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Raw material impact strength and flaked stone projectile point performance

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ABSTRACT

Archaeologists have previously proposed several different measures of flaked stone raw material “quality”, but this variable has proven difficult to quantify, and the precise characteristics that improve performance remain unclear. This paper presents the results of controlled experiments that were designed to test projectile points made from stones with varying impact strength. By comparing an independent measure of strength with projectile point experimental data, our research suggests that this variable can be objectively measured, and it is a good predictor of some aspects of projectile tip function. Our results show that highly homogenous fine-grained materials with low impact strength (e.g., obsidian) perform well when penetrating elastic materials such as skin and muscle. These same materials, however, function poorly when penetrating more inelastic materials like rawhide, and they are substantially less durable.

1. Introduction

For a number of reasons archaeologists generally consider obsidian to be a high “quality” flaked stone raw material (Callahan, 1979; Kuzmin et al., 2002; Shackley, 2005; Smith, 2015; Tripkovic, 2003; Whittaker, 1994). First, obsidian is an isotropic stone with no preferred direction of fracture (Shackley, 2005:185). Second, obsidian requires less force to detach flakes than other material types. Because of these two characteristics, obsidian can more readily be reduced into complex shapes such as projectile tips. Third, the edges of obsidian flakes are exceptionally sharp. Fourth, obsidian was widely employed for flaked stone tool manufacture and it was transported across long distances, which suggests it was a highly valued raw material (Ellis, 1997; Eerkens et al., 2008; Frahm and Hauck, 2017; Kuzmin et al., 2002; Loendorf et al., 2013; Thomas, 2012; Tripkovic, 2003). As an example, Norton (2008) reports that obsidian from western North America has been recovered from archaeological sites located over 2500 km overland to the east.

This traditional assessment of raw material quality, however, does not reflect all aspects of the performance of tools made from these materials (Braun et al., 2009; Smith, 2015). Instead, materials that perform exceptionally well in some tasks (e.g., warfare) may not be ideal in all respects for others (e.g., hunting). Therefore, in order to understand the performance characteristics of a raw material, it is first necessary to define the relevant functional parameters of tools made from them (Knecht, 1997). This paper focuses on the performance of projectile points manufactured from materials with varying impact strength. Our investigations suggest that while projectile tips made from highly brittle materials such as obsidian excel in some ways, they perform poorly in others.

Rather than replicating prehistoric technology, this investigation instead consisted of controlled experiments in which, to the extent possible, all variables were held constant, and the only factor

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that differed among experimental armatures was the impact strength of the raw materials. Therefore, our experiments provide an objective evaluation of performance when penetrating media with varying elasticity for 58 morphologically similar flaked stone projectile points made from four categories of raw materials.

The perception of raw material quality is not merely a semantic issue. Instead, it affects how researchers interpret the archaeological record, including factors like defining the technological organization of lithic industries (Andrefsky, 1994, 2005; Brantingham et al., 2000; Braun et al., 2009; Daniel et al., 2007; Ensor, 2009; Feinman et al., 2006; Nelson, 1991; Smith, 2015; Tripkovic, 2003; Woods, 2011). Presumed quality also conditions assumptions regarding the value of materials, including the identification of high status goods (McGuire, 1992; Tripkovic, 2003; White et al., 2013). Research presented here suggests that it is impossible to rank order flaked stone point raw materials from low to high quality with respect to projectile performance. Instead, understanding "quality" in this sense necessitates the definition of specific functional traits, and optimization of one design parameter usually results in compromising others (Bousman, 1993; Braun et al., 2009; Knecht, 1997).

2. Quantifying quality

While lithic researchers commonly incorporate the concept of raw material quality in their analyses, this term frequently is not defined, and it is "assumed that certain types of stone were selected for the predictability with which they fractured" (Braun et al., 2009). In general, definitions of stone quality tend to focus on flaking characteristics, with less attention given to durability and other factors (Brantingham et al., 2000; Braun et al., 2009; Feinman et al., 2006; Woods, 2011). Although previous assessments of quality have often been subjective measures based on the observations of modern flintknappers, several approaches for the quantification of this variable have also been proposed, including recording the crystalline properties of stone and conducting mechanical fracturing or hardness tests (Andrefsky, 1994; Brantingham et al., 2000; Braun et al., 2009; Callahan, 1979; Cotterell and Kamminga, 1987; Dibble and Rezek, 2009; Feinman et al., 2006; Lerner et al., 2007; Smith, 2015; Whittaker, 1994; Woods, 2011).

Unlike much of the previous work, our study focuses exclusively on flaked stone projectile point performance. This research, in part, tests the relationship between impact strength and point function. Impact strength describes the ability of an object to resist structural failure when subjected to a rapid collision (Mabry et al., 1988). Lithic analysts generally employ the word "toughness" when referring to the ability of stone to resist breakage, but this term is usually defined as the energy required to propagate a crack in the material (Cotterell and Kamminga, 1987, 1992; Woods, 2011). Although "strength" and "toughness" are similar, the following discussion exclusively employs "strength" because cracks were not intentionally introduced to the materials prior to testing, and strength is therefore a more accurate description of the tested property.

2.1. Impact strength research methods

In order to independently assess the materials employed in the projectile point experiments, their strength was measured using a falling-weight impact tester and sample slabs (see Mabry et al., 1988). Variables affecting fracture were first tested using soda-lime window glass slabs, which were also subsequently used as controls. The glass varied in thickness and was cut into fragments of various sizes and shapes. This testing indicated that the primary variables affecting slab fracture were the distance to the edge and the thickness. Consequently, to control for differences in slab geometry impact locations were always at a constant distance from the nearest edge, and variation in thickness was standardized by dividing the energy necessary to break the slab by the thickness.

The raw material sample slabs were cut using a tile saw with a wet diamond blade. Between 3 and 10 slabs were cut from each of the available materials. Tile saws are a comparatively inexpensive method for producing uniform test slabs, but it was difficult to cut thicker nodules and the slabs varied by a maximum of 1.3 mm in thickness.

The experimental setup consisted of a stand with a height adjustable electromagnet that held a steel ball bearing (Fig. 1; Mabry et al., 1988). For each slab, the bearing was released progressively higher until the slab fractured. This incremental-height method has been shown to produce more consistent results (Mabry et al., 1988). In order to control the contact location, the ball impacted a hardened steel punch with a 4.75 mm diameter tip that was placed directly on the slab, 5 mm from the nearest edge. The punch was placed along an edge that lacked cortex, and had an approximately 90° angle to the impacted face. Slabs were placed directly on a sheet of aluminum that rested on a steel anvil. The slab was repositioned after each impact, so that no spot was hit more than once. Using these procedures we completed 287 impacts to 102 test slabs.

The raw materials employed in the projectile experiments included two obsidian varieties (Government Mountain and Mule Creek), two chert types (Whetstone and Tolchaco), a black fine grained volcanic stone, and a metamorphosed fine grained

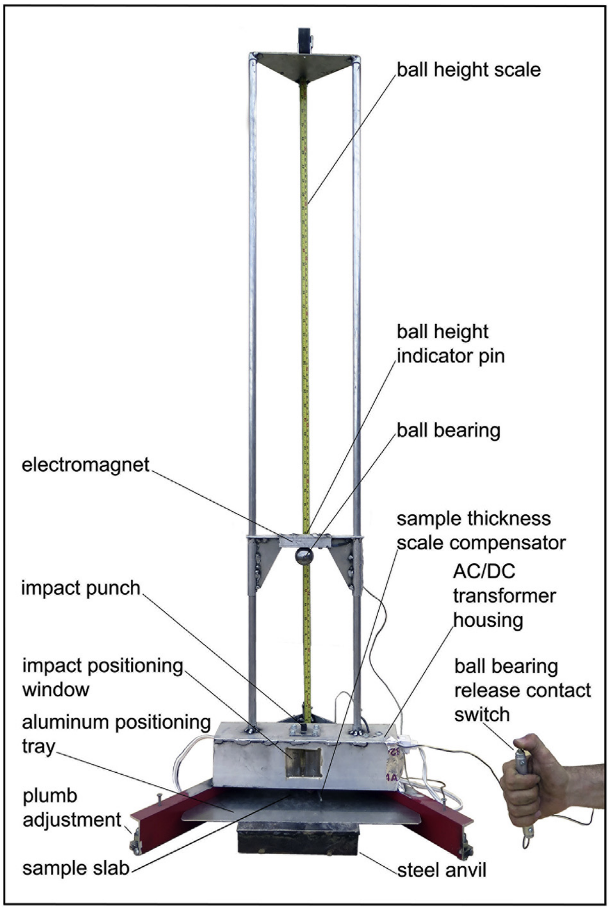

Fig. 1. Device employed to test slab impact strength (illustration by Robert Ciaccio).

sedimentary stone. For convenience, hereafter the latter two materials are respectively referred to as "basalt" and "siltstone". All of the raw materials are from Arizona sources, and they were selected to reflect a wide of a range of variation in impact strength. Although two types of chert projectile points were employed, sufficiently large nodules were unavailable for the Tolchaco Chert, and only the Whetstone Chert was tested.

Table 1 shows the results of the ball bearing impact experiments. The minimum strength is the lowest measured value for impacts that broke the slabs, whereas the average strength is the mean value for impacts that fractured slabs. These data show that the strength of the raw materials varies by a factor of approximately 2.6–2.8. While the values measured for obsidian are lower than the window glass, irregularities on the surface of the obsidian caused by the diamond saw may have weakened the material, and it is possible that all of the results may be slightly lower than would be the case if the slabs had more uniform surfaces. In addition, the values reported for kinetic energy do not incorporate the effects of air resistance on the ball bearing, and because the falling weight impacted a punch, some energy was necessarily lost in this process. Theoretically, however, because they are constant, these factors should not have altered the relative differences observed among the experimental materials. In addition, the glass control samples provide a reference point for other researchers to calibrate their results with ours, and our data can also therefore be rescaled to other measures. Finally, because the two obsidian types have similar values for strength, and only Whetstone chert was measured, the two obsidian types and two chert types are combined in the following analyses.

3. Projectile point performance research methods

To test projectile point performance we conducted laboratory experiments in which shot distance, point of aim, bow strength, point morphology, and arrow characteristics were all controlled. To minimize variation, data were collected in 28 trials during which the target type and distance were fixed. In total 35 commercially prepared wooden arrows were employed. Arrows were matched based on morphological similarity into groups of four, and were fired sequentially by group during trials. Three arrows that lacked stone points were used as controls during the course of the trials.

At the start of each trial, all points were socket hafted and secured with 30 cm of 1 mm wide artificial sinew and commercially prepared pine pitch adhesive. Any points that remained on arrows from previous trials were removed and reattached to different arrows. The points were tightly wrapped with the sinew in a figure 8 pattern. Obsidian, chert, siltstone, and basalt points were secured to one arrow in each matched group. The armatures were all morphologically similar isosceles triangular shapes. Side notches were present in the lower third of the blade, and all points had straight blade margins and straight bases. These characteristics were selected because this is one of the most common designs found in North America (Fig. 2).

Fig. 2. Hafted experimental points, from left: siltstone, chert, basalt, and obsidian.

The experimental armatures approximated the average size of arrow points in a survey collection from 53,000 ha of the Phoenix Basin in southern Arizona (Loendorf and Rice, 2004). Points were fired between 1 and 127 times, with an average of 16 times each. The Mule Creek obsidian, Whetstone chert, siltstone, and basalt armatures were produced by Allen Denoyer. Because of damage to the obsidian and chert points it was necessary to also include Government Mountain obsidian points made by Chris Loendorf, and Tolchaco Chert armatures produced by William Bryce. However, one individual made points of each of the four material categories, all points were produced using the same design template, and they do not vary substantially by material type (Table 2).

In order to minimize shot to shot variability, all projectiles were fired using a fixed stand that maintained a constant draw length and point of aim (Fig. 3). A modern recurve bow with a draw weight of 17 kg at a draw length of 66 cm was employed. Arrow velocities were measured with a Caldwell Ballistic Precision™ chronograph, and they averaged 43 m per second. This velocity is at the lower end of the data summarized by Tomka (2013) for Native American archery equipment in general, and is consistent with data reported by Parks (2017) for his reconstruction of Southwestern US bows.

Arrows were fired indoors in order to minimize variances caused by wind and other factors. In separate trials, targets were positioned at 2.3 m and 7.8 m from the bow, which allows comparison of slightly higher and lower energy impacts. Sample sizes for the 7.8 m trials were small; consequently penetration data reported below do not include foam and rawhide targets at this distance. However, in order to increase sample sizes, breakage data for rawhide targets at both 2.3 and 7.8 m are included when assessing this characteristic. The first arrow shot into a given test media lacked a stone point. This arrow was employed to establish the point of aim for the launching mechanism. These control arrows had sharpened tips, but were otherwise the same as arrows with points. Breakage patterns, velocity, depth of penetration, point detachments, and other data were collected. To maintain consistent conditions, arrows with obsidian, chert, basalt, and siltstone were sequentially fired into the test media. Approximately every 13th

Table 1
Impact strength values for raw materials employed in the experiments.

Material	Avg. Slab Thickness (mm)	Avg. Drop Height (cm)	Ball Weight (g)	Avg. Ke (μJ)	Minimum Strength (μJ/mm)	Average Strength (μJ/mm)
Government Mountain Obsidian	6.93	43	67.3	28,379	4095	4573
Mule Creek Obsidian	6.63	46	67.3	30,359	4579	4739
Window Glass	2.52	20	67.3	13,200	5238	5440
Whetstone Chert	6.63	58	67.3	38,279	5774	5807
Basalt	5.61	92.5	67.3	61,049	10,882	10,954
Siltstone	5.71	100	67.3	65,999	11,558	11,813

Table 2
Metric attributes for the experimental points.

Material		Thickness (mm)	Blade Width (mm)	Length (mm)	Cross Section Area (mm)	Weight (g)
Basalt (n = 10)	Mean	3.4	8.2	19.8	14.1	0.5
	Median	3.4	8.0	19.8	13.5	0.5
	Std. Deviation	0.2	0.5	0.4	1.3	0.1
	Interquartile Range	0.1	1.1	0.4	2.1	0.1
Chert (n = 18)	Mean	3.2	9.0	20.2	14.6	0.6
	Median	3.2	8.9	20.3	14.5	0.6
	Std. Deviation	0.2	0.3	0.3	1.0	0.1
	Interquartile Range	0.2	0.4	0.4	1.9	0.1
Obsidian (n = 20)	Mean	3.1	8.3	19.1	12.8	0.4
	Median	2.8	8.3	19.9	12.1	0.4
	Std. Deviation	0.6	0.5	1.6	2.4	0.1
	Interquartile Range	0.9	0.4	1.4	4.0	0.1
Siltstone (n = 10)	Mean	3.3	9.1	20.6	15.1	0.6
	Median	3.4	8.8	20.4	14.4	0.6
	Std. Deviation	0.3	0.4	0.4	1.9	0.1
	Interquartile Range	0.6	0.9	0.6	4.3	0.1

arrow shot into a given target lacked a stone point. This was done to control for possible shot to shot sources of variation, and to check the point of aim.

Trials using increasingly inelastic targets were undertaken, beginning with foam blocks, then ballistics gel, next rawhide of different thicknesses, and finally bovine scapula covered with ballistic gel (Fig. 4). Although no artificial target can perfectly replicate the effects of a projectile on a living organism, the materials employed have the advantage that they are widely available and comparatively uniform (Rots and Plisson, 2014). Points were first fired into foam targets that consisted of 5 layers of 70-mm thick polystyrene that were covered with a layer of 5-mm thick foam core poster board, and 2 layers of 0.15-mm thick plastic. These targets are analogous to human and other animals in the sense that the exterior consists of elastic materials (i.e., plastic and poster board), which covered a more inelastic material (i.e., foam) as is the case with skin and muscle. Following the foam block trials, points were fired into commercially prepared synthetic ballistic gelatin that was made by Clear Ballistics ™. These targets were more than 15 cm thick, they match the density of human tissue, and they are more stable at a wider range of temperature than organic gelatin. Next, to examine impacts with less elastic materials, rawhide with thicknesses between 2.6 mm and 3.0 mm was placed in front of the ballistics gel. Finally, points were fired at a block of approximately 5 cm thick ballistic gelatin covering two bovine scapula.

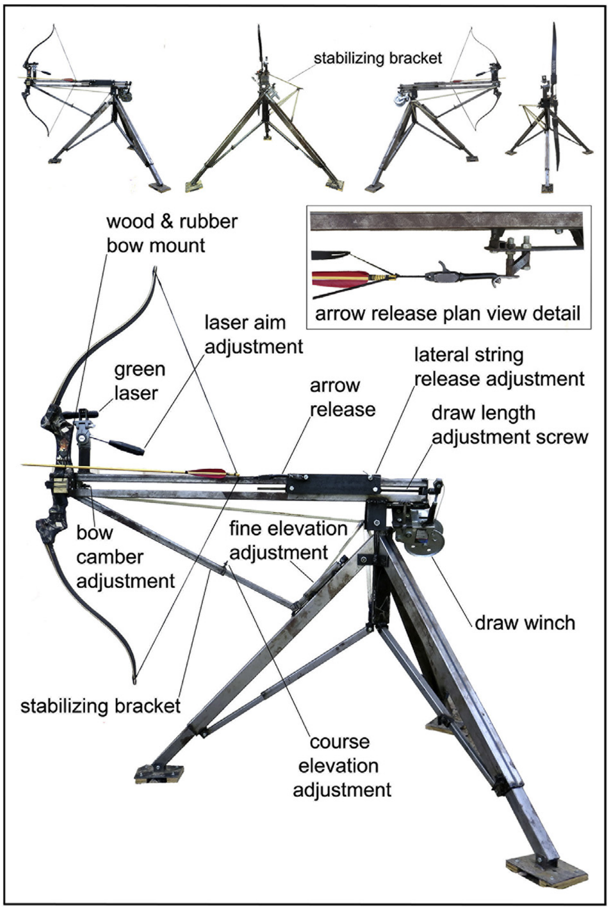

Fig. 3. Bow rest designed and built by Lynn Simon (illustration by Robert Ciaccio).

4. Results

The following analyses present data for 818 arrow impacts to the four target types that were employed (Table 3). Two fundamental projectile performance factors that were quantified in the experiments are examined in the following analyses (Christenson, 1997; Cheshier and Kelly, 2006; Cotterell and Kamminga, 1992; Loendorf, 2012; Loendorf et al., 2017; Rots and Plisson, 2014; Shott, 1993; Sisk and Shea, 2009; Sliva, 2015; Tomka, 2013). 1). *Wound size*; in this analysis projectile sectional area was held constant, and wound size was quantified based on the depth of penetration. Because the draw weight and length were fixed, the potential energy of the bow was held constant, and arrow weight was therefore used to standardize the penetration data. 2). *Projectile durability*; breakage and point detachment patterns were used to assess this variable.

4.1. Projectile wound size (penetration depth)

Fig. 5 shows boxplots of penetration data for arrows tipped with points of the four materials, and the control arrows that had wood tips (Table 4). Data for the bone targets are not shown because most of the arrows failed to penetrate this material, and the sample sizes are small due to the damage caused to the points. Similarly, data for foam and rawhide targets at 7.8 m are not reported here due to small sample sizes. Within the foam (unpaired *t*-test: t = −7.4, df = 54.7, p = .0) and ballistics gel (unpaired *t*-test: t = −6.9,

Fig. 4. Foam block (upper left), ballistic gel (upper right), rawhide (lower left), and ballistic gel encased bovine scapula (lower right) targets.

df = 18.5, p = .0), all arrows that were tipped with stone penetrated significantly deeper than arrows that lacked stone armatures. Not only is this consistent with previously reported experimental results, but the patterning by tip type is also similar for the more elastic foam and less elastic ballistic gel targets (Loendorf et al., 2015a, 2015b; Waguespack et al., 2009).

In general, lower impact strength materials penetrated deeper than higher strength stones within the elastic targets. The variation among arrow tip types is similar at higher energies (close range) and lower energies (longer range) for the ballistic gel data (Fig. 6). However, the siltstone performance is inconsistent, and in some cases siltstone penetrated better than expected. It is unclear if this is simply a result of stochastic variation in the dataset, or if the variable performance of the siltstone is a product of the nature of the raw material itself. Siltstone is heterogeneous, and it is possible that the irregularity of the material may have resulted in varied performance of the points made from it. This possibility is supported by the fact that although similar stone is widely available in southern Arizona, where the siltstone used in the experiments was derived, this material was rarely used for point manufacture. For example, it accounted for only 4 of the collection of 985 points (0.4 percent) from the Gila River Indian Community (Loendorf and Rice, 2004).

Although obsidian penetrated slightly deeper on average than all of the other point types for the foam and gel targets, it did not perform well when penetrating rawhide (see Table 4 and Fig. 5). Obsidian had the lowest median and mean penetration depths into rawhide, being outperformed even by wooden tips. These data suggest that obsidian is poorly suited for applications where high durability is essential. Finally, while the differences in penetration depths that were measured among the material types are relatively modest, this statistic probably underestimates the actual degree of variation in real world performance, especially with respect to damage of veins and arteries. This is because these data suggest that the sharpness of low strength stones is most important for penetrating elastic materials, which may otherwise stretch without structural failure. The round shape and elastic nature of veins and arteries are likely to limit damage by dull projectiles, especially for wooden tipped arrows that will only effectively cut at the tip. In contrast, the entire width of a stone point has sharp cutting edges, which increases the area where elastic materials will be effectively damaged, and cutting efficiency is increased by sharper edges.

Comparison of point attributes that have previously been shown to affect performance suggests that the differences observed by material type are not the result of morphological variation among the points. For example, based on their experimental results, Sisk and Shea (2009) observed that the penetration ratio (depth of penetration/point length) and penetration depth are “more strongly correlated with point width and cross-sectional perimeter than with thickness or cross-sectional area”. As can be seen in Table 5, however, our data show only weak correlations for width and perimeter data, and it does not appear that patterned variation

Table 3
Shot counts by target type and point type.

Target Type	Basalt Point	Chert Point	Obsidian Point	Siltstone Point	Wood Point	Total
Bone	5	5	5	3	3	21
Foam	124	74	95	93	46	432
Gel	63	63	68	60	27	281
Rawhide	13	16	24	15	16	84
Total	205	158	192	171	92	818

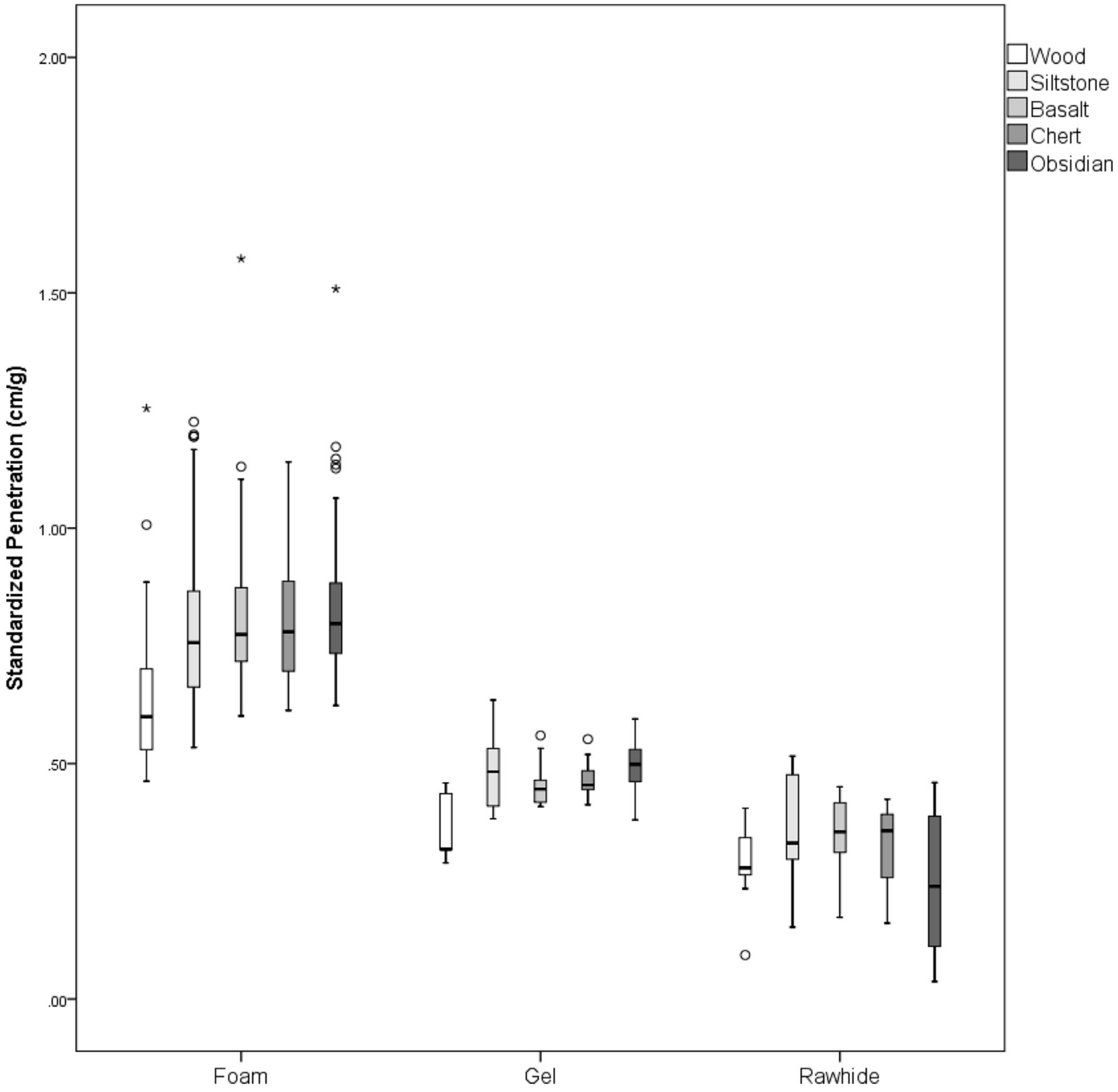

Fig. 5. Standardized penetration data by tip type for 2.3 m targets.

in these attributes affected our results.

4.2. Projectile durability (point detachment)

Although these data show a substantial range of variation, obsidian and chert projectile points detached more readily from arrow shafts than did siltstone and basalt (Fig. 7). Data are only reported from the foam trials because arrows were not fired until all points detached for the other target types. The detachment rates for obsidian and basalt are significantly different (unpaired *t*-test: $t = -2.64$, $df = 15.5$, $p = .02$), and the chert and basalt rates are statistically significant at the 90 percent confidence interval (unpaired *t*-test: $t = -1.97$, $df = 21.7$, $p = .06$). This appears to be because the pine pitch adhesive used to attach the points did not bond well with the obsidian or chert due of the fine surface textures of these materials. These data suggest that it is more difficult to firmly affix obsidian and chert points to arrow shafts, and secure attachment would require alternate strategies. Finally, the detachment rate for the siltstone is lower than expected based on the comparatively coarse grain structure, and this may also be related to the heterogeneous nature of this stone.

4.3. Projectile durability (point breakage patterns)

Table 6 shows point breakage patterns by material type for the rawhide and bone targets. In order to increase sample sizes, these data include targets at both 2.3 and 7.8 m. Not surprisingly, little damage occurred to points in both the foam and ballistic gel; however, individual obsidian points broke in each of these targets. Also not surprisingly, damage occurred to all stone types in the rawhide impacts, and every armature that impacted bone broke.

Overall, arrows with wooden tips were by far the most durable, and in some cases these projectiles were still able to penetrate the rawhide even after being blunted by previous impacts. These data show that if arrow tip durability was a paramount concern, then none of the stone types tested in the experiments would have been selected for the production of armatures.

As expected, the rawhide breakage patterns are inversely associated with the strength values that were measured in the weight drop experiments (Fig. 8). These data suggest that the strength values are a good predictor of point durability. However, additional data, especially for materials of intermediate strength, are necessary to more thoroughly assess this relationship.

Table 4
Standardized penetration (cm/g) data summary statistics by target type.

		Foam 2.3 m	Gel 2.3 m	Gel 7.8 m	Rawhide 2.3 m
Wood	N =	46	17	10	10
	Mean	0.63	0.36	0.33	0.29
	Median	0.60	0.33	0.32	0.28
	Std. Deviation	0.15	0.06	0.03	0.09
	Interquartile Range	0.17	0.12	0.04	0.09
Siltstone	N =	93	36	24	9
	Mean	0.79	0.48	0.46	0.35
	Median	0.75	0.48	0.45	0.33
	Std. Deviation	0.16	0.08	0.05	0.12
	Interquartile Range	0.21	0.12	0.11	0.21
Basalt	N =	124	39	24	8
	Mean	0.80	0.45	0.44	0.34
	Median	0.77	0.45	0.45	0.36
	Std. Deviation	0.13	0.04	0.05	0.10
	Interquartile Range	0.16	0.06	0.11	0.15
Chert	N =	74	38	25	10
	Mean	0.80	0.46	0.45	0.33
	Median	0.78	0.45	0.45	0.36
	Std. Deviation	0.11	0.03	0.02	0.10
	Interquartile Range	0.19	0.04	0.04	0.17
Obsidian	N =	95	46	22	17
	Mean	0.82	0.50	0.50	0.25
	Median	0.78	0.50	0.50	0.24
	Std. Deviation	0.14	0.05	0.50	0.15
	Interquartile Range	0.16	0.07	0.06	0.29

Finally, all of the points that impacted bone failed, and the damage to materials with lower strength was severe. Fig. 9 shows all of the pieces that were recovered from the six obsidian points that hit bone. Despite the controlled conditions, it was not possible to collect most of the fragments because of their small size. While the higher strength siltstone and basalt armatures were more durable, all of them were severely damaged. For example, Fig. 10 shows one of the largest fragments that was recovered from the five basalt points that were shot into bone, and it received extensive damage to the tip, edges, and base. These results suggest that even under relatively modest impact energies, small flaked stone points that strike thick bone are unlikely to remain sufficiently intact to be reworked, especially for highly brittle stone like obsidian. The degree and type of damage to points, however, varies substantially under different conditions (Rots and Plisson, 2014).

5. Discussion

Our experiments suggest that while low strength stones like obsidian are ideal for penetrating elastic materials such as skin, muscle, and veins, they perform poorly when penetrating inelastic materials including rawhide and bone. Fine-grained stone, especially obsidian, is also more difficult to firmly attach to arrow shafts than are coarser grained materials. This material is also substantially less durable than high strength stone types. These differences show that the finest grained materials with the lowest strength are better suited for some tasks than others.

Extensive ethnographic evidence suggests that flaked stone projectile points were primarily employed for large game hunting or warfare, and stone points were often designed differently for these two tasks (Ahler, 1992; Ellis, 1997; Keeley, 1996:52; Loendorf, 2012; Loendorf et al., 2015a, 2017; Mason, 1894; Stevens, 1870:564). One of the most common distinctions is that points intended for warfare were loosely attached to arrows, while hunting points had design features that facilitated secure hafting (Loendorf et al., 2015a). Since secure hafting is not a concern for warfare designs, obsidian is better suited for this task, and the low durability of obsidian tips is also advantageous. First, if points readily break then adversaries will not be able to pick up shot arrows and fire back an effective weapon. Second, fragmentation within wounds makes it more difficult to remove the point, creating a more serious injury (Bill, 1862, 1882; Nelson, 1997). Third, arrow wounds received in warfare are also most likely to occur to the extremities, where blood loss is the primary threat, and the superior cutting characteristics of obsidian are therefore advantageous (Bill, 1862, 1882; Milner, 2005).

While obsidian may be ideal in some ways for warfare point designs, any raw material choice is conditioned by multiple factors, and availability has been shown to be one of the paramount issues (Andrefsky, 1994, 2005; Smith, 2015). For example, in regions where obsidian was abundant, it was commonly employed for many tasks where its performance may not have been ideal. Modifying other attributes of the projectile delivery system is one way of addressing factors that compromise given performance characteristics. For example, a method to compensate for the difficultly in firmly attaching fine grained stone points is by using other more secure binders, such as asphaltum (Fauvelle et al., 2012; Thomas, 2012).

The middle Gila region within the Phoenix Basin of south central Arizona is an interesting case study because almost all of the stone that was used to manufacture projectile points had to be imported (Loendorf, 2012; Loendorf and Rice, 2004). Consequently, examination of patterning in raw material usage over time provides insight to changes in stone preference that are not related to availability (Table 7). For example, basalt is the most common stone used for Middle Archaic dart points, which were distinguished based on their size as well as morphology (see Loendorf and Rice, 2004). Archaeologists have long recognized that atlatl points are generally larger than arrow points, and size is commonly employed to separate these types (Erlandson et al., 2014; Heldebrandt and King, 2012; Thomas, 1978; Shott, 1993, 1997). The use of basalt then declined until the Classic period when it was again used to make small numbers of points. Chert was popular throughout the sequence, but use of this material peaked during the pre-Classic period, when it comprised nearly half of all points. Obsidian use was greatest during the Classic period, a pattern that has also consistently been observed throughout the southern Southwestern US (Bayman and Shackley, 1999; Fertelmes et al., 2012; Peterson et al., 1997:103; Rice et al., 1998:110; Ballenger and Hall, 2011:146–148; Loendorf et al. 2013; Marshall, 2002; Shackley, 2005).

The temporal patterning in raw material use within the Phoenix Basin suggests that technological changes such as the introduction of the bow and arrow altered the choice of materials employed to manufacture projectile points. Middle and Late Archaic period atlatl darts tips were rarely made from obsidian, and more durable coarser grained stones were substantially more prevalent. The larger size of atlatl darts makes them more difficult to transport, and this may have increased the importance of having fewer but more durable weapons (see Ellis, 1997:56–63). In addition, because of their larger size, dart points could be employed for a wider range of functions including cutting tasks, and this may also have favored the use of more durable materials.

The general trend toward increasing reliance on obsidian is also consistent with patterning in point types that suggests the proportion of warfare tips increased progressively over time. While warfare designs are rare for Archaic points, half of the Preclassic armatures are warfare types, and by the Classic period approximately 65 percent of the points have design features that suggest they were made for use in conflict with other people (Loendorf, 2012; Loendorf et al., 2015a). At the same time, our data suggest

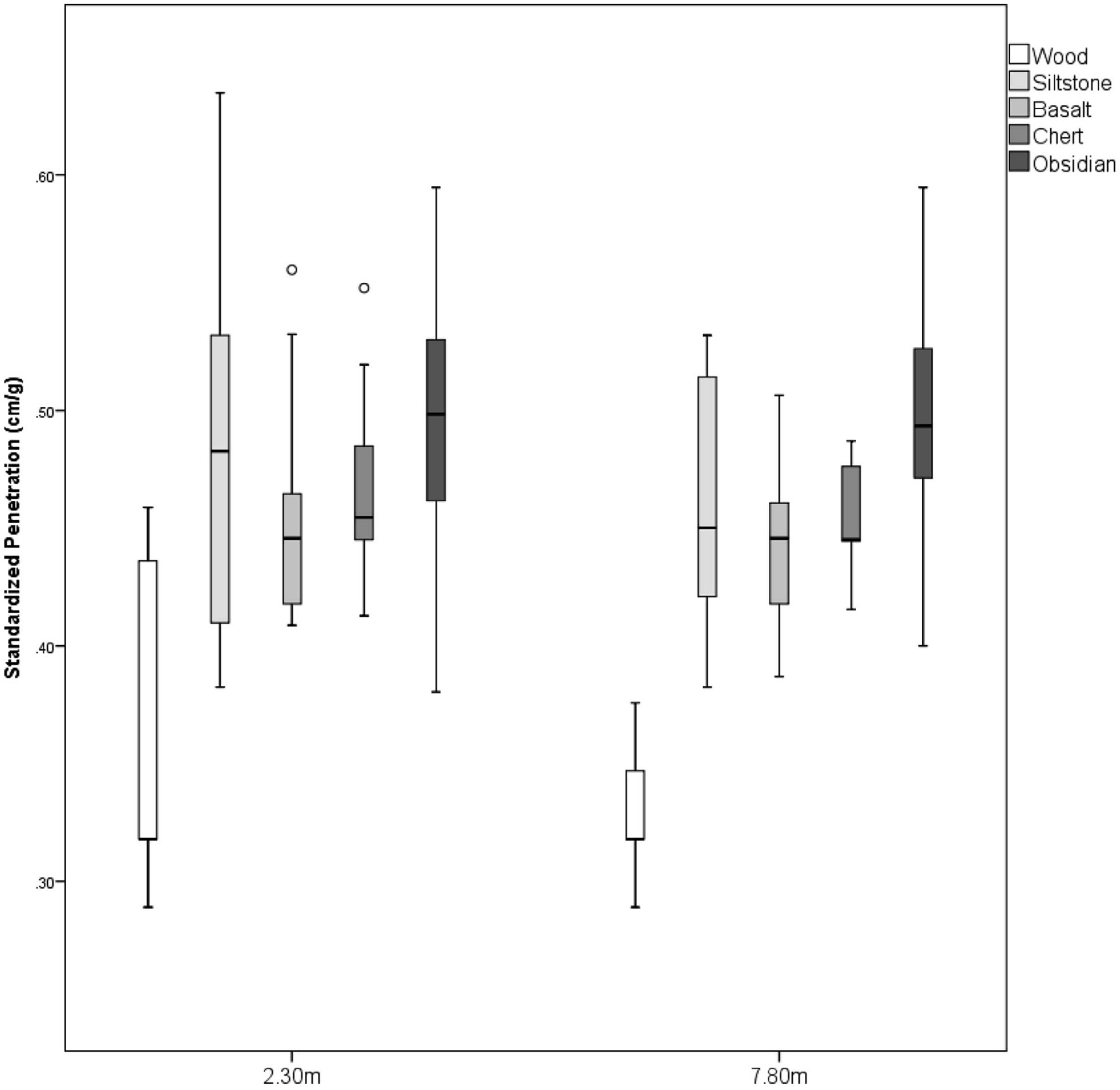

Fig. 6. Penetration data for ballistics gel targets at 2.3 and 7.8 m from the bow.

Table 5
Pearson correlation coefficients and significances for point impacts with foam, gel, and rawhide targets at 2.3 m.

		Width	Thickness	Area	Perimeter
Foam 2.3 m Penetration Ratio	Pearson Correlation	0.17	−0.13	−0.03	0.14
	Sig. (2-tailed)	0.00	0.01	0.52	0.01
Foam 2.3 m Penetration	Pearson Correlation	0.32	−0.16	0.02	0.28
	Sig. (2-tailed)	0.00	0.00	0.68	0.00
Foam 2.3 m Stand. Penetration	Pearson Correlation	0.16	0.02	0.11	0.17
	Sig. (2-tailed)	0.00	0.71	0.03	0.00
Gel 2.3 m Penetration Ratio	Pearson Correlation	−0.2	−0.07	−0.15	−0.19
	Sig. (2-tailed)	0.01	0.41	0.05	0.02
Gel 2.3 m Penetration	Pearson Correlation	0.02	0.09	0.08	0.04
	Sig. (2-tailed)	0.78	0.24	0.35	0.6
Gel 2.3 m Stand. Penetration	Pearson Correlation	−0.07	−0.27	−0.2	−0.06
	Sig. (2-tailed)	0.41	0.01	0.01	0.45
Rawhide 2.3 m Penetration Ratio	Pearson Correlation	0.1	−0.06	0.01	0.04
	Sig. (2-tailed)	0.53	0.71	0.97	0.82
Rawhide 2.3 m Penetration	Pearson Correlation	0.14	−0.08	0.01	0.07
	Sig. (2-tailed)	0.38	0.62	0.98	0.68
Rawhide 2.3 m Stand. Penetration	Pearson Correlation	0.21	−0.08	0.04	0.13
	Sig. (2-tailed)	0.18	0.63	0.83	0.4

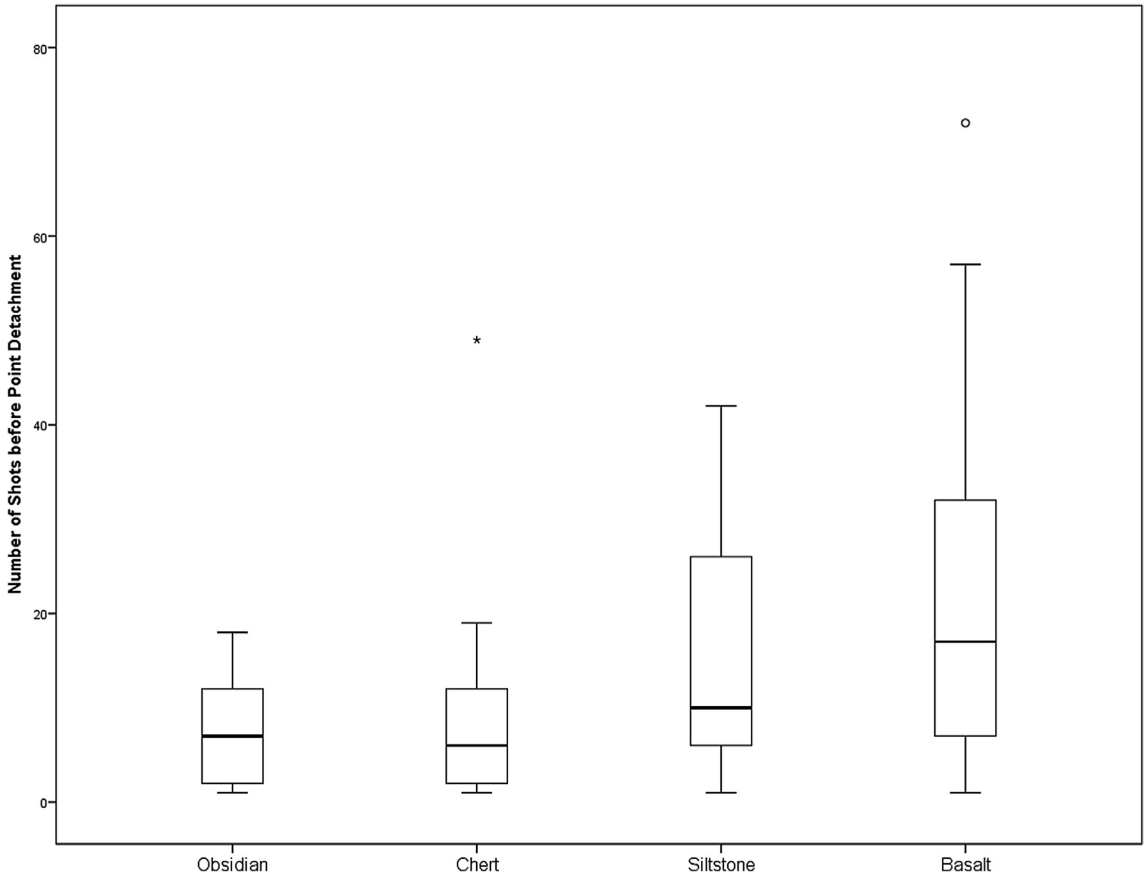

Fig. 7. Shot count before point detachment in foam target blocks.

that obsidian performs poorly when penetrating even relatively thin rawhide, and the use of rawhide armor may have limited the effectiveness of obsidian in combat. Based on archaeological data including rock art (Baldwin (1997):11–14), argued that thick rawhide shields were introduced to the Southwestern US by Apachaen populations around A.D. 1400, and the increase in the use of higher strength basalt in late Classic period and early Historic periods may have been an attempt to overcome this defense. Finally, the comparatively high incidence of chert throughout the sequence suggests it may have been preferred for projectile point manufacture in part because it offers a compromise between relatively sharp cutting edges and greater durability than obsidian.

Table 6
Point breakage patterns by target media (includes rawhide targets at 2.3 and 7.8 m).

			Point Break		Broken	Total
			No	Yes		
Rawhide		Wood	16	0	0%	16
		Siltstone	13	2	13%	15
		Basalt	11	2	15%	13
		Chert	9	7	44%	16
		Obsidian	14	10	58%	24
	Subtotal		59	25	29%	84
Bone						
		Wood	1	2	67%	3
		Siltstone	0	3	100%	3
		Basalt	0	5	100%	5
		Chert	0	5	100%	5
		Obsidian	0	5	100%	5
	Subtotal		1	20	96%	21

6. Conclusions

The raw materials employed to produce flaked stone projectile points varied substantially across space and time. However, little research has previously been done on the performance of different types of stone. This study focused on the effects of raw material impact strength on the performance of small side-notched triangular flaked stone projectile points. Through controlled experimentation, this research provides an objective evaluation of raw material performance against target media with varying elasticity. The results of this investigation therefore provide insight into temporal and spatial variation in the raw materials that were selected to manufacture flaked stone projectile points. This research has also described a methodology for falling-weight impact testing of raw materials that is inexpensive and produces semi-quantitative results that are correlated with the results of the projectile tip experiments.

Research presented here shows that all stone tipped arrows are significantly better at penetrating elastic targets than are wooden tipped arrows, but this comes at the cost of decreased durability, and performance against inelastic media varies. Similarly, obsidian and chert provided the best performance for the penetration of elastic targets, but they are substantially less durable. In particular, because obsidian points readily break, they perform especially poorly against inelastic targets including rawhide and bone, where they suffered catastrophic failures. Given that obsidian was one of the more common materials used to make arrow points, this patterning suggests that durability was not a primary concern (Smith, 2015). It is also more difficult to firmly attach obsidian points to arrow shafts. This characteristic, as well as the poor

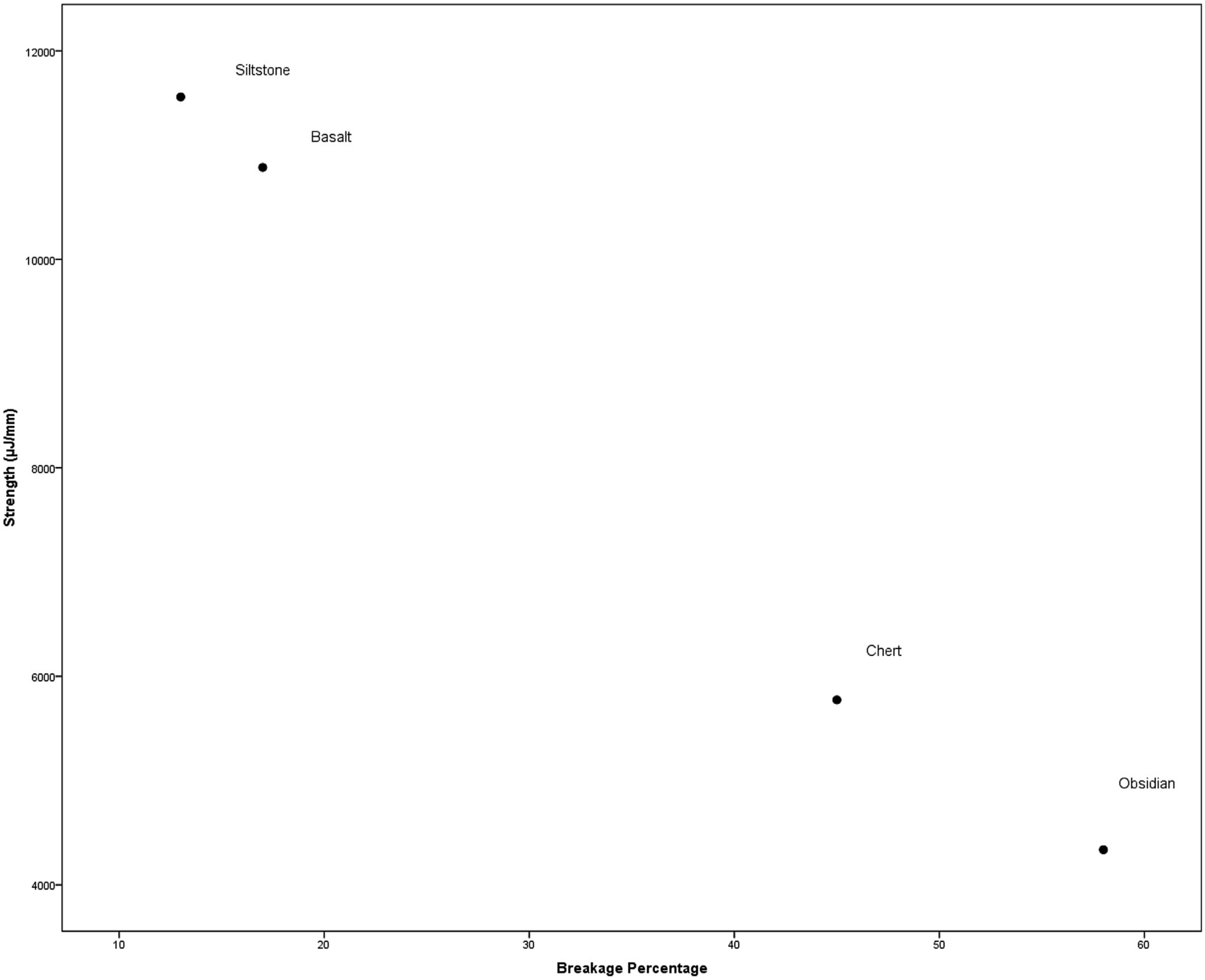

Fig. 8. Percentage of points broken in rawhide impacts and impact toughness.

durability of the material, may have been properties that were preferred for the manufacture of points intended for use in warfare. This possibility is supported by data from southern Arizona that show a general trend of increasing obsidian use, which coincides with an increase in the incidence of points designed for warfare. At the same time, the use of rawhide and other types of armor may have limited the effectiveness of obsidian in combat.

In general, durability does appear to have been a greater concern

Fig. 9. All obsidian point fragments recovered from six points that impacted bone.

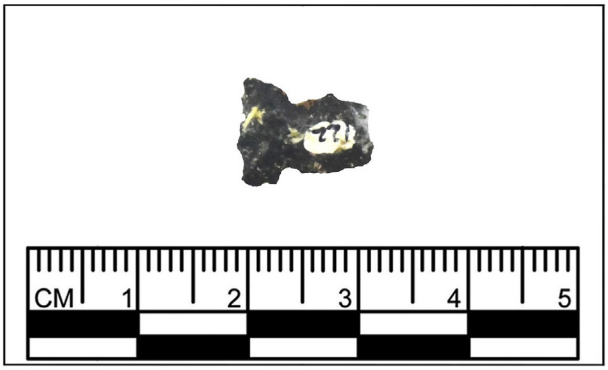

Fig. 10. Basalt point fragment recovered from the bone impact tests.

Table 7
Projectile point raw material by time period (adopted from Loendorf and Rice, 2004).

Period	Obsidian	Chert	Chalcedony	Rhyolite	Basalt
Middle Archaic Dart Point ca. 5000 B.C. - 2500 B.C.	2%	29%	1%	12%	56%
Late Archaic Dart Point ca. 2500 B.C. - A.D. 650	3%	35%	0	32%	30%
Preclassic Arrow Point ca. A.D. 650 - 1150	39%	47%	10%	4%	0
Classic Arrow Point ca. A.D. 1150 - 1500	49%	36%	4%	0	11%
Historic Arrow Point ca. A.D. 1500 - 1900	33%	36%	6%	1%	24%

for larger atlatl dart tips, which is also consistent with indications that they were more frequently reworked (Bettinger and Eerkens, 1999; Flenniken and Raymond, 1986; Hoffman, 1985; Loendorf, 2012:19–20). Finally, chert points offer a compromise between good penetration of elastic materials and higher durability than obsidian, which may account for the temporally and spatially widespread use of this stone for the manufacture of both atlatl and arrow tips. Additional experiments are necessary to further test these observations regarding the performance of flaked stone raw materials, and this investigation has presented methodological approaches to guide these studies.

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