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Shooting out the slate: working with flaked arrowheads made on thin-layered rocks

Carlos Rodríguez-Rellán [a,*], Ramón Fábregas Valcarce [a], Elías Berriochoa Esnaola [b]

[a] *Department of History I, University of Santiago de Compostela, Praza da Universidade, 1. 15782, Santiago de Compostela, Spain*
[b] *Department of Applied Mathematics, University of Vigo, Spain*

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ABSTRACT

Although there are many archaeological and ethnographic evidences for the use of slate and similar rocks for flaking purpose, they raised little interest among specialists, leading to a general ignorance of specific problems associated with these raw materials. Starting from the study of several Neolithic and Chalcolithic slate collections of the Western Iberia, the mechanical properties of slate and its impact on knapping process has been defined; subsequently, manufacturing and use of slate and phyllite projectiles have been undertaken. The results show that the ease with which these materials break into sheets of uniform thickness and morphology would provide an ideal basis for a fast and easy manufacture of arrowheads. In addition, these projectiles have shown a penetration capability and resistance statistically equivalent to those made on more standard materials (i.e. chalcedony or rock crystal). Therefore, slate and other rocks with a high degree of fissility would have been very attractive to prehistoric knappers endeavouring to make arrowheads.

1. Introduction

Slate, phyllite, schist or similar stones, have a medium hardness and a layered structure marked by cleavage planes (slaty cleavage, schistosity) that result in a high anisotropy and a splintery fracture with an unpredictable progression that somewhat hinders the control of the knapping process. As a result, these rocks were not traditionally rated as suitable raw material (Andrefsky, 1998; Odell, 2004) with the exception of, perhaps, the more "siliceous" varieties (Callahan, 1990; Whittaker, 1994).

However, that view is at odds with the importance accorded to these raw materials during Prehistory. While it is true that a significant portion of these industries are polished, especially in the Arctic Regions of America and Europe (Clark, 1982; Mandelko Sierra, 2006; Zvelebil, 2006), where its use has persisted almost into the 20th Century (Ellis, 1997; Graesch, 2007), there are also references to flaked industries on foliated rocks in many archaeological sites with different chronologies across Europe (Ljubin and Bosinsky, 1995; Baales, 2001; Marín Señán, 2001; Olofsson, 2003), reaching special significance in certain areas of Western Iberia during the Neolithic and Chalcolithic(IV-III Millennium BC) (Jorge, 1986; Enríquez Navascúes, 1989) (Fig. 1). Here, though less common than flint and other rocks, this raw material is subject of specialized work (Bradley et al., 2005), it is integrated into the exchange networks and is used in funerary offerings, along with prestige goods such as long flint blades or metal objects (Fábregas Valcarce, 1991; Bueno Ramírez, 1988).

Unfortunately, scholars have not paid much attention to the processes of production and use of flaked artefacts on slate and only valuable information has been gathered about the fabrication of polished objects such as spears, arrows or knives (Banahan, 2000; Morin, 2004; Graesch, 2007). We shall try to fill that gap by working with data derived from the study of slate and phyllite flaked industries from Western Iberia (Rodríguez Rellán, 2010).We will characterize the mechanical properties of the slate and phyllite, specifically on the more fissile varieties, therefore, gaining a knowledge on how their mechanical properties differ from those of more traditionally used materials, such as flint. Also, the process of manufacture and use of arrowheads on slate/phyllite has been reproduced experimentally. Thus, we aimed to define the specific knapping problems, identify particular technical solutions and also check if those projectiles made in rocks with a high degree of foliation and apparently less resistant to impacts, were competitive with their equivalents made of harder materials.

2. Physical attributes of slates

Slate is a rock that originates in regional-scale metamorphism characterized by relatively low temperatures in clay sediments. It is

* Corresponding author. Tel.: +34 981 563 100 12696; fax: +34 881 812 710.
E-mail address: carlos.rellan@usc.es (C. Rodríguez-Rellán).

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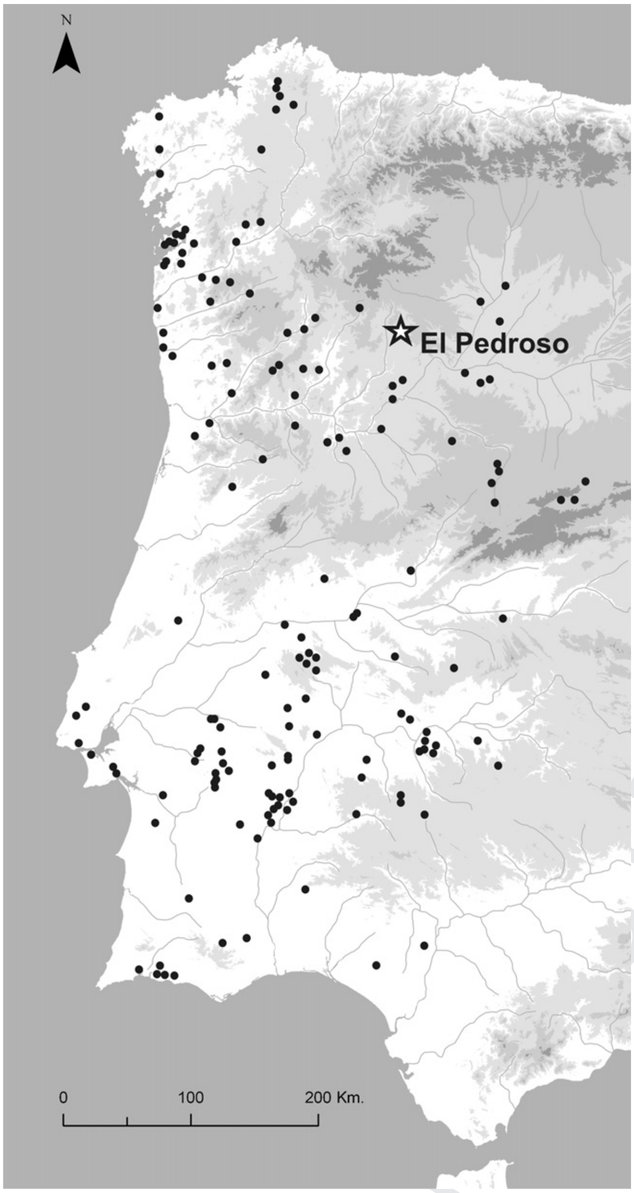

Fig. 1. Map of Western Iberia with the location of El Pedroso and other archaeological sites where lithic industries on slate, phyllite or schist are recorded.

a crystalline and microgranular material, whose main feature is the foliation or fissility, also known as "slaty cleavage": the separation of plates or sheets arranged in parallel. These planes filled with mica and other minerals are generally less resistant and are responsible for the slate's fissility. Other allied processes can affect the mechanical characteristics of slate, causing irregularities and imperfections in its structure such as quartz veins and inclusions, crenulation cleavage and presence of microfractures or kink-bands.

There is some terminological confusion among archaeologists, who use interchangeably terms such as shale, slate or schist. On the other hand, terms such as "siliceous" or "silicified slate" have been used to mistakenly identify rocks as phyllite, shale or metamorphosed lutite and even lydite. In this paper, we deal with different types of slates (gray and black slate) and phyllites of Silurian-Devonian age from North-western Iberia. Our choice has to do with the fact than the Chalcolithic site of El Pedroso (Zamora) is located in this area, and it is the studied site where the knapping of slate achieved more importance (Delibes de Castro, 1995; Bradley et al., 2005).

The petrographic characterization of these materials was done by XRD, XRF and thin section. The results showed the presence of certain elements, mainly Si, FeO and Ca, which often function as "cement", resulting in a greater cohesion and hardness of the material and, ultimately, a greater tendency to conchoidal fracture. However, the presence of Al, K and Cr, associated with mica-like sericite and muscovite present in the cleavage planes, tends to be related with more foliated materials producing a, sometimes very marked, splintered fracture.

There are many varieties of slate, differentiated by the degree of compaction of their internal structure, affecting their fissility, hardness and type of fracture. Despite this variability, there are a number of common features: a hardness of 3–5 on the Mohs scale and an elasticity coefficient that is rather high, making it very shock-resistant, especially if the impacts occur perpendicularly to the cleavage planes. Elastic waves and other forces advance much more easily along the softer sub-parallel layers of mica and other materials (Rodríguez Sastre and Calleja, 2004), a fact that, while obvious, is important for the exploitation of this raw material. Aliste slates used during experimental reproduction of the projectile points were subjected to a test, employing an Equotip durometer, to measure the specific capacity of penetration by elastic waves in relation to the direction of the cleavage planes.

The Equotip is a device consisting of a piston that rebounds against a solid surface. The quotient of impact and rebound velocities of this piston will indicate the hardness of a material based on the Leeb hardness test (in a scale of 0–1000). The Equotip works in a similar way to the Schmidt Hammer (Aydin, 2009), although it has certain advantages such as the smaller diameter of its piston (3 mm), allowing greater accuracy of measurement, or the automatic correction of the angle, which minimizes alterations in measurements caused by the gravity force. However, the most obvious advantage from our perspective lies in its low invasiveness (Aoki and Matsukura, 2008), allowing the use on archaeological materials (Mol and Viles, 2010).

Although less accurate than other devices, both Equotip and Schmidt Hammer can be used to measure beyond hardness, tensile stress or weathering degree (Aydin, 2009; Katz et al., 2000). However, the main interest of Equotip in our case is allowing us to observe the level of anisotropy, information that will be most useful when dealing with a strongly anisotropic material such as slate.

We used the Equotip on the main varieties of slate and phyllite present in the studied assemblages: 40 readings were made on each sample, distributed according to their orientation with respect to the cleavage planes (perpendicular, oblique and parallel to the cleavage planes) (Fig. 2). In every case, there is a significant direct relationship between the rebound of elastic waves and the inclination with respect to the direction of the schistosity or cleavage planes. Resistance is much higher when impacts are made perpendicular to the cleavage planes so that, the penetration of a mechanical force applied will be much less if done in this direction; exactly the opposite happens when impacts occur in a parallel orientation, where the rebound is drastically reduced. In this sense, several authors have studied and reproduced experimentally the fracture parameters of rocks with a high degree of planar anisotropy (Lérau et al., 1981; Gatelier et al., 2002; Aydin, 2009), and all observed a relationship between fracture parameters and structural anisotropy, because the fracture propagation occurs mainly along the cleavage planes.

3. Projectile manufacture

The technological analysis of the El Pedroso assemblages shows that the primary goal in the reduction of slate blocks was to obtain sheets of appropriate thickness to make arrowheads (Fig. 3), so the

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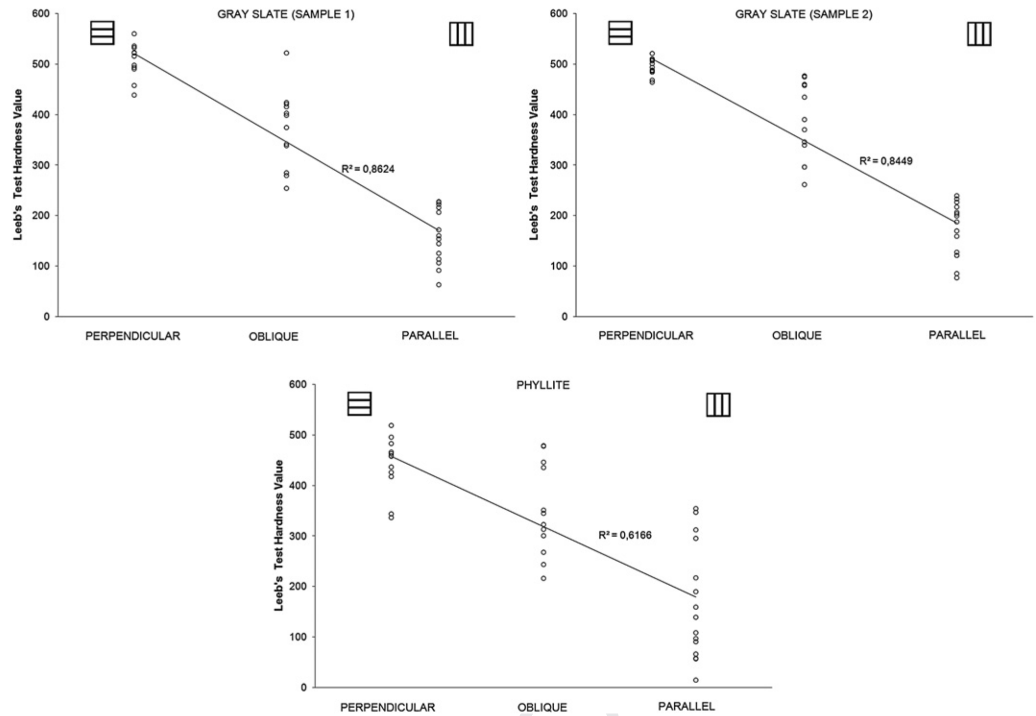

Fig. 2. Variation on the values of slate and phyllite hardness as recorded by the Equotip when applied at different angles with respect to the cleavage planes.

experimental protocol focused first on reducing slate blocks to get blanks with a suitable thickness, regardless of shape or size. To tackle the same problems confronting prehistoric knappers, the use of the same raw material was an obvious priority. Different varieties of slate and phyllite were collected, using them according to the frequency with which they were worked at the site. The material presented different degrees of compactness, cementation and weathering, a variability that is present in the local quarries as well.

The techniques used during experimentation were direct percussion with hard and soft hammer, indirect percussion and pressure flaking. The experimental reduction of slate and phyllite blocks clearly showed the importance of cleavage planes during the knapping. However, that importance varies by the attributes of specific rocks: those more compact and cemented varieties will not display as much difference when struck in parallel or perpendicular directions to the cleavage planes. Thus, perpendicular percussion is only feasible on these harder varieties, for the force of the blow easily overcomes the internal planes (Fig. 4A), resulting in conchoidal or subconchoidal fractures; consequently, the technical gestures and chaînes opératoires will be closer to those found on raw materials like flint. However, on those rocks with a pronounced slaty cleavage a splintery fracture with an uncontrolled progression will take place or, if the blank is too thick, a rebound of the shock waves will hinder the fracture initiation. If the impact occurs in a parallel direction, the progression of waves will be facilitated, but softness of the material in that direction causes a rapid destruction of the striking plane (employing cortical platforms could diminish that), something particularly evident in bipolar percussion.

The best results in producing tool blanks on all materials were obtained by a careful percussion in an oblique direction to the foliation planes (between 35 and 50º) (Fig. 4B). Precisely these oblique angles had been defined by various authors as the most favourable for achieving a more effective split of the slate blocks (Aydin, 2009). No marked differences between hard and soft hammer were observed in the flakes obtained. The use of a not too heavy hammer is critical to avoid fractures and cracks in the material. On the other hand, the impact should be executed further to the interior of the striking platform, lest the cornice collapse.

Indirect percussion would have been another alternative for the reduction of the slate blanks. Again, this technique was applied both in a perpendicular and parallel direction to the cleavage planes. The results were disappointing in the first case (as happened with direct percussion), while the latter was particularly effective during the early stages of reduction, especially on thicker blocks. The fact that the parallel reduction does work with indirect percussion is due to the impact occurring against a smaller number of cleavage planes, thus concentrating the energy of the blow (more like a wedging initiation) and facilitating the initiation and propagation of fractures (Fig. 4C). Nevertheless, in less thick nuclei (3 cm or less), parallel reduction is less suitable, as there is a high probability of an early termination of the fracture. It is safer hitting this type of cores on an oblique angle to the cleavage planes (Fig. 4D), slightly smaller than that used in direct percussion (15–40°).

The number of sheets obtained experimentally from blocks varied depending on raw material and technique. Slate blocks between 500 and 1000 gr. of weight reduced by direct percussion have provided between 15 and 20 sheets that are suitable for the manufacture of projectiles, while similar blocks reduced by indirect percussion have exceeded the 30 sheets. Indirect percussion, then, has proved the most effective technique, producing a greater number of sheets and causing less destruction of the blocks. However, due to limitations evidenced by each technique (mainly to do with the thickness of the available blocks), it is probable that various methods would have been used along the reduction process according to the specific needs of each moment.

The products have a variable morphology and size according to the technique used and the reduction phase to which they belong. Those made by direct percussion on harder varieties of slate usually are similar to those obtained on more traditional raw materials: distinct faces, bulb of force and lenticular or triangular transversal sections. In varieties with a marked fissility, the products display a longitudinal and transverse quadrangular section with a small

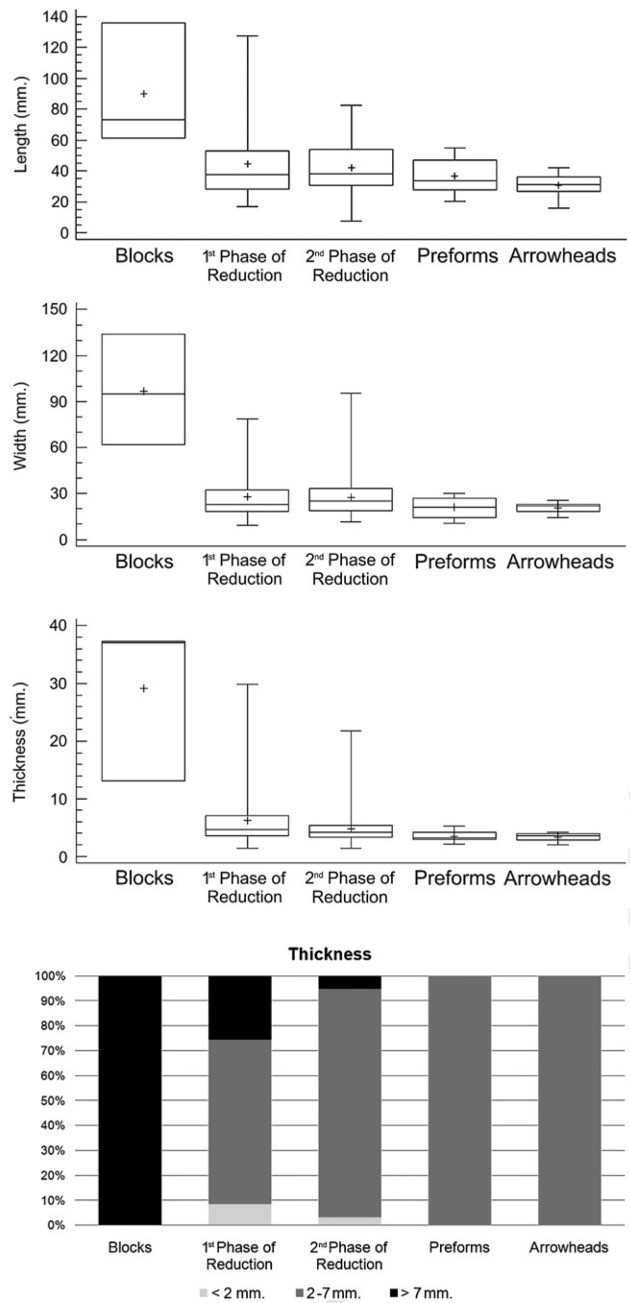

Fig. 3. Dimensions of the slate artefactsof El Pedroso according to the reduction phase to which they belong. Percentage of sheets with a suitable thickness for making arrowheads (2–7 mm).

variation in thickness over the entire piece. The shape of these sheets also tends to be rectangular, as well as trapezoidal or triangular. Along with these, a large number of fragments and small splinters are also obtained, caused by the collateral small fractures resulting from the progression of residual mechanical forces through cleavage planes next to those through which the main fracture occurs.

Generally, these pieces do not have the features on which lithic specialists have traditionally based their classification categories and they may have gone unnoticed in the archaeological record. In this sense, the very morphological distinction between cores and flakes is complicated, being necessary to pay attention mainly to size criteria. Likewise, it can be hard to distinguish between dorsal and ventral faces in flakes: both have a rectilinear or extremely

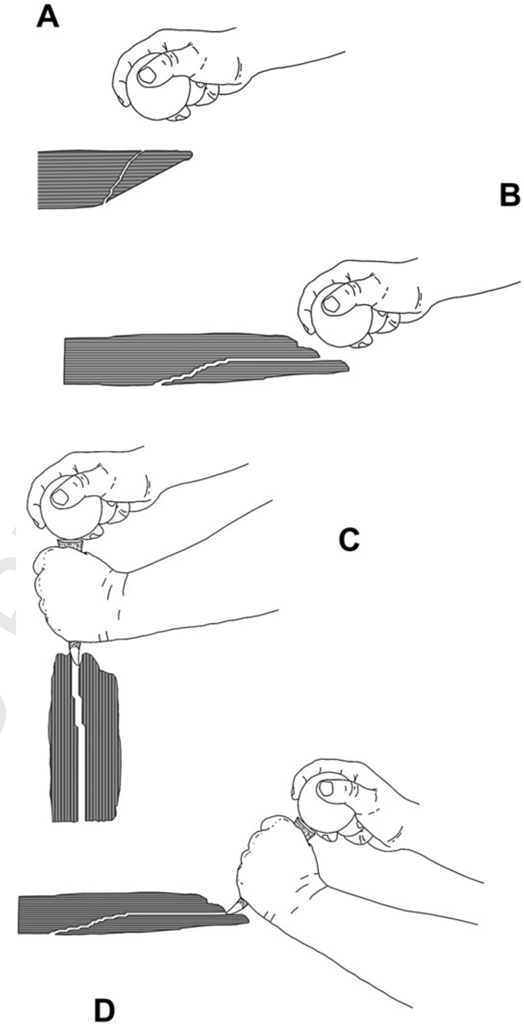

Fig. 4. A, B: Direct percussion perpendicular (only possible on harder varieties of slate) and oblique to the cleavage planes; C, D: Indirect percussion parallel and oblique to the cleavage planes.

irregular delineation without the presence of bulb or percussion waves; it is also difficult to differentiate the flake's platform as it has not a greater thickness, and is not easy to detect the marks of the technical process, as the point of impact.

Likewise, it is very difficult to establish the kind of specific technique that was used in the manufacture of a particular product, unless there are obvious marks (crushes or impact cones) of the tool used on the surface, as other authors already noted (Graesch, 2007). Although the products obtained by direct percussion usually have a greater thickness than those produced by indirect percussion, this feature is useful only as a statistical discriminator.

In the experiments the ideal thickness of a sheet for the realization of a projectile varied between 2 and 7 mm. When sheets are too large in dimensions such as length and width, we break them by smashing them on a soft anvil. Subsequently, preforms are configured by direct or smashing percussion, giving a morphology that is already close to the final form, which will be achieved by retouching. However, percussion can be omitted, resorting only to the retouch for the final configuration. Both methods have been documented in the studied assemblages (Rodríguez Rellán, 2010) and have also been described during the manufacturing process of "ulus" (polished knives) as well as polished arrows (Morin, 2004; Graesch, 2007).

Table 1
Average manufacturing time of the arrowheads used in the experiment.

Raw material	Core preparation	Blank production	Arrowhead configuration	Total time
Black slate	–	23 min.	14 min.	37 min.
Gray slate	–	20 min.	12 min.	32 min.
Phyllite	–	15 min.	13 min.	28 min.
Chalcedony	27 min.	31 min.	48 min.	106 min.
Rock crystal	15 min.	20 min.	42 min.	77 min.

The peculiar characteristic of these artefacts highlight both the inadequacy of the application to slate and other rock types of the usual classification systems and our ability to recognize all of the by-products of tool manufacture. In the slate and phyllite assemblages, fractures difficult to distinguish from those produced by natural degradation should be expected, since in both cases they occur preferentially along the cleavage planes and, in the former, do not necessarily display the usual marks produced during the flaking. The latter can be identified in the archaeological record through concentrations which, were they the result of a projectile production, tend to have numerous polymorphic blanks or sheets with a flat-regular section and a suitable size for the making of arrowheads (a thickness chiefly lower than 20 mm and a length lower than 80 mm) as well as many sub-centimetric splinters and debris. On the other hand, the by-products obtained during the final stages of the production process are sometimes easier to identify, especially those resulting from the configuration of the preforms on which peripheral marks caused by smashing or retouching are more visible.

According to the archaeological assemblages analysed and the experiments performed, we believe that blank thickness is basic for classifying the different products within the reduction process; nevertheless, the simultaneous generation of thin sheets and splinters from the very early stages of the production, makes quite

Table 2
Experimental projectiles.

Code	Raw material	Typology	Weight (gr.)	L (mm.)	W (mm.)	T (mm.)	DA (°)	TCP	Hafting[a]	APR (cm.)
CA01	Chalcedony	Concave	22.66	28.5	13.6	4.6	57	28.71	M	10.49
CA02	Chalcedony	Tanged	22.41	22.7	18.1	5.2	56	37.66	V	4.24
CA03	Chalcedony	Triangular	23.80	29.1	17	6.6	62	36.47	V	4.52
CR01	Rock crystal	Concave	19.40	29.2	16.8	4.6	61	34.83	M	9.06
CR02	Rock crystal	Triangular	22.01	32.8	15.5	5.3	63	32.76	M	5.98
CR03	Rock crystal	Convex	23.58	25.8	17.2	5.8	43	36.30	V	4.89
CR04	Rock crystal	Concave	21.92	38.1	15.4	5.2	46	32.50	M	5.49
CR05	Rock crystal	Concave	21.44	28.6	15.2	3.9	53	31.38	M	5.59
PI01	Phyllite	Barbed-and-tanged	24.35	33.7	27.1	4.9	65	55.07	M; V	3.54
PI02	Gray slate	Concave	21.82	29.4	15.6	3.5	70	31.97	M	3.66
PI03	Phyllite	Tanged	26.56	43.8	26.2	3.6	63	52.89	V	5.50
PI04	Gray slate	Concave	28.08	36.2	21.6	4.6	64	44.16	M	3.00
PI05	Gray slate	Barbed-and-tanged	25.42	35.8	27.9	4.5	62	56.52	M; V	5.12
PI06	Phyllite	Concave	23.95	34.8	18.1	3.6	44	36.90	M	8.96
PI07	Phyllite	Concave	22.82	37.3	20.1	4.2	65	41.06	M	6.29
PI08	Gray slate	Concave	26.05	32	24.5	3.2	64	49.41	M	1.00
PI09	Phyllite	Concave	24.34	30.6	25.6	4	66	51.82	M	4.30
PI10	Phyllite	Barbed-and-tanged	24.53	34.9	29.6	3.3	56	59.56	M	4.82
PI11	Phyllite	Barbed-and-tanged	29.56	42	34.6	4.9	56	69.89	M	6.61
PI12	Gray slate	Tanged	24.01	37	25.1	4.3	55	50.93	V	5.29
PI13	Black slate	Concave	27.88	32.1	19.1	5.6	54	39.80	M	11.33
PI14	Gray slate	Tanged	26.56	36.9	24.2	6.4	57	50.06	M; V	5.88
PI15	Black slate	Concave	22.88	41.2	16.5	3.9	58	33.90	M	9.40
PI16	Gray slate	Concave	28.98	31.7	18.1	7	53	38.81	V	3.49
PI17	Gray slate	Tanged	23.81	34.1	18.2	5.1	64	37.80	M; V	5.64
PI18	Black slate	Concave	23.63	27.7	13.8	5.7	52	29.86	V	5.85
PI19	Gray slate	Concave	24.75	37.6	21.8	5.8	57	45.11	M	5.43
PI20	Gray slate	Straight	30.27	33.3	29.5	6.2	66	60.28	M	3.00
PI21	Black slate	Concave	23.99	38.6	25	4.8	56	50.91	M	4.89
PI22	Black slate	Barbed-and-tanged	22.52	36.4	22.1	3.3	56	44.69	M	5.62
PI23	Black slate	Concave	24.88	33.2	16.4	4.5	55	34.01	M	4.50
PT01	Phyllite	Barbed-and-tanged	30.31	50.1	39.6	3.5	64	79.50	G	–
PT02	Phyllite	Barbed-and-tanged	24.39	42.1	27.1	3.4	64	54.62	G	3.16
PT03	Phyllite	Concave	25.29	49	26.2	3.9	54	52.97	G	3.50
PT04	Gray slate	Barbed-and-tanged	25.91	45.3	31.5	4.6	59	63.66	G	–
PT05	Black slate	Tanged	28.84	44.4	24.2	5.8	46	49.77	G	5.76
PT06	Gray slate	Tanged	24.42	47	30.3	6.4	67	61.93	G	3.80
PT07	Phyllite	Concave	27.51	50.4	39.8	6,1	65	80.52	G	2.24
PT08	Gray slate	Concave	28.66	57.4	27.2	4	58	54.98	G	4.90
PT09	Gray slate	Tanged	26.38	44.5	27.6	5.5	70	56.28	G	6.83
PT10	Gray slate	Tanged	45.97	62.4	31.9	6.8	70	65.23	G	–
PR01	Rock crystal	Composite	19.92	–	–	–	–	–	M	3.82
PR02	Quartz	Composite	20.94	–	–	–	–	–	M	3.30
PR03	Quartz	Composite	21.38	–	–	–	–	–	M	3.00
PR04	Rock crystal	Composite	25.57	–	–	–	–	–	M	3.24
PR05	Rock crystal	Composite	23.70	–	–	–	–	–	M	4.15
PR06	Rock crystal	Composite	22.04	–	–	–	–	–	M	3.91
BP01	Quartz	Composite	20.04	–	–	–	–	–	M	3.46
BP02	Quartz	Composite	20.04	–	–	–	–	–	M	3.50
BP03	Quartz	Composite	22.08	–	–	–	–	–	M	5.00
TE01	Quartz	Composite	20.51	–	–	–	–	–	M	7.00

[a] Hafting adhesive: Mastic (M); Vegetal Fibres (V); Gut (G).

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uncertain that classification, especially in those smaller pieces. The difficulty of this process is increased by the limited possibilities of refitting.

The retouching technique employed on the slate and phyllite must necessarily be by pressure. Gestures differ: in the case of shale and siliceous slate they are quite close to those used on flint or other cryptocrystalline materials. However, on the varieties with a high level of cleavage, the gestures employed are quite specific. Thus, on flint or obsidian the pressure flaker is situated on the very edge, pressing inward and downward; with the slate, however, to avoid indenting, the pressure must be applied further inside the piece (about 2/3 mm from the edge) and must be exerted only downward, in a similar way to the abrupt retouching on other rocks. Retouch invasiveness can be controlled, to some extent, by compressing the piece with the finger, while its angle will depend on the distance from the edge of the actual pressure point and also on the inclination of the piece itself.

During flaking, the strengthening of thinner parts of the edge by abrasion and scraping is not possible using slate. This action, almost essential on flint or quartz to avoid edge collapse during flaking, is very unwise on slate: its low hardness leads to a fast grinding of the area, thus making the item difficult to retouch by eliminating the necessary angle. Ridges created by previous removals cannot be taken as a guide for new removals either, so that a denticulated, pseudo-scalar and always marginal retouch often results.

In spite of that, it is much easier to get straight and aerodynamically well-balanced faces with slate. The reason lies on the straight morphology of the sheets and its virtual absence of thickening, saving the trouble of performing flat retouch series and making possible to get fully operational arrowheads only from a marginal retouch, which in other rocks would be just the first phase of projectile configuration (these features can also facilitate the repair of the projectiles after fractures happened during use). Thus, the time of manufacture of projectile points in slate and phyllite with a high degree of fissility was always below 15 min, much less than that when using chalcedony, opal and rock crystal (an average of 45 min). The composite projectiles, made up of retouched and also un-retouched microliths, were not taken into account in this comparative analysis. These artefacts were produced using very different techniques, from the pressure flaking to bipolar percussion or even the fire-cracked technology, entailing a strong variation in the manufacturing time (from just 10 min to several hours) that discouraged its comparison with the manufacturing of arrowheads.

The main advantage of thin-layered rocks lies, as we said, in saving time during its work (Table 1). Although processing times shown here may vary profoundly depending on the knapper experience, the fact is that this saving takes place along the three key stages of the manufacturing process of the projectiles and start from the very beginning. Thus, the chalcedony core (of approximately 950 gr. weight) required the cortex removal by direct percussion as well as obtaining a sustainable strike platform; the latter process was also necessary in the rock crystal prisms exploited (a total of 5, with an average weight of 77 gr.). It must be taken into account also the need for maintenance of striking platforms and flaking surfaces during exploitation. By contrast, in the slate and phyllite (6 blocks weighing no more than 1000 gr. each) preparation of the nuclei was unnecessary, the operation starting directly on natural surfaces and using the cleavage planes for separating the blanks.

Also at the blank production stage, slate and phyllite have proven their worth: to start with the number of suitable blanks per weight (15–38) is much greater than in other raw materials. With chalcedony and rock crystal, direct percussion yielded, respectively, 15 and 3 blanks (in the latter the number was determined by the size of the prism). Although the reduction process in these raw materials could have been accelerated by employing other techniques, like bipolar percussion, yielding a bigger number of blanks, most of these would be unsuitable for arrowhead manufacture and could only be used for the making of microliths to be mounted into composite projectiles.

It is, however, in the configuration phase of the projectiles, where the slate and phyllite have been more advantageous; the creation of preforms and the subsequent retouching did not take more than 15 min, far less time than that consumed with rock crystal or, above all, chalcedony. In addition, the need for a more invasive retouch in the latter increased the time expenditure. Thus, the projectile manufacturing time may be reduced to a third by using thin-layered rocks.

4. Experimental shooting of slate flaked projectiles

The scarcity of experimental programs testing the use of slate projectiles (Holmerg, 1994), led us to design a protocol with two main objectives: evaluate the effectiveness of projectiles made on fissile rocks in terms of impact resistance, stability and, above all, penetration capacity and determine their performance compared to those made on other materials.

A set of 51 projectiles of different materials (both slate as well as finer-grained rocks), morphologies and sizes was created (Table 2, Fig. 5), the significance of each variable being determined by its importance in the archaeological contexts. Thus, the collection is

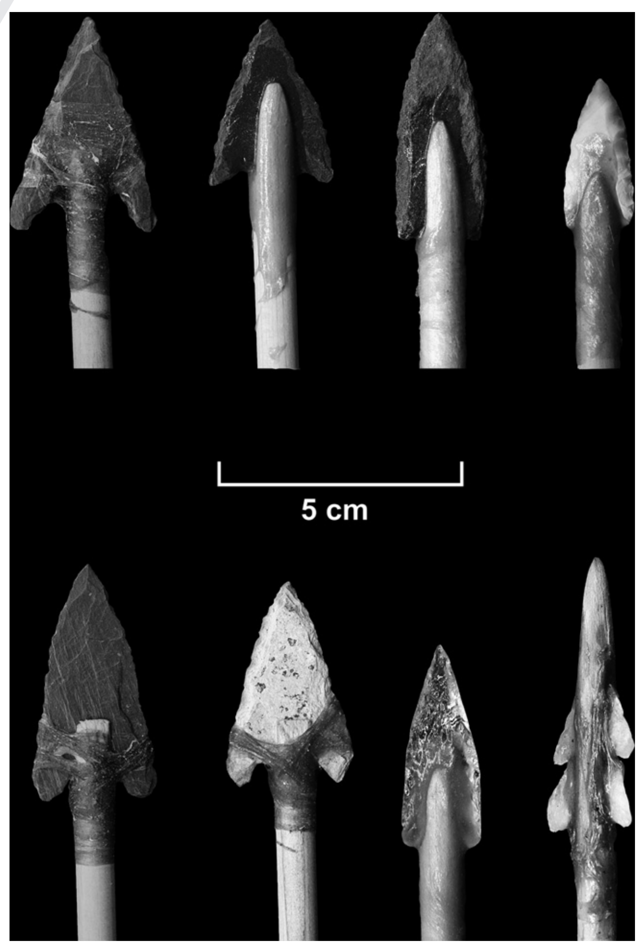

Fig. 5. Experimental projectiles made on slate, chalcedony, phyllite, rock crystal and quartz.

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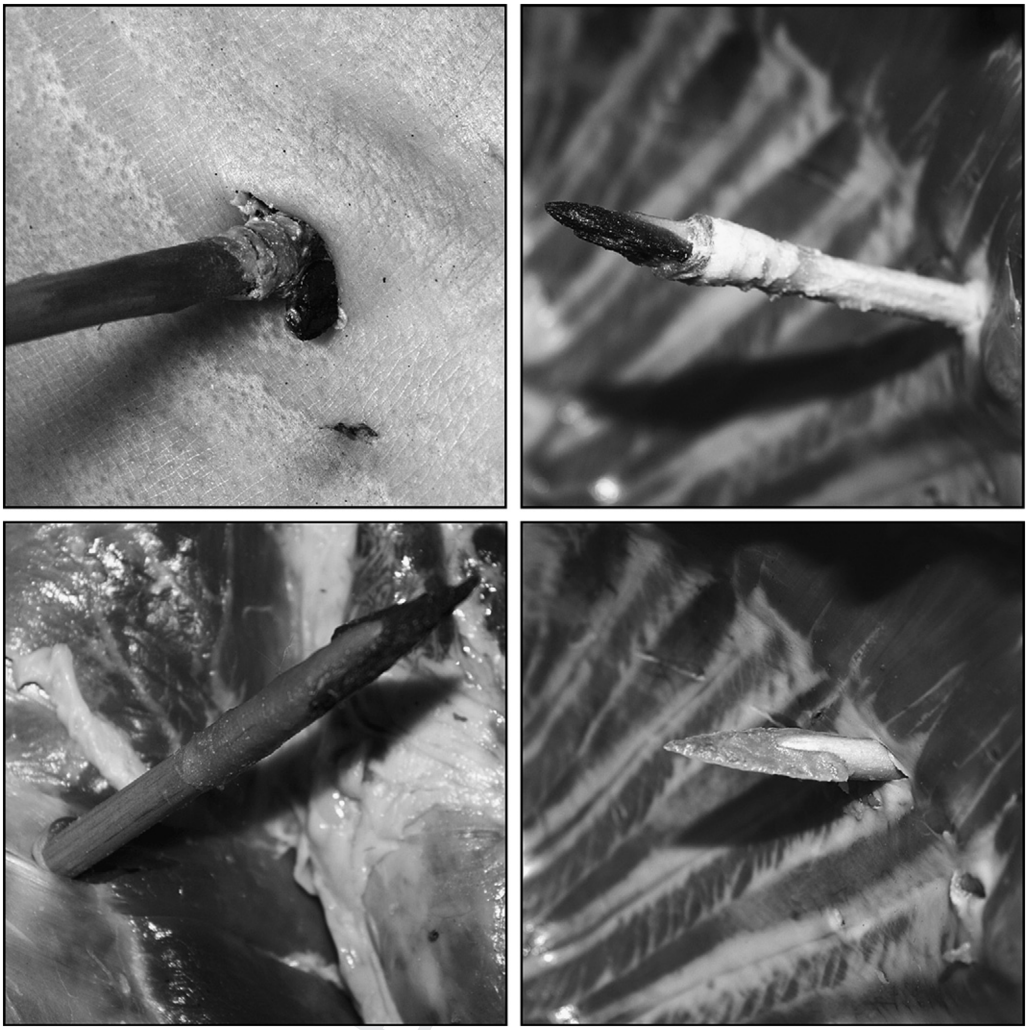

Fig. 6. Examples of the lower and highest penetration (perforating the chest) reached by the experimental projectiles.

dominated by points made on raw materials present in the lithological environment of the studied sites, with those manufactured in Silurian-Devonian gray and black slates the most numerous, followed by other local raw materials.

The arrowheads were inserted in industrial shafts of cedar wood 81 cm long and 8 mm thick. The hafting was achieved by three systems: lamb gut casing, vegetable fibres hardened with birch resin and mastic: a mix of animal glue and ochre. The use of ochre as a binder in adhesives is well known (Wardley, 2005; Lombard, 2007) and had a special interest in our case because the grinding of this oxide was recorded in some of the studied sites (Rodríguez Rellán, 2010).

A compound fibreglass modern bow 62 inches long with 32 pounds of draw weight was used, and the target was a 45 kg gutted pig held approximately 50 cm above the ground. Two additional shots (PT1, PT10) were made against a 5 mm thick wood panel covered with a tanned goatskin. The purpose was to test the effectiveness both against a living body and protective devices such as shields or breastplates. The use of an eviscerated carcass greatly improves the penetration of the projectiles, by avoiding the resistance exerted by internal pressure and bowels. There are significant differences among the different authors as to the type of target (Bergman and Newcommer, 1983; Flenniken, 1985; Sisk and Shea, 2009) but this factor has no direct impact on our experiment, since the aim was not to measure the penetration of the projectile in absolute terms but to compare the piercing capability of slate and phyllite arrows against those made in other materials. Moreover, the target's lesser resistance has been partially compensated for the weight of the bow, which is considerably lower than those generally known in Prehistoric Europe (Clark, 1963).

Shooting distances ranged between 8 and 20 m, which would be within the usual range for hunting and warfare (Pétrequin and Pétrequin, 1990; Bartram, 1997). The depth and position of each shot were recorded to see if a lower penetration or a rebound were caused by the skeletal structure or by the particular density of the

Table 3
Spearman's Rank Correlation Coefficientsand Significance Levels for the Average Penetration Rate (APR).

Variables	Correlation	Significance
Length	−.031	.852
Width	−.369[b]	.023
Thickness	.008	.961
L/W Index	.433[a]	.007
W/T Index	−.072	.667
L/T Index	−.303	.064
Weight	−.090	.541
Distal angle	−.303	.065
TCP	−.372[b]	.021

[a] Correlation significant at 0.01 Level.
[b] Correlation significant at 0.05 Level.

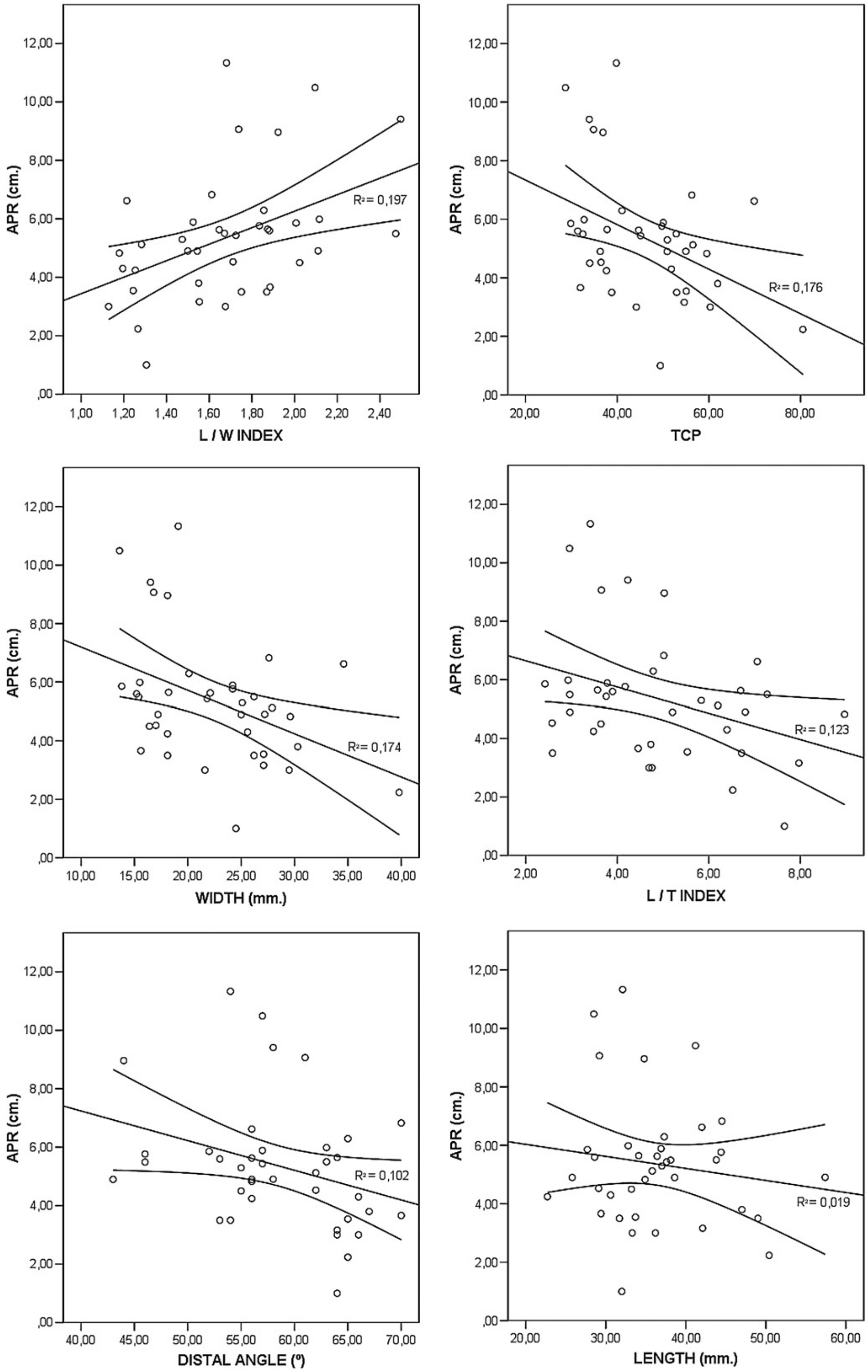

Fig. 7. Scatter plots and regression line showing the correlation between arrowhead's main quantitative variables and the Average Penetration Rate (APR).

muscular tissue. A total of 213 shots were made with the 51 projectiles. The maximum number of shots per projectile was 10, with a mean at 4.17. Of these, 36 (16.90%) missed the target, while 23 (10.79%) rebounded; to these we must add the two projectiles fired at a target composed of wood and leather, which got through it completely. Thus, the experimental program ended with a total of 154 shots that penetrated the target (a success rate of 71.62%). The impacts reached a maximum depth of 18.5 cm; those with a lower penetration (4 cm or less) are located mostly on the fore part of the animal where they hit its bone structure or heavy muscle masses. The deeper impacts (more than 8 cm) are located in the middle section, most shots slipping through the intercostal spaces (Fig. 6).

The resulting average penetration rate (hereafter APR) of the projectiles was analyzed statistically and checked against the quantitative and qualitative variables considered in our performance (Table 3), in order to see if any of those significantly affected the projectile effectiveness. Several non-parametric tests were run (Kendall's Tau Rank Correlation and Spearman's Rank Correlation Coefficient) with the aim of defining the level of relationship among quantitative variables and the APR reached for different projectiles.

The test results show a correlation between various variables and the APR that could be euphemistically described as discrete; in most cases this correlation is negative, while in others, namely the L/W Index, there is a positive correlation. The statistical analysis shows that there is a different level of correlation among several of the variables and the APR: L/W Index, Tip Cross-Sectional Perimeter (TCP), Width and, to lesser extent, the Distal Angle seem to play a leading role; in fact, all these variables had been previously defined as conditioning factors (Odell and Cowan, 1986; Hughes, 1998; Sisk and Shea, 2009). However, none of the variables considered in this experimental program exhibits a degree of correlation good enough to be considered a decisive factor in explaining, much less predicting, the APR of a given projectile, one can observe in the regression plots (Fig. 7).

Regarding to qualitative variables, we conducted a non-parametric analysis of variance based on the Kruskal–Wallis test. The results show an Asymptotic Significance well above 0.05, and, therefore, we concluded that no statistical evidence endorses the existence of significant differences among raw materials based on APR or Penetration in the first shot (Table 4). Also, statistical analyses were conducted to determine whether there was a significant correlation between the variables considered and the number of ricocheting arrows. As in the previous case, results showed that both quantitative and qualitative variables, including raw material (Table 4), did not have a clear impact on the number of bounces. However, certain variables (again the L/W Index and the TCP) showed a comparatively higher relative correlation.

As for the resilience of the projectiles, the level of fractures was relatively high, fundamentally as a result of an intensive use: a total of 28 projectiles (54.90%) were broken; however, in 6 occasions (11.76%) the fracture would not involve the discard of the piece for, in some cases, it reaches the highest penetration after taking one such fracture. The greatest percentage of fractures occurred in the phyllite, followed by quartz and black slate while chalcedony and crystal are at the opposite extreme. However, if we relate the level of fracture and discard to the intensity of use, the results become fairly balanced and black and gray slate have equal or even lesser fracture rates than their quartz and chalcedony counterparts. Moreover, if we consider the percentage of projectiles whose fracture has involved discard, the gray slate stands as the second most effective material (Table 5).

It should be noted that the stress induced on the projectiles launched against a stationary target would have been different from that against a moving one, because the level of fracture within the wound would have been significantly different (Flenniken, 1985). The internal structure of the thin-layered rocks may have been an advantage in relation to the increasing severity of the injury inflicted: the parameters of fracture observed in the experimental arrowheads show that this occurs primarily through disintegration of the distal half into tiny sheets, these sub-centimetric detached fragments acting as "shrapnel" that would increase bleeding and the risk of infection.

Table 4
Kruskal–Wallis Test of APR, number of Ricochets and Penetration reached with the first shot according to the raw material. Test Statistics.[a,b]

	APR	Penetration 1st shot	Ricochets
Chi-Square	6940	.599	2983
df	5	5	5
Asymp. Sig.	.225	.988	.703

[a] Kruskal–Wallis test.
[b] Grouping variable: raw material.

Table 5
Incidence of fractures among the experimental projectiles.

Raw material	Broken projectiles		Fractures causing discard			Accidents vs. Number of Shots	
	N	%	N	% Fractures	% Projectiles	% Fractures	% Discards
Quartz (6)	4	66.67%	3	75.00%	50.00%	25.00%	18.75%
Chalcedony (3)	1	33.33%	1	100%	33.33%	8.33%	8.33%
Rock Crystal (9)	2	22.22%	1	50.00%	11.11%	5.41%	2.70%
Phyllite (11)	9	81.82%	8	88.89%	72.73%	25.00%	22.22%
Black Slate (7)	4	57.14%	4	100%	57.14%	8.70%	8.70%
Gray Slate (15)	8	53.33%	5	62.50%	33.33%	12.12%	7.58%
TOTAL (51)	28	54.90%	22	78.57%	43.14%	13.15%	10.33%

5. Conclusions

Given the repeated use of slate, phyllite and schist for manufacturing flake industries, mainly projectile points, in many archaeological sites of Western Iberia and other parts of the World, one might assume that these rocks would have had a number of advantages making profitable their use despite its a priori unattractive features for knapping and its low hardness in comparison with flint. The common use of slate and other fissile rocks during the Prehistory and up to the last century, however, has not been led to a similar degree of attention among specialists in lithic technology.

This paper has approached the mechanical properties of slate and phyllite with a high degree of fissility, assessing the effect that internal cleavage planes would have on the knapping of these materials. The experimental manufacture and shooting of projectile points made on fissile rocks has shown, on the one hand, the existence of specific technical gestures and chaînes opératoires, requiring some technical adaptation but, at the same time, allowing a quick and easy manufacture of ideal blanks for making projectiles, due to the tendency of this raw material to separate into sheets with a straight section and a regular thickness and the ease of configuration, being sufficient, generally, a marginal retouch to obtain a fully operational arrowhead.

When compared to rock crystal and chalcedony points, the slate and phyllite specimens required fewer steps to complete, basically limited to marginal retouch on blanks that are already thin due to the tendency of these materials to separate into sheets. In contrast, our chalcedony and quartz points had a more difficult configuration, being necessary a more invasive and complex retouching, resulting in an average of 45 min to completion against 13 min for the fissile rocks. This difference is even bigger if we consider the whole manufacturing process, which in chalcedony and quartz includes a necessary preparation of nuclei and a more difficult production of blanks; as a result, the total time for producing arrowheads on thin-layered rocks can be reduced to a third of that in other raw materials.

Also, it could be assumed that arrowheads made on slate or phyllite would have been effective as part of projectile weapons. In this regard, the launch of the projectiles made on fissile rocks and the comparison with those made from other raw materials, confirmed the initial hypothesis, namely that slate and phyllite projectiles were perfectly competitive with their equivalents made of cryptocrystalline rocks with conchoidal fracture: arrowheads made on black slate reached the maximum penetration (18.5 cm), while other varieties of thin-layered rocks fared similarly to those

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made on rock crystal and chalcedony (around 11 cm). Thus, while the Average Penetration Rate is slightly lower in slate and phyllite, statistical analysis shows that the difference is not significant enough to sustain their inferior effectiveness. Something similar occurs with the resistance to fracture because, being lower in absolute terms in slate and phyllite, once analysed with respect to the intensity of use, we get comparable values in the different raw materials. Moreover, one variety of slate even has a lower tendency to the occurrence of fractures involving discard.

Summing up, despite their somewhat coarse aspect casting doubts over its functionality, arrows on foliated rocks display a level of effectiveness and strength comparable to those made on other “traditional” raw materials, as observed in its ability to penetrate the target and resistance to fracture. This fact, coupled with their quick and easy fabrication and repair, makes slate and phyllite projectiles an ideal choice as part of a strategy to minimize energetic costs. The ubiquity of this type of rocks over many areas of Western Iberia would mean a virtual absence of restrictions on their availability and facilitated their acquisition by prehistoric communities. At the same time, its internal structure allowed the production of a considerable number of exploitable blanks from relatively small quantities of raw material without the need to employ complex technologies, as in other stones. These features must have made these raw materials particularly attractive in a context of rising socioeconomic complexity and more sedentary lifestyles, thereby reducing the catchment areas and increasing the intensity of its exploitation, causing human groups to explore the use of new lithologies, a fact that undoubtedly will be at the origin of the massive use of such raw materials in certain areas from the middle and final stages of the Neolithic, as compared with earlier periods, when these rocks were only used sporadically.

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