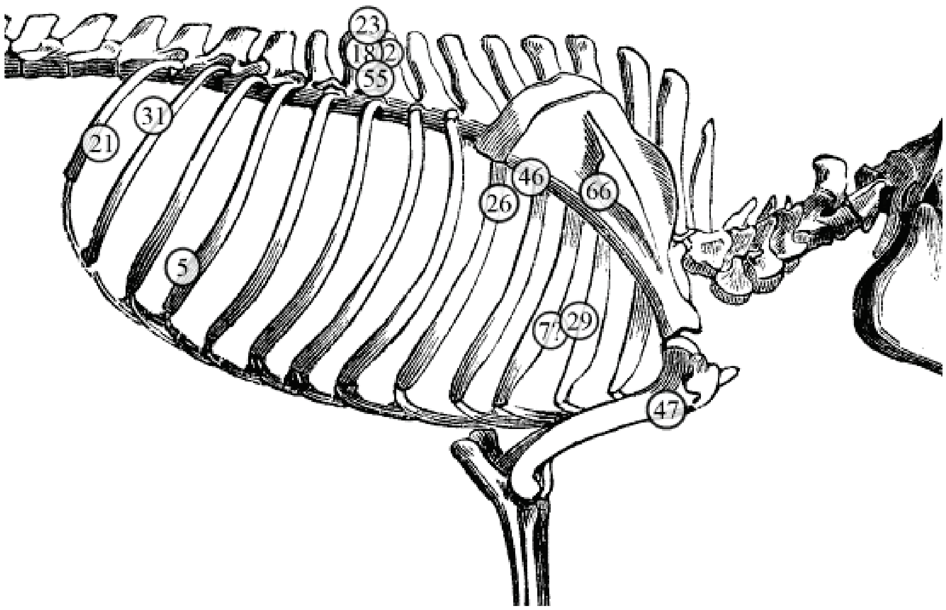

Figure 28. The placement of several shots that struck bone in the carcass experiment (illustration from Theobald 1899:Figure 27, modified from the original).

handle of the bow without hitting it and being deflected (Klopsteg 1943). Darts also need proper spine to counter the deflection of the tail in the throwing motion (Cundy 1989). An amount of variation is allowable in dart spine because atlatlists learn to quickly adapt their throwing form to a degree of functional variation. Fletchings increase this allowable variation by introducing additional drag on the tail and making darts more stable in flight (see Cundy 1989 for a detailed discussion). This also means that a range of point weights are allowable on individual darts, since the weight of the point affects the spine. Both arrows and darts can also be matched with heavier points by selecting shafts with stronger spines. Points that are heavier typically have higher TCSA/P, and the projectiles in this study were mated with a range of point sizes. This is the cause of the poor correlation between TCSA/P and penetration depth, and the deviation from ethnographic and archaeologic samples. Future studies should be cautious when using TCSA/P to determine what projectile technologies were used with certain point types.

Velocity results in this project are consistent with previous studies (Hughes 1998; Raymond 1986; Whittaker and Kamp 2007), and suggest that typical dart velocities range between 18 and 28 m/s (40-62 mph). Not surprisingly, velocity can increase with harder throws (Table 1). My typical throw hovers around 22 m/s (49 mph) but has ranged up to 28.7 m/s (64 mph) when throwing very hard. Disregarding some past measurements that are probably aberrant (see Whittaker and Kamp 2007), no legitimate record yet stands for throws over 28.7 m/s. For now this should be considered an upper limit to dart velocity.

There has been some debate over the adequacy of either kinetic energy (KE) or momentum (P) for comparisons of the killing potentials of various projectiles (Ashby 2005a; Hughes 1998; Tomka 2013). The two measurements can be simplified to "how hard it hits (kinetic energy)", and "how hard it is to stop (momentum)" (Hrdlicka 2003). Arrows typically have higher KE than darts, since KE increases exponentially as velocity increases. However, this also means that KE is shed more rapidly than P due to the simultaneous increase in resistance that the projectile meets when moving through any given substance (Ashby 2005a). The lines of best fit for KE and P when compared to penetration of darts in this experiment show a slightly higher favor for KE (Figures 2 and 3). However, a comparison with arrow KE and P indicates that both measurements are important. This is illustrated when comparing atlatl darts to arrows in KE and P in Tables 4 and 5. For example, Frison's (1989) exceptionally heavy elephant darts were added to Table 4 and given an estimated velocity of 20 m/s, since heavier darts are typically harder to throw at high velocity. These darts were used to produce fatal wounds on elephants. Still, KE is well under the range recommended by African countries for elephant hunting (Tomka 2013:Table 2), yet P is over triple the amount suggested. The WDC darts at average velocity are typically within P ranges suggested for large game, but with KE far down in the small game category. Penetration depths of each weight class (Figures 18 and 19) suggest that in comparing dart KE and P to the recommended values for arrows, lethality actually lies somewhere in between. So WDC darts traveling at 21 m/s with KE under the recommendation for small game, and P just inside the recommendation for large game, just meet the recommendation for medium game such as white-tailed deer (Tables 4 and 5). This is well illustrated in the hog experiment, where several of the hits with WDC darts may not have been lethal to the hog. One shot (#5) only penetrated 7 cm into the skin and thick layer of fat, but stopped after impacting a rib (Figures 22 and 23a). The mid-weight cane darts in the experiment are only slightly heavier and were thrown at slightly higher velocities. These darts are perfectly capable of producing lethal wounds on animals the size of the hog. Several shots with these darts penetrated to a lethal depth even after striking bone. These results correlate well with the KE and P values in Tables 4 and 5, where the cane darts have higher P than the recommended values for very large game, but KE values for medium game, and seem suitable for hunting large game.

This data shows that atlatls and darts found preserved in North America are comparable in killing potential to many ethnographic Native American bows (Tomka 2013). The average bow from North America meets the KE and P recommendations for medium game, and this may be a reflection of greater reliance on small to medium prey, as well as tactics to get close to very large game (Tomka 2013). Such tactics are not limited to bow and arrow times on the western plains, where archaeological evidence for bison natural and manmade traps and funnels goes back 11,000 years (Frison 2004; Kornfeld et al. 2010:217–289). Both Basketmaker and Great Basin kits with removable foreshafts of various types that expand the functionality of the projectile kit while simultaneously reducing the necessary number of mainshafts carried, and thus the mass of the kit as a whole (LaRue 2010), are good examples of maintainable weapon systems (Bleed 1986). Hill (1948) may have displayed no small degree of insight in suggesting that these systems were "utility types for everyday use", and that heavier systems may have existed for hunting big game. Frison's (1989) experiments on elephant carcasses showed that the atlatl is perfectly capable of killing very large animals through penetration and hemorrhaging when heavy darts are used. Evidence of powerful impacts to very large animals in prehistory have come from likely dart points lodged in bison skeletal remains, such as a calf creek point lodged in a bison cranium (Bement et al. 2005), and points lodged in bison vertebrae (Frison 1974:85; Kornfeld et al. 2010:Figure 4.31).

Additionally, poisoned projectiles do not need significant KE or P to kill big game (Bartram 1997). One goal of the project was to test the shouldered socket design on Basketmaker darts. The results reflected Callahan's (1994) experience that penetration will often stop at the socket. The use of foreshafts that detach rather easily helps preserve mainshafts that quickly detach from running animals, rather than breaking as the animal dives through brush. This effect has also been noted of arrows with poisoned foreshafts and detachable mainshafts used by the San of the Kalahari (Hitchcock and Bleed 1997). Darts with shouldered sockets and short, narrow foreshafts that were covered in poison were also used by the Aleutians for warfare (Jones 2007). Poison can increase success rates of hunts because poisoned projectiles do not need to strike an animal's vital organs. Once the distance has been closed between hunter and prey, the primary factor of success is an accurate shot, and poison significantly increases the suitable target area (Hitchcock and Bleed 1997). As yet poisoned foreshafts have not been found in the assemblages from the Ozarks or Southwest, but there is also no indication that they have been looked for.

Heavy darts are more reliable for hunting very large game through penetration and hemorrhaging, but increasing dart weight substantially also increases the energy necessary to carry and use them. Big game darts benefit from refined point and haft profiles that reduce drag and maximize penetration. Some ancient point designs such as Agate Basin, Folsom and Clovis are probably examples of this concept at work (see Howard 1995). Similar points with smooth haft profiles probably aided the penetration of the mid-weight cane darts in this experiment, in addition to the increase in velocity and mass.

Beveling on modern archery broadheads is thought to increase penetration through significant reductions in shaft drag when dense bone is torqued and split (Ashby 2007). This study showed that beveling on Archaic points will also induce rotation of darts when penetrating flesh; an effect that may have been noticed by Archaic hunters. All experimenters easily felt the rotation when retracting darts from the carcass. However, beveled points in this project failed to produce splits in pig scapulae (Figure 23) (Pettigrew et al. 2015). Considering other effects of point beveling that may increase lethality (Ashby 2007), this does not mean that Archaic hunters wouldn't have selected for point beveling to maximize the killing potential of their equipment. However, most beveled point types start out with straight, bifacial profiles and become beveled through unifacial resharpening, suggesting that the optimized resharpening scenario (Sollberger 1971) remains the best one. Unifacial resharpening increases the longevity of points and knives, and use of the same points as both projectiles and knives is well documented (Kay 1996, 2012). Furthermore, Archaic hunters were seeking to retrieve broken points and renew them whenever possible (Kay 2012). That worked down points are still effective was indicated in this project by one point (#79) made by Whittaker to mimic a reworked Dalton point (Appendix C). This point was thrown 10 times on the lighter cane dart and consistently penetrated deep into the carcass, but showed little sign of macroscopic damage.

4.1 Problems and recommendations for further research

A similar experiment should be carried out on a bison carcass. This would provide more information about the killing potential of Late Archaic systems, and produce more samples of penetration and impact damage at recorded velocities. Several improvements could be made to the protocol of the experiment that would improve the results. The high speed video has proven invaluable, but major improvements could be made with higher resolution. The flight camera (EX-F1) was set to record at 300 fps because it had been bogging down prior to the experiment when filming at 600 fps. However, 600 fps provides a clearer picture for interpreting projectile flight and impact. Additionally, the best impacts recorded with the EX-F1 have been taken with the camera zoomed in closer on the target, and situated closer to the path of the projectile to catch more of its flight (Pettigrew et al. 2015:Video 5). Ultimately the EX-F1 is capable of providing better quality impact video. Connecting the camera directly to a laptop in the field for instant video playback would make refinements to the camera's settings more evident.

Similarly, the EX-ZR1000 was set to film at 240 fps. Although the camera is capable of higher film speed, video resolution diminishes quickly. Initially 240 fps was thought to be acceptable. Analysis of the video in Tracker, however, produced a higher range of variability between shots than expected. Resolution was not high enough to closely track the tips of projectile points when viewed edge-on, and shadows in the backdrop due to creases in the white sheet also reduced clarity. Refinement of the data by rejecting unclear frames brought the velocity numbers closer, but the results would have benefitted from a more homogenous backdrop and filming velocity with a camera that shoots better resolution at higher speed, preferably an EX-F1 at 600 fps. This would also result in video more suitable for impact analysis viewed from the side, and the ability to set the scale of the video from the scale on the projectile itself while still in flight. Slight changes in the scale can dramatically affect velocity readings on Tracker, and in some cases dart shafts were not oriented properly for an accurate reading after hitting the carcass and stopping.

Additional improvements could be made through better records of weather, the timing of key events, and characteristics of the carcass such as its girth and the depth of the thoracic cavity. A high degree of familiarity with the weapons is necessary to reproduce past events as closely as possible, and although significant time was put into preparing and practicing with the equipment, the heavy darts should have been focused on more. Future tests should also match arrow mainshafts and foreshafts more strictly for optimal arrow flight. Bleeding the carcass helped preserve meat quality, but this may have removed some degree of realism in the penetration data since blood aids penetration to some degree by lubricating the projectile (Ashby 2005a). According to Ashby (2005a) the carcass should be shot within a few minutes of death, but this is not feasible for most experiments.

Finally, during butchering one experimenter should be set aside to photograph and record details about shot results and butchering tool use. Photographs of shot markers and wound channels were helpful in tracking the results of specific shots, as were notes on impact damage, but both of these were lacking in some cases. While butchering, to save time only a portion of the spine, the right front leg, and the ribs facing the experimenters were kept. Two shots in particular (#s 46 and 66) probably contacted vertebrae, but these were not represented in the sample of the spinal column, and other shots may have contacted bone as well. Future experiments should attempt to keep as much of the skeleton as possible. A majority of these problems actually reflect the limited time frame of the experiment and a rush to get things done.

5. Conclusion

This study set out to test the killing potential of darts of various sizes. Atlatl equipment represented in the archaeological record in North America incorporates darts of small size, and adequate information about their killing potential did not exist. A naturalistic approach was used that involved replicated equipment tested against a fresh carcass. This approach simultaneously allowed beveled dart points to be tested, and a host of other effects to be captured. Given their velocity and mass, atlatls and darts from North America are comparable in their killing potential with later ethnographic bows and arrows. Although these weapons do not meet the suggested momentum and kinetic energy for modern bow hunting of very large game such as bison, their lethality against those animals should be further tested in similar future experiments, especially with consideration given to very hard throws from close range.

Perhaps the most significant contribution of the project is an effective experimental protocol that can be fairly easily reproduced. High speed cameras allowed a detailed analysis of the impacts of darts and arrows, while a video analysis program called Tracker and a radar gun were effective at capturing projectile velocity. Importantly, for effective analysis the camera needs to capture high enough quality video in at least 600 fps. The video, in addition to shot markers, photographs, and detailed notes allowed points to be traced to impacts with bone, and thus impact damage to be accurately assessed. The main obstacle to conducting the experiment smoothly was time. To setup and run the experiment took from the early morning hours to late at night, and all participants were exhausted by the end. However, quality of the meat was exceptional, and everyone enjoyed a grilled pork dinner.

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Appendix A: A curtailed version of the Projectile Measurements and Shot Record tables. When available, *KE* and *P* are calculated from radar.

Codes by column:

1) Set number:…………………………....S1) WDC dart lethality and socket type test, S2) WDC bevel test, S3) Mid-weight cane bevel test, S4) Heavy dart bevel test, S5) Arrows, S6) Scapula break attempt, NS) No particular set.
2) Shot number
3) Shooter:……………………………...DP) Devin Pettigrew, JG) Justin Garnett, JW) John Whittaker, PH) Patrick Hashman
4) Shooting platform:…………………..Bow) Catawba bow, BRC) Broken Roof Cave atlatl, Clo) Clovis atlatl, GBI) Great Basin inspired atlatl, Mag) Magdalenian spearthrower, WDC) White Dog Cave atlatl
5) Point number
6) Point max width (mm)
7) Point max thickness (mm)
8) Foreshaft diameter (mm)
9) Foreshaft length in dart socket (mm)
10) TCSA (mm)
11) TCSP *rhomboid* (mm)
12) Mainshaft number
13) Complete projectile mass (g)
14) Cutting index (Friis-Hansen 1990)
15) V *radar* (m/s)
16) V *film* (m/s)
17) P (kg-m/s)
18) P (slg-ft/s)
19) KE (j)
20) KE (ft/lbs)
21) Shot result
22) Penetration depth (cm)
23) Wound surface area (cm^2)
24) Impact qualifier
25) Point damage
26) Damage from

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
S1	**1**	JG	BRC	36	25	5.3	10.5	143	66	57	1	88.6	2.3	21		1.9	0.42	20	14	Hit			hit ear		
S1	**2**	JG	BRC	36	25	5.3	10.5	143	66	57	1	88.6	2.3	22	24	1.9	0.43	20	15	Hit	14	79	point lost in carcass		
S1	**3**	JG	BRC	90	24	5.4	9.1	125	65	55	2	84.2	1.9							Miss					
S1	**4**	JG	BRC	90	24	5.4	9.1	125	65	55	2	84.2	1.9		23	2.0	0.44	23	17	Hit	18	98	point lost in carcass		
S1	**5**	JG	BRC	37	25	5	10.2	173	63	56	1	86.2	2.3	21	24	1.8	0.41	19	14	Hit	7.3	41	point lost in carcass	tip snap	bone
S1	**6**	JG	BRC	42	23	5.8	9.6	152	67	54	2	87	2.0	21	21	1.8	0.41	19	14	Hit	14	75		friction abrasion-one edge	bone
S1	**7**	JG	BRC	42	23	5.8	9.6	152	67	54	2	87	2.0		23	2.0	0.45	23	17	Hit	16	88			
S1	**8**	DP	WDC	54	28	6.4	11.3	149	90	66	1	89.7	2.1							Miss		88	hit house base	longitudinal flaking from tip	concrete
S1	**9**	DP	WDC	86	26	4.9	10.6	108	64	58	1	85.3	2.4							Miss		88	hit foam backdrop		
S1	**10**	DP	WDC	86	26	4.9	10.6	108	64	58	1	85.3	2.4							Miss		88	hit foam backdrop		
S1	**11**	DP	WDC	86	26	4.9	10.6	108	64	58	1	85.3	2.4							Miss		88	hit house base	longitudinal flaking from tip	concrete
S1	**12**	DP	WDC	47	26	6.5	10	219	85	63	1	91.2	1.9							Skip		88			
S1	**13**	JG	BRC	47	26	6.5	10	219	85	63	1	91.2	1.9		21	2.0	0.44	21	15	Hit	4.6	29			
S1	**14**	JG	BRC	47	26	6.5	10	219	85	63	1	91.2	1.9	22		2.0	0.44	21	16	Miss			hit target frame		
S1	**15**	JG	BRC	87	28	5.3	9.6	122	74	63	1	89.1	2.0							Miss			hit target frame		

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
S1	**16**	JG	BRC	87	28	5.3	9.6	122	74	63	1	89.1	2.0		22	2.0	0.45	22	16	Hit	11	69			
S1	**17**	JG	BRC	87	28	5.3	9.6	122	74	63	1	89.1	2.0		22	1.9	0.44	21	16	Hit	12	72			
S2	**18**	JG	BRC	85	23	7.8	9.5	70	90	61	2	93.1	1.6		22	2.0	0.45	22	16	Hit					
S2	**19**	JG	BRC	85	23	7.8	9.5	70	90	61	2	93.1	1.6							Miss			hit target frame		
S2	**20**	JG	BRC	85	23	7.8	9.5	70	90	61	2	93.1	1.6		22	2.0	0.45	22	16	Hit	4.7	29			
S2	**21**	JG	BRC	85	23	7.8	9.5	70	90	61	2	93.1	1.6							Hit	19	113			
S3	**22**	DP	GBI	77	23	7.4	12.7	262	85	60	4	112	2.2							Miss					
S3	**23**	DP	GBI	77	23	7.4	12.7	262	85	60	4	112	2.2	24		2.7	0.61	33	24	Hit	18	107	bevel rotation		
S3	**24**	DP	GBI	77	23	7.4	12.7	262	85	60	4	112	2.2	24	27	2.7	0.61	33	24	Hit	32	193	bevel rotation		
S3	**25**	DP	GBI	77	23	7.4	12.7	262	85	60	4	112	2.2	25	27	2.8	0.63	35	26	Hit	22	129	bevel rotation		
S3	**26**	DP	GBI	77	23	7.4	12.7	262	85	60	4	112	2.2	26	26	2.9	0.64	36	27	Hit	20	116		tip snap	bone
S3	**27**	DP	GBI	76	25	8	12.7	270	100	66	5	133	2.1	23	26	3.1	0.69	36	26	Hit	21	138	bevel rotation		
S3	**28**	DP	GBI	76	25	8	12.7	270	100	66	5	133	2.1	25	27	3.3	0.74	40	30	Hit	20	132	bevel rotation		
S3	**29**	DP	GBI	76	25	8	12.7	270	100	66	5	133	2.1	25	25	3.3	0.75	42	31	Hit	24	156		longitudinal flaking from tip	
S3	**30**	DP	GBI	76	25	8	12.7	270	100	66	5	133	2.1	25		3.3	0.75	42	31	Miss			hit house base	obliteration	concrete
S3	**31**	DP	GBI	78	26	7.6	12.7	265	99	66	5	131	2.1	23	26	3.0	0.68	35	26	Hit	17	112		edge flaking	bone
S3	**32**	DP	GBI	78	26	7.6	12.7	265	99	66	5	131	2.1							Skip			hit house wall	tip snap	wood
S3	**33**	JG	GBI	79	21	6.3	12.7	242	66	52	4	107	2.5	21		2.2	0.50	24	17	Miss					
S3	**34**		GBI	79	21	6.3	12.7	242	66	52	4	107	2.5		25	2.6	0.59	33	24	Hit	11	59	bevel		

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
																							rotation		
S3	**35**	JG	GBI	79	21	6.3	12.7	242	66	52	4	107	2.5	22	25	2.3	0.53	26	19	Hit	15	79	bevel rotation		
S3	**36**	JG	GBI	79	21	6.3	12.7	242	66	52	4	107	2.5	21	23	2.2	0.49	23	17	Hit	20	102			
S3	**37**	JG	GBI	79	21	6.3	12.7	242	66	52	4	107	2.5		26	2.8	0.63	36	27	Hit	20	104	bevel rotation		
S3	**38**	JG	GBI	79	21	6.3	12.7	242	66	52	4	107	2.5	20	24	2.1	0.48	22	16	Hit	18	94			
S3	**39**	JG	GBI	84	39	8.3	12.7	255	162	95	5	133	1.9	21		2.7	0.62	28	21	Miss					
S3	**40**	JG	GBI	84	39	8.3	12.7	255	162	95	5	133	1.9	21	24	2.7	0.62	28	21	Bounce					
S3	**41**	JG	GBI	84	39	8.3	12.7	255	162	95	5	133	1.9	20	22	2.7	0.60	27	20	Hit	24	231	point lost in carcass		
S3	**42**	DP	GBI	83	47	8.4	12.8	263	197	112	5	145	1.8	24		3.5	0.79	42	31	Skip				longitudinal flaking from tip	
S3	**43**	DP	GBI	83	47	8.4	12.8	263	197	112	5	145	1.8	23	26	3.3	0.74	38	28	Hit	27	304			
S4	**44**	DP	Mag	62	22	9.9	12.3	287	109	69	3	225	1.9		23	5.2	1.17	60	44	Hit	30	202			
S4	**45**	DP	Mag	62	22	9.9	12.3	287	109	69	3	225	1.9		21	4.8	1.07	51	38	Skip			bevel rotation		
S4	**46**	DP	Mag	88	30	7.5	12.8	260	113	74	7	191	2.1	20	23	3.8	0.86	39	28	Hit	14	101		longitudinal flaking from tip	bone
NS	**47**	DP	Mag	93	37	7.2	0	NR	133	87	7	217			25	5.4	1.21	67	49	Bounce			hit humerus	longitudinal flaking from tip	bone
NS	**48**	DP	Mag	70	39	8.2	14.4	220	160	95	7	195	2.1		22	4.4	0.98	49	36	Hit	18	166	point lost in carcass		
NS	**49**	DP	GBI	48	38	6	14.5	194	114	85	5	117	2.7	23	27	2.7	0.61	32	23	Hit	12	102	point lost in carcass		

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
NS	**50**	PH	Mag	21	22	7	10.5	188	77	56	4	95.8	1.9	21		2.0	0.45	21	16	Miss			hit target frame	tip snap	wood
NS	**51**	PH	Mag	27	24	6.5	9.9	172	78	59	4	91.8	1.9	24	26	2.2	0.49	26	19	Hit	21	121			
NS	**52**	JW	Clo	71	50	9	14.1	225	225	120	7	199	1.9							Skip					
NS	**53**	JW	Clo	82	43	8.7	12.7	263	187	105	7	200	1.8	21		4.2	0.94	44	33	Miss			hit foam backdrop		
NS	**54**	JW	Clo	82	43	8.7	12.7	263	187	105	7	200	1.8	21		4.1	0.93	43	32	Hit	11	116			
S5	**55**	DP	Bow	73	27	6.9	8.2	146	93	66	A2	34.9	1.5							Hit	14	91	point lost in carcass	longitudinal flaking from tip	bone
S5	**56**	DP	Bow	19	16	6.5	9.1	200	52	43	A2	33.5	1.9							Miss			hit foam backdrop		
S5	**57**	DP	Bow	19	16	6.5	9.1	200	52	43	A2	33.5	1.9							Hit	19	83	point lost in carcass		
S5	**58**	DP	Bow	9	19	7.6	8.6	141	72	52	A2	29.5	1.6							Hit	18	92			
S5	**59**	DP	Bow	92	19	3.7	7.1	111	35	41	A1	26.5	2.1							Hit	16	66			
S5	**60**	DP	Bow	92	19	3.7	7.1	111	35	41	A1	26.5	2.1							Hit	11	46			
S6	**61**	DP	GBI	79	21	6.3	12.7	242	66	52	4	107	2.5	24		2.5	0.57	30	22	Hit	NR				
S6	**62**	DP	GBI	79	21	6.3	12.7	242	66	52	4	107	2.5							Hit	25	127			
S6	**63**	DP	GBI	79	21	6.3	12.7	242	66	52	4	107	2.5							Hit	20	101			
S6	**64**	DP	GBI	79	21	6.3	12.7	242	66	52	4	107	2.5	24		2.5	0.57	30	22	Hit	33	172			
S6	**65**	DP	GBI	59	26	8.4	12.3	262	109	70	5	129	2.0							Hit	15	106			
S6	**66**	JG	GBI	59	26	8.4	12.3	262	109	70	5	129	2.0							Hit	10	71	point lost in carcass	tip snap	bone

Appendix B: A sample page from the shot record sheet used in the carcass experiment

Archaic Beveled Points vs Carcass Experiment—Shot Record Form

brought to you by the MADPIGs

Shot # 5 Projectile Point # 37

Thrower JL Atlatl BRC Dart 1

Flight Video # 1782 Velocity Video # 1150 Still Camera Photo#(s) 3096, 7, 8

Radar Gun Reading 47 mph

Nature of Impact: *Miss*_____ *Good hit* X *Bounce off*_____ *Skip off*_____

*Struck frame*_____ *Other*_____

Impact Damage From: *Bone* X *Flesh*_____ *Dirt*_____ *Rocks*_____ *Wood*_____

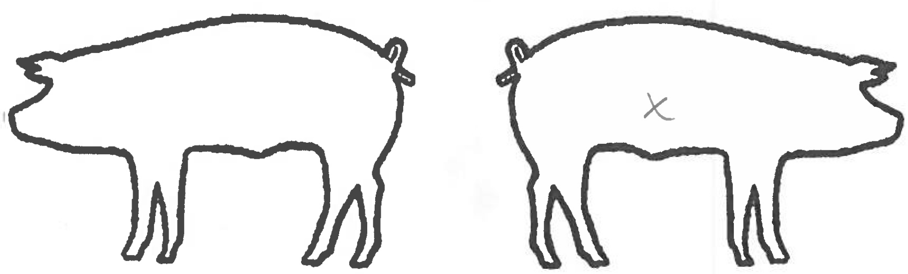
*Other*_____

Nature of Damage: *Edge wear*_____ *Edge flaking*_____ *Basal damage*_____

Latitudinal flaking from tip X *Longitudinal break at body*_____ tip snap

*Longitudinal break at base*_____ *Hafting/foreshaft damage*_____

Approximate Shot Placement:



Comments on shot:

Point came off inside, 10cm back to socket / 3.7 cm to tip off FS - shallow penetration

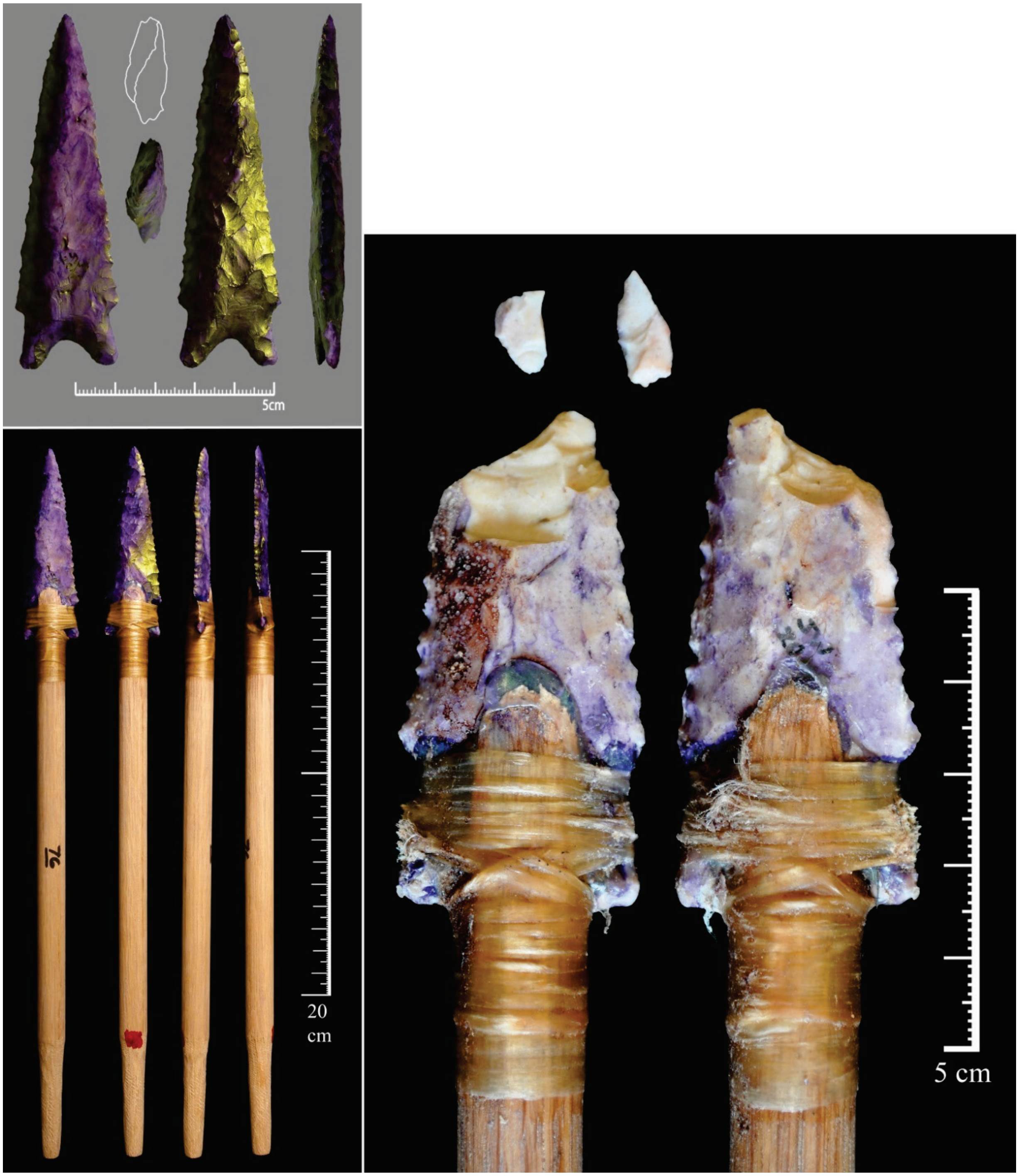
appears to have hit rib - stopped penetration snapped tip

Comments on butchering observations:

Significant nicking in one rib

possible nicking in another adjacent

Appendix C: Additional points mentioned in the text or that received substantial damage.



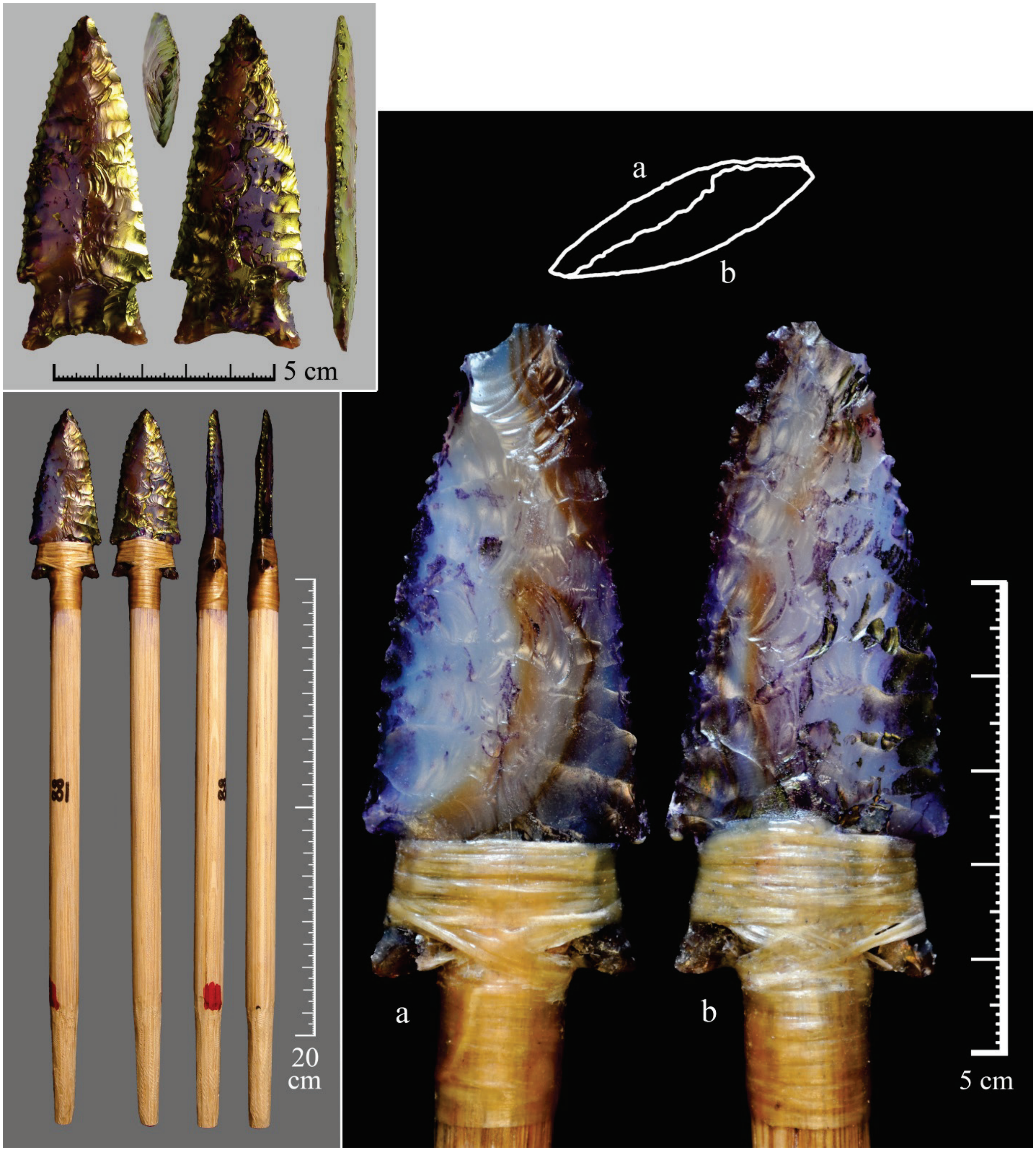
Point #76 had a strong bevel and was thrown three times into the carcass, exhibiting good penetration and bevel rotation. On the fourth attempt it struck the concrete house base and shattered. Upper left) four views of the point prior to hafting, with a line drawing of the profile. Lower left) four views of the complete foreshaft prior to the carcass experiment. Lower right) both faces of the point after hitting a concrete wall.

Point #79 mimics a heavily reworked Dalton point. It was thrown 10 times with one miss and nine hits to the carcass, exhibiting good penetration and bevel rotation, and only slight chipping on the tip. Top) four views of the point prior to hafting, with a line drawing of the profile. Bottom) four views of the complete foreshaft prior to the carcass experiment.

Point #83 is a large "Thebes" style beveled point with a high TCSA, but penetrated better than expected on a mid-weight cane mainshaft on shot #43. Top) four views of the point prior to hafting. Bottom) four views of the complete foreshaft prior to the carcass experiment.

Point #84 is also a "Thebes" style beveled point with a high TCSA due to outward flaring barbs, but also penetrated better than expected on a mid-weight can mainshaft on shot #41. Top) four views of the point prior to hafting. Bottom) four views of the complete foreshaft prior to the carcass experiment.

Point # 86 was attached to a WDC dart that went over the back of the hog on shot # 11 and struck the concrete base of an old house. Upper left) four views of the point prior to hafting. Lower left) four views of the complete foreshaft prior to the carcass experiment. Bottom right) both faces of the point after the carcass experiment.



Point #88 most likely struck a vertebra (not recovered) on shot #46. It was mounted on the heavy cane mainshaft and hit with high KE and P. The impact loosened the point in its haft and shattered the tip. Upper left) four views of the point prior to hafting. Lower left) four views of the complete foreshaft prior to the carcass experiment. Bottom right) both faces of the point after the carcass experiment. Upper right) the point's orientation on impact.