Breakage, scarring, scratches and explosions: understanding impact trace formation on quartz

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Abstract

Quartz projectiles have received attention in the recent years due to, for instance, their discovery at prominent South African Middle Stone Age sites. However, very few methodological studies have been dedicated to quartz armatures and the ones published so far are not built on an understanding of the particular behaviour of quartz under mechanical stress. Here we investigate impact damage formation on automorphic and xenomorphic quartz (crystal quartz and vein quartz) through the microscopic analysis of 91 experimental armatures using a combination of low and high magnifications and SEM. Our results show that the structural properties of quartz affect the attributes of impact breaks and other damage. We also examine wear patterns on three different types of projectiles, and offer preliminary guidelines for identifying them in archaeological assemblages. We argue that while quartz assemblages withhold significant potential for understanding past hunting technologies, the methods used for identifying and interpreting quartz projectiles need to be adjusted so that they take into account the notable differences between the macrocrystalline and cryptocrystalline varieties of this raw material.

Keywords

quartz; projectiles; barbs; transverse points; impact damage; microwear

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1 Introduction

Quartz is a key component in southern African MSA industries that have become important for the study of the early development of hunting technologies (Lombard 2011; Rots et al. 2017; de la Peña et al. 2018). Quartz projectiles have recently been reported from for example Sibudu Cave (South Africa), where quartz backed elements have been interpreted as evidence of the use of bow and arrow 60 Kya (Lombard 2011). Despite the increasing importance of this lithic raw material for archaeological interpretations, very little methodological work has been done to understand impact wear on it. Until very recently (Fernández-Marchena et al. 2017), quartz projectiles have mainly been characterised using methods originally developed for flint and other cryptocrystalline rocks (e.g. Pargeter 2013), and a limited amount of systematic work has been done to understand the differences between quartz and flint-like rocks in in this respect. This is regardless of the fact that the recent decades have seen advances in functional analysis of quartz tools and a renewed interest in quartz industries in general (e.g. Knutsson 1988; Knutsson et al. 2015b; de Lombera-Hermida and Rodríguez-Rellán 2016 and references therein; Márquez et al. 2016; Ollé et al. 2016).

Both automorphic (crystal) and xenomorphic (vein) quartz differ to a significant extent from cryptocrystalline rocks in their mechanical properties that affect fracture formation (Callahan et al. 1992; Domanski et al. 1994; Mourre 1996; de Lombera Hermida 2009; Driscoll 2010; Tallavaara et al. 2010; de Lombera-Hermida and Rodríguez-Rellán 2016; Rodríguez-Rellán 2016). This has been established in technological studies aimed at understanding the seemingly chaotic fragmentation of quartz flakes during knapping and the differences between the technological attributes of quartz and flint or chert flakes (Callahan et al. 1992; Driscoll 2010, 2011a; Tallavaara et al. 2010; Manninen 2016; Tardy et al. 2016).

We believe that there is a need for a solid experimental foundation that acknowledges these idiosyncrasies (see Knutsson 1988; Callahan et al. 1992; Domanski et al. 1994; Mourre 1996; de Lombera Hermida 2009; Tallavaara et al. 2010; Rodríguez-Rellán 2016). We present the results of a functional analysis of 91 experimental armatures made on automorphic quartz and xenomorphic quartz. Our aim is to gain a preliminary understanding of the specifics of impact wear formation on these raw materials using their key physical and mechanical properties discussed in recent archaeological literature as a frame of reference. In addition to evaluating the implications of these properties on projectile identification on the basis of our experimental data, we compare damage patterns on three different projectile types – barbs, transverse points, and convergent points – and discuss the possibilities of identifying these different armature types archaeologically based on use-wear evidence.

Our sample partly derives from the experiments designed to understand impact damage formation on small quartz artefacts from the Howiesons Poort layers of Sibudu Cave (de la Peña et al. 2018), and was complemented with further experiments. The goal of these exploratory experiments was to produce material that can serve as a realistic (even if preliminary) referential basis for the analysis of archaeological quartz armatures. To reach this goal, we used materials that would have been available in prehistory, and included several armature types to be able to cover the variability we assume existed in the past. In addition, we analysed a number of transverse and oblique arrowheads from an earlier experiment (Seppä 1995) that had a slightly different setup. We examine the characteristics and frequency of impact damage, MLITs, and other microwear on these armatures paying special attention to the consequences of hafted use. We show that the particular properties of quartz affect fracture patterns also on microscale, and point out possible difficulties and sources of confusion in quartz projectile identification.

2 Background

Projectile identification very often relies on the detection of so-called diagnostic impact fractures (DIFs). This approach builds on experimental studies that have dealt with projectiles in flint and flint-like rocks (e.g. Odell 1978; Barton and Bergman 1982; Moss and Newcomer 1982; Odell and Cowan 1986; Geneste and Plisson 1990). It is based on the observation that certain types of breaks recur in projectile use and rarely result from other processes (knapping, other types of tool use, taphonomic events), and can therefore be considered diagnostic of impact (Fischer et al. 1984). The reliability of the method as well as the consistency of the criteria and terminology used by different analysts have recently been called into question (Rots and Plisson 2014; Coppe and Rots 2017), but it still serves as a basis in many projectile studies.

Pargeter has discussed DIFs on quartz in several recent publications (Pargeter 2011, 2013; Pargeter et al. 2016). He experimented with various rock types common at South African sites, including xenomorphic (vein) quartz (Pargeter 2013). The results led him to conclude that DIFs occur on all rock types examined, and that tool use is thus a factor that overrides lithic raw material variability in macrofracture formation (Pargeter 2013). In a more recent study (Pargeter et al. 2016), Pargeter and colleagues tested the possibilities of distinguishing between experimental quartz arrow and spear heads using the macrofacture method. They report high frequencies of DIFs on their experimental transversely hafted arrow and spear heads (Pargeter et al. 2016: fig. 8 and table 3). While they acknowledge that some of the differences between their dataset and those published earlier can be attributed to the variability in raw materials used in the experiments, they do not explicitly discuss the impact of the properties of quartz on fracture formation.

We agree that approaches where large samples are coupled with appropriate quantification procedures and statistical treatment of the data, such as the one proposed by Pargeter et al. (2016), should be encouraged in projectile studies. However, all methods that aim at reconstructing weapons involving quartz components should in our view rely on a firm understanding of the particular fracture mechanical properties of quartz and their effect on the appearance of impact damage. Only after the particularities of break and damage formation are understood can these features be quantified in a way that yields archaeologically relevant information. In the case of quartz, one of the questions that remain is whether or not the structural properties of the raw material intervene with fracture formation to such an extent that some of the variation in feature characteristics (dimensions) can be considered random and therefore not useful for understanding weapon systems.

Interestingly, Fernández-Marchena et al. (2017) report an absence of DIFs in their pilot study that examined projectile tips made of automorphic (crystal) quartz. Since they do not report their sample size and since the definitions of DIFs often vary from one analyst to another (for a critical review of literature, see Coppe and Rots 2017), the significance of this absence is difficult to evaluate. Even so, both Pargeter et al.'s and Fernandez-Marchena et al.'s studies seem to suggest that the differences between quartz and cryptocrystalline rocks are not trivial for impact damage formation.

3 Terminology

For distinguishing between the two main types of macrocrystalline quartz, we apply here the terms 'automorphic' and 'xenomorphic' following Mourre (1996) and Rodríguez-Rellán (2016). Automorphic quartz occurs as hexagonal crystals of varying sizes, and is usually referred to as rock crystal, crystal quartz, or hyaline quartz in archaeological literature (Rodríguez-Rellán 2016). Xenomorphic quartz, commonly called vein quartz or milky quartz, is a polycrystalline aggregate

where the individual crystals lack the distinctive shape typical of automorphic quartz (Rodríguez-Rellán 2016), which usually gives the quartz a less glassy and grainier appearance. We consider the terms automorphic and xenomorphic the least confusing of the ones in current use since automorphic crystals can occur in quartz veins (de Lombera Hermida 2009), making 'vein quartz' a rather non-descriptive (albeit established) term.

For describing macroscopic damage from impact, we use the term 'break' to refer to a fracture that cuts the piece from one edge to another, while removals limited to one edge are considered 'scars'. A recent review of literature has shown that the term 'burination' is used for a variety of features and that the results of individual studies are not therefore easily comparable (Coppe and Rots 2017). Here, the term is used purely for its descriptive value to separate "burin-like" features from the rest, and the type of feature (primary or secondary removal) referred to is each time specified in the text.

4 Macroscopic and microscopic wear on quartz

4.1 Mechanical properties and macrotrace formation

Wear formation on quartz is not easily comparable to flint (see Knutsson 1988; Knutsson et al. 2015b; Ollé et al. 2016). Both automorphic and xenomorphic quartz have particular mechanical properties that cause them to behave differently from cryptocrystalline rocks under mechanical stress. These qualities have been acknowledged and discussed in the recent decades in the context of technological analysis (for a summary, see de Lombera-Hermida and Rodríguez-Rellán 2016), but the role of each physical property in the outcome of the knapping (or other fracturing) process is still not understood in detail. Continuity (measure of amount of cracks and flaws), isotropy (measure of directional properties) (Domanski et al. 1994; Rodríguez-Rellán 2016) and homogeneity all play a role in the predictability of fractures in quartz (Rodríguez-Rellán 2016). In terms of these properties, the relationship between automorphic and xenomorphic quartz is not strictly hierarchical. Xenomorphic quartz can for example be more isotropic than automorphic quartz (Rodríguez-Rellán 2016).

4.1.1 Automorphic quartz

While fracture formation on automorphic quartz can be more predictable and features formed through conchoidal fracture are more pronounced than on xenomorphic quartz, crystal quartz does not behave in the same way as flint (Driscoll 2010). Further, only the apical parts of crystals can be considered isotropic and homogenous. The rest of the crystal is anisotropic due to presence of cleavage planes and diaclasis (Mourre 1996; de Lombera Hermida 2009; Fernández-Marchena and Ollé 2016; Rodríguez-Rellán 2016; Tardy et al. 2016), and especially the basal parts of the crystals often have flaws and impurities that significantly affect the fracturing qualities of the raw material (de Lombera Hermida 2009; Rodríguez-Rellán 2016).

The direction in which the quartz is knapped (parallel, oblique, or perpendicular to the length of the crystal) affects the extent to which the features responsible for anisotropy interfere with fracture propagation (Mourre 1996; Tardy et al. 2016), and the strength of bonds between molecules is not the same in all directions (Rodríguez-Rellán 2016). Anisotropy is manifested in features such as ripple amplification, which appears when the crystal is knapped in the direction of its length or its thickness and disappears when the direction is oblique to the length (Tardy et al. 2016: fig. 17). These qualities can be hypothesized to also affect impact damage, for instance the morphometrics of removals.

Another recent study reports that lancets (hackles), often pronounced in automorphic quartz, affect the shape of microscopic use-related scars (Fernández-Marchena and Ollé 2016), but the impact of hackles on the formation of impact scars remains to be evaluated.

4.1.2 Xenomorphic quartz

Fracture patterns in xenomorphic quartz can be quite complex. The material shows both conchoidal and uneven fracture (de Lombera Hermida 2009). Its tensile and compressive strength is relatively low, and qualities such as the presence of internal planes and flaws, the anisotropy of crystals, and the grainy structure can result in irregular and unpredictable fracture patterns (Callahan et al. 1992; Domanski et al. 1994; de Lombera Hermida 2009; Tallavaara et al. 2010; de Lombera-Hermida and Rodríguez-Rellán 2016).

In good-quality flint a fracture propagates through the material and ideally results in the detachment of a single intact flake with a clear cone initiation, whereas in quartz the energy is dispersed throughout the material as the crack propagates along existing planes of weakness in multiple directions (de Lombera Hermida 2009). The effect is twofold: quartz flakes often fragment upon detachment, and typical features such as bulbs of percussion tend to be absent or diffuse on them (Callahan et al. 1992; Rankama 2002; Tallavaara et al. 2010). The unwanted fracture propagation along discontinuities in the material can occur not only during blank production but also shaping (Mourre 1996), which suggests that this behaviour also has an effect on impact break and damage formation.

We predict that in impact fracture formation the above-mentioned properties of xenomorphic quartz will result in breakage along fault planes and other zones of weakness, in removals with irregular and/or diffuse and consequently hard-to-read morphologies, and in frequent and unpredictable interruption of fracture propagation. Even though these properties do not necessarily result in the absence of “diagnostic” breaks and removals in quartz (cf. Pargeter 2013; Pargeter et al. 2016), they can be expected to increase the variability in feature attributes and dimensions, and also to yield lower frequencies of “diagnostic” breaks and removals when compared to rock types with a more predictable behaviour.

4.2 Microwear

Under high magnification, one of the most striking features of quartz is the highly varied structure of its surfaces (Fig. 1a-f; see also Fernández-Marchena and Ollé 2016 for similar features on automorphic quartz). This abundancy of natural features can be problematic especially for analysts accustomed to the more homogenous microtopography of cryptocrystalline rocks such as flint. The existence of natural linear surface features has been repeatedly pointed out by analysts since the origins of high magnification analysis of quartz (e.g. Fullagar 1986; Knutsson 1988). Nevertheless, these features, visible as sets of fine parallel lines under the microscope (Fig. 1c), have become misinterpreted as use-wear also in recent studies. This is the case in Lombard’s study on Howiesons Poort segments from Sibudu. These artefacts were argued to be transverse arrowheads partly on the basis of linear features with suitable orientations found at the tools’ edges (Lombard 2011). These features are, in fact, commonly occurring natural formations, as already pointed out in other studies dealing with quartz (Fernández-Marchena and Ollé 2016; de la Peña et al. 2018).

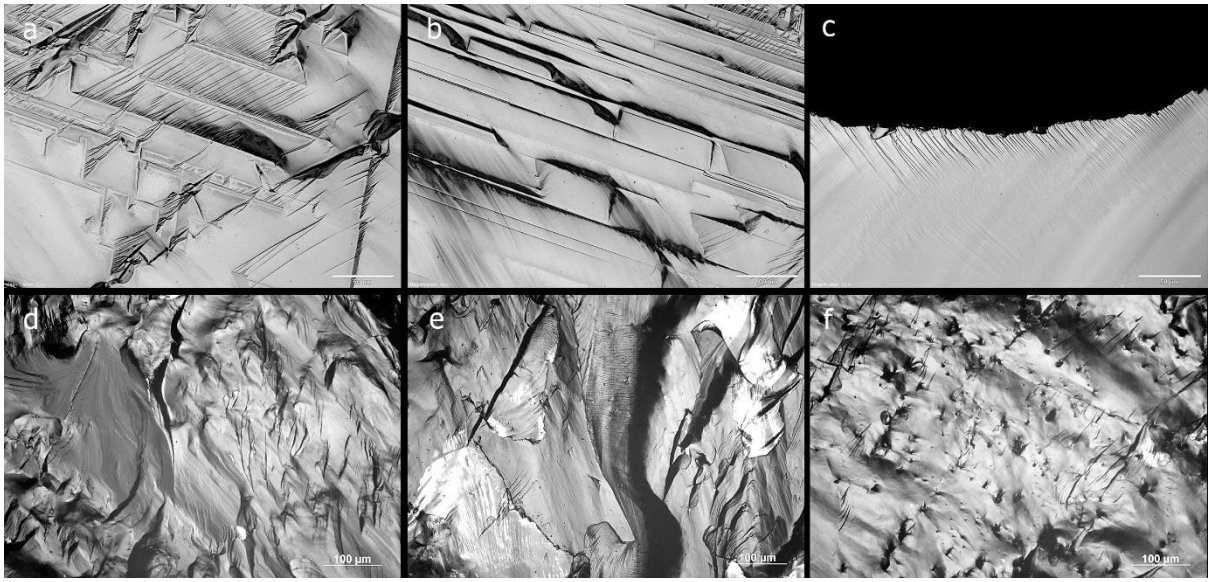

Fig. 1 Examples of the varied microtopography of automorphic (crystal) and xenomorphic (vein) quartz (unused pieces). a. Automorphic quartz, original magnification 200×, scale bar 50µm. b. Automorphic quartz, original magnification 100×, scale bar 100µm. c. Natural linear surface features oriented obliquely to the edge on an experimental unmodified and unused automorphic quartz flake (de la Pena et al. 2018, fig. 23). d.-f. Xenomorphic quartz, original magnification 200×, scale bars 100µm (for a description of the microscopic structure of xenomorphic quartz, see Knutsson 1988)

The formation of actual microwear on quartz is characterised by quick appearance of chipping, rounding (microchipping) and cracking of the outermost edges accompanied with the formation of linear features, and relatively slow and limited development of polish that only forms when working certain materials (Knutsson 1988). This is due to the poor response of quartz to high pressure, which gives rise to edge fracturing and subsurface damage at the expense of abrasive processes, making microwear on quartz very different from wear on flint (de Lombera Hermida 2009). Linear features form the bulk of use-wear on quartz and are easily detectable under appropriate magnifications. It has been proposed that they form either through brittle fracture wear, in which case they are linear arrays of surface and subsurface cracks, or through plastic deformation (Kamminga 1982; Knutsson 1988; Derndarsky and Ocklind 2001).

K. Knutsson's experimental work employing scanning electron microscope analysis and surface etching led him to conclude that the wear formation process on quartz is as a whole a combination of micro-fracturing, material fatigue, silica precipitation, dissolution, plastic deformation, polishing and phase transformation (Knutsson 1988; Knutsson et al. 2015b). When the co-occurrence of different types of wear features (striations, plastic deformations, polish, etc.; (Knutsson 1988) is treated statistically, it seems that certain worked materials form clusters according to their physical and chemical properties, and that given associations of wear features can thus serve as indications of various worked materials (Knutsson et al. 2015b). In the context of projectiles, different forms of micro-fracturing together with linear features can be said to be the main interest, as these forms of wear are quick enough to develop even through short contact with the worked material.

5 Material and methods

5.1 Material

We analysed a total of 91 experimental armatures under low magnification and 76 of them under high magnification. This material comes from two sets of experiments: the ones conducted at TraceoLab (a total of 87 armatures shot, 11 of which could not recovered after the experiment, leaving 76 for analysis) and an earlier experiment (Seppä 1995) from which 15 armatures were analysed (Table 1).

The main body of experimental material in this study consists of barbs and transverse points. This choice was motivated by the fact that these armature types have received most attention in recent literature dealing with archaeological contexts where quartz was used abundantly (Lombard 2011; Knutsson et al. 2015a; Pargeter et al. 2016; de la Peña et al. 2018). A majority of the experimental armatures presented here derive from the experiments done in the context of the study of micro-notches from Sibudu (de la Peña et al. 2018). For the purposes of the present methodological study, the transverse point sample was expanded to include morphologies more similar to Mesolithic quartz arrowheads to further evaluate impact damage patterns on transverse points. These armatures are transverse points in the strict sense: the alignment of the cutting edge is perpendicular to the axis of the arrow. The armatures from Seppä's (1995) experiment are oblique and transverse points. They were examined to gain a preliminary understanding of the possible effects of cutting edge alignment on damage formation. Finally, ten convergent tips of morphologies roughly similar to those of the barbs and segments were added to the sample to understand possible sources of confusion in identifying armature orientation on the basis of macroscopic and microscopic wear (Fig. 2).

Projectile type	**Production**		**Analysis**		**Σ analysed**	**Σ lost**	**Σ shot**
	Knapper	**Method**	**Low magn.**	**High magn.**			
Barbs / automorphic	CL	freehand	14	14	14	4	18
Barbs / xenomorphic	CL	freehand	26	26	26	1	27
Transverse / automorphic	CL	freehand	11	11	11	3	14
Transverse / xenomorphic	CL	freehand	16	16	16	2	18
Transverse / automorphic	JS	bipolar	8	0	8	0	8
Transverse / xenomorphic	JS	bipolar	7	0	7	0	7
Convergent / automorphic	CL	freehand	4	4	4	1	5
Convergent / xenomorph	CL	freehand	5	5	5	0	5
Total			91	76	91	11	102

Table 1 Summary of the experimental material included in the study

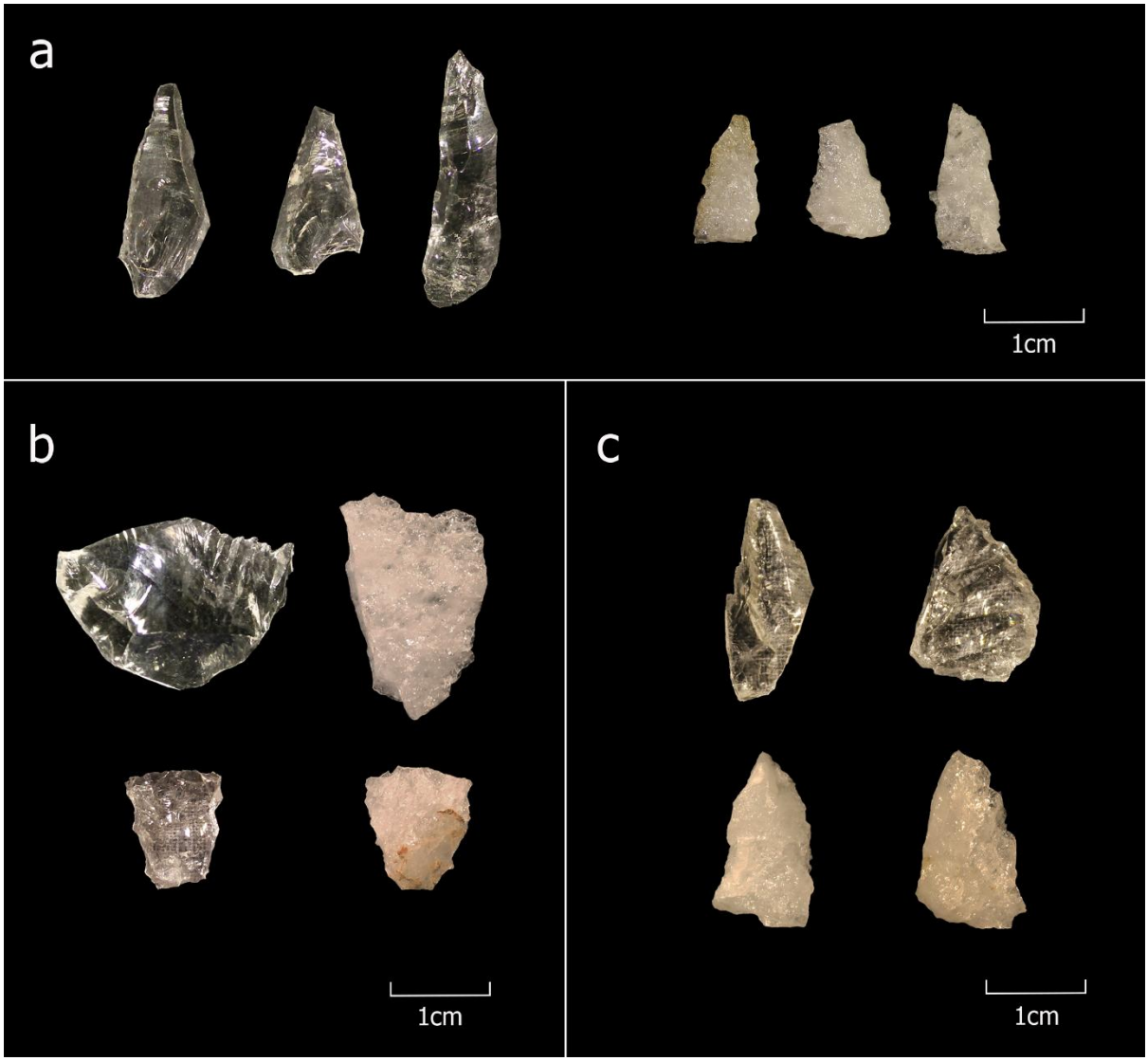

Fig. 2 Examples of experimental armatures before hafting (all dorsal views). a: barbs (Exp. 86/48 and 53), b: transverse points (86/65, 84, 88 and 91), c: convergent points (86/95, 97, 100 and 103)

Unmodified and unused flakes and fragments from earlier knapping experiments were used as a control sample for addressing specific issues such as damage formation during bipolar knapping, and secondary scarring associated with breaks. This material includes both automorphic and xenomorphic quartz, and represents two main blank production methods, bipolar and freehand platform flaking.

5.2 Experimental setup

The blanks for the armatures were produced by experienced knapper Christian Lepers (CL) from unidirectional platform cores using freehand percussion, and some of them were further shaped by minimal retouching of the non-active parts to make the tools easier to haft. Eighteen barbs were made out of automorphic quartz and 27 out of xenomorphic quartz, whereas for the transverse points, the ratio was 14 to 18, respectively. Five tips with convergent distal edges were made per raw material category, resulting in a total of ten tips.

The armatures were photographed before hafting and examined under low magnification. All production-related features (retouch, breaks, scarring, crushing, etc.) were noted on photos to

ensure that they would not be confused with impact wear. Also zones with macroscopically visible cracks and other flaws – expected to be fragile and thus susceptible to irregular breakage upon impact – were marked on the photos when observed.

The barbs were attached laterally on self-pointed wooden arrows, always in aligned sets of three. Two of the 15 shafts used had grooves made for the barbs. For five arrows, including the two grooved ones, only sinew was used for attaching the barbs. Five arrows were put together using adhesive only. For the remaining five arrows, both sinew and adhesive were used (Fig. 3a-c). Throughout the experiment, the adhesive used was a mixture of natural spruce resin (70%) and beeswax (30%).

Fig. 3 Examples of barbed arrows before the experiment. Left: sinew and adhesive (Exp. 86/45), middle: adhesive (spruce resin and beeswax) only (86/51), right: sinew only (86/53)

The transverse points and the convergent points were fitted at the extremities of split wooden shafts. For six points, only sinew was used. Two points were hafted using adhesive only. The remaining 24 were mounted using a combination of sinew and adhesive.

The arrows were photographed before the experiment and then shot by CL from a distance of 10 meters with a 47-pound flat bow made of elm wood (29-inch draw distance). A pony skeleton encased in ballistic gel moulded in the form of the animal and covered with a stretched, fresh hide

was used as a target (for details see Coppe and Rots 2017). Each arrow was shot three times at most. If the armatures broke or detached sooner, the experiment was stopped.

Documentation sheets were used to record for example the penetration depth of the projectile, possible breakage and/or detachment of the lithic armature, and the arrow's position in the target. All arrows were photographed also after the shoot to allow a better understanding of use-wear formation.

The transverse and oblique arrowheads coming from Seppä's experiment are made of xenomorphic (milky) quartz and of automorphic (rose) quartz. The armatures were hafted with sinew bindings and shot with a 39-pound flat bow and a 51-pound long bow. This experiment was designed to evaluate the performance of the arrowheads, and included a preliminary test using a paraffin target and a more actualistic experiment where a roe deer carcass was used. The shooting distances were 15 and 10 metres, respectively (Seppä 1995).

5.3 Analysis

Our analytical approach combines low and high magnifications in a phased procedure. Low magnifications have been previously used in quartz studies (e.g. Broadbent and Knutsson 1975; Rankama 2002), but practically all extensive methodological work has been done in the field of high magnification analysis (e.g. Knutsson 1988), and the combination of the two approaches has been advocated only recently (Taipale 2012; Taipale et al. 2014; Rots et al. 2017; de la Peña et al. 2018).

Low magnification analysis was done using Olympus and Zeiss stereomicroscopes (Olympus SZX7, magnifications 8–56×, and Zeiss Stemi, magnifications 6.5–50×). The observed features were compared with notes on production-related features, and the presence, location, and basic characteristics of impact-related breaks and damage were then recorded. For barbs, where break and scar patterns are quite complex especially due to scars caused by bindings and the contact of detached barbs with each other on impact (see below), a more detailed recording was employed using an attribute-based documentation system recently developed for projectile analysis (see Coppe and Rots 2017). The main break types referred to in sections 6.4–6 are shown in Fig. 4. The macroscopic features were photographed with a Zeiss Macro-Zoom microscope V16 (magnifications 5.6–180×) and stacked in Helicon Focus.

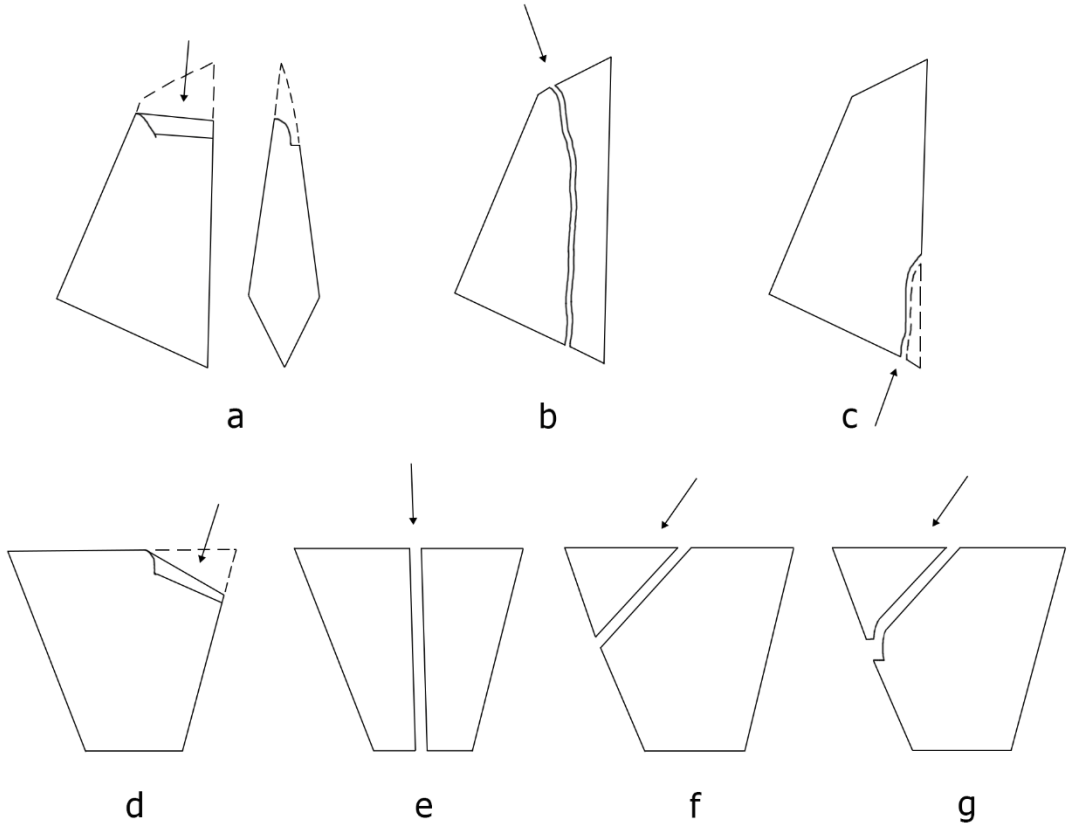

Fig. 4 Different types of breaks observed on experimental armatures (see sections 6.4–6 and tables within). a. Transverse bending-initiated step-terminating surface-to-surface break on a barb/tip. b. A longitudinal edge-to-edge break on a barb. c. A longitudinal removal ("burination") on a barb. d. An oblique (nearly transverse) surface-to-surface break on a transverse point. e. A longitudinal edge-to-edge break on a transverse point. f. An oblique edge-to-edge break on a transverse point. g. A step-terminating oblique edge-to-edge break on a transverse point. For description of other impact-related traces such as spin-offs, see e.g. Coppe and Rots 2017

Spotting small lateral removals on xenomorphic quartz is not always easy, whereas on automorphic quartz, even the smallest scars can be observed and recorded in detail without difficulty. One outcome of the structural properties of xenomorphic varieties is the generally varied surface topography of knapped quartz. When coupled with the high reflectivity of the raw material, this quality makes the identification and characterisation of retouch and other removals on xenomorphic quartz edges sometimes difficult. These problematics are well illustrated by blind tests where participants on the one hand identified unmodified xenomorphic quartz pieces as retouched implements and on the other hand sometimes severely struggled with detecting retouch (Lindgren 1998; Driscoll 2011b). These results suggest that caution will also be needed when identifying used edges solely on the basis of macroscopic features, as some irregularities formed during blank detachment can mimic secondary removals.

The projectiles were examined under high magnification using an Olympus metallurgical microscope BX51M (magnifications 100–1000×) and a Zeiss AxioImager (magnifications 50–500×) equipped with polarising filters and DIC to record microscopic linear impact traces (MLITs) (Moss 1983) and other impact-related features. Prior to high magnification analysis, the pieces were cleaned of resin and other residues. They were first dipped in freshly boiled water to soften the

resin, most of which was then wiped off with cotton. If needed, they were next immersed in weak NaOH solution (1 mol/l) for two minutes and the partly dissolved remains of resin were removed in an ultrasonic bath using tap water, or alternatively wiped off with cotton dipped in acetone. The treatments were repeated when necessary. During analysis, ethanol and acetone were frequently used to remove handling grease.

Surfaces of xenomorphic quartz are often irregular, which leads into "blind spots" during analysis. Magnification of 500× was therefore abundantly used to ensure that all the relevant areas could be properly observed despite the varied microtopography. For both raw material categories, the presence of original crystal surfaces and recrystallization surfaces, sometimes formed on quartz as the result of instability in quartz veins due to tectonic activity (Driscoll 2010; Fernández-Marchena and Ollé 2016), occasionally posed limitations for observations. These surfaces were excluded from high magnification analysis and their location recorded together with other data.

The main set of data discussed in the following sections comes exclusively from the experiments done at TraceoLab. This allows us to keep certain critical variables (bow, target, shooting distance) constant. Seppä's (1995) arrowheads serve here as a point of comparison that permits evaluating the representativeness of the main results. These armatures are briefly discussed in section 6.5 and are not included in the tables. The material from Seppä's experiment was not examined under high magnification since the purpose was to evaluate whether the general damage patterns on oblique arrowheads differ from those on transverse ones. This experiment was not designed for microwear analysis, and the armatures were not examined microscopically before the experiment. Therefore, only features that are obviously impact-related – i.e. breaks and larger damage – are considered here.

A number of pieces with macroscopic damage that was particularly difficult to characterise, interpret, or photograph were selected for more detailed analysis and imaging using a JEOL IT300 SEM in low vacuum mode. Several researchers have used scanning electron microscopy in exploring and documenting wear on quartz and similar materials, and it has obvious advantages (e.g. Knutsson 1988; Márquez et al. 2016; Ollé et al. 2016). We limit its use here to the documentation and further analysis of certain ambiguous features observed under low magnification.

Our approach here is essentially qualitative. We describe a number of relevant microscopic features in detail to illustrate the particularities in the behaviour of quartz. While we in the following sections summarise the frequencies of certain impact features in our experimental samples, this is only done to provide the reader with an overview of the wear patterns and to allow a discussion on how different features co-occur. The (sub)samples presented here are too small for reliable statistical analysis. The exclusion of statistics at this stage, however, is primarily motivated by a conscious methodological choice. Treating the data statistically would mean operating on the level of feature frequencies, which translates into DIFs. We do not believe that focusing on individual features is an advisable approach, and in fact argue that this is an important methodological issue that requires further attention in the field of projectile studies (see Rots and Plisson 2014; Coppe and Rots 2017).

6 Results

6.1 Projectile performance

The outcomes of the projectile experiments done at TraceoLab are summarised in Tables 2–4. For the 13 barbed arrows that successfully entered the target, penetrations from 1cm up to 19cm were measured. Seventeen of the arrows tipped with transverse points successfully pierced the skin and entered the target, causing wounds between 7cm and 19.5cm in depth. For the eight arrows with convergent tips, the depth of penetration varied between 6.5 and 16.5cm.

Exp. 86/ID	Quartz type	Hafting	Nr of shots	Contact material				Outcome
				skin	gel	bone	wall	
44a-c	Automorphic	Adhesive	1					Explosion, barbs lost
45a-c	Automorphic	Sinew + adhesive	2	●	●			Two barbs de-hafted
46a-c	Automorphic	Sinew	2	●	●			Two fragments remain in shaft
47a-c	Automorphic	Sinew	1	●	●			Barbs collided
48a-c	Automorphic	Sinew + adhesive	2	●	●			One fragment remains in shaft
49a-c	Automorphic	Adhesive	1	●	●			One barb de-hafted
50a-c	Xenomorphic	Sinew	1	●	●			Two barbs de-hafted
51a-c	Xenomorphic	Sinew + adhesive	1	●	●			One barb de-hafted
52a-c	Xenomorphic	Sinew + adhesive	1	●	●			One barb fragmented
53a-c	Xenomorphic	Sinew, in groove	1	●				All barbs de-hafted
54a-c	Xenomorphic	Sinew + adhesive	3	●	●	●		All barbs still attached
55a-c	Xenomorphic	Adhesive	1	●	●	●		Barbs still attached, one broken
56a-c	Xenomorphic	Adhesive	1	●	●			Barbs still attached, one broken
57a-c	Xenomorphic	Sinew, in groove	3	●	●			Two fragments remain in shaft
58a-c	Xenomorphic	Adhesive	1	●	●	●		One barb de-hafted

Table 2 Outcome of the barb experiment (three barbs per arrow, a-c)

Exp. 86/ID	Quartz type	Hafting	Nr of shots	Contact material				Outcome
				skin	gel	bone	wall	
62	Automorphic	Sinew + adhesive	1	●			●	Point broken in shaft
63	Automorphic	Sinew + adhesive	1				●	Point broken in shaft
64	Automorphic	Sinew	1				●	Point lost
65	Automorphic	Sinew	1	●	●	●		Point damaged and de-hafted
66	Automorphic	Sinew + adhesive	1	●				Point broken in shaft
67	Automorphic	Sinew	2	●	●		●	Point broken in shaft
68	Xenomorphic	Sinew + adhesive	1				●	Point broken and de-hafted
69	Xenomorphic	Sinew	3	●	●	●		Point lost
70	Xenomorphic	Sinew + adhesive	1	●				Point broken and de-hafted
71	Xenomorphic	Sinew	1	●	●			Point damaged in shaft
72	Xenomorphic	Sinew	1	●				Point damaged in shaft
73	Xenomorphic	Sinew + adhesive	1	●	●	●		Point broken in shaft
74	Xenomorphic	Sinew + adhesive	1	●				Point damaged and de-hafted
75	Xenomorphic	Sinew + adhesive	1	●				Point broken in shaft
76	Xenomorphic	Sinew + adhesive	1	●	●	●		Point broken in shaft
77	Xenomorphic	Adhesive	1	●	●	●		Point broken and de-hafted
78	Xenomorphic	Adhesive	1	●	●			Point broken and de-hafted
79	Xenomorphic	Sinew + adhesive	1	●	●	●		Point broken in shaft
80	Automorphic	Sinew + adhesive	1	●	●	●		Point lost
81	Automorphic	Sinew + adhesive	1	●	●	●		Point damaged and de-hafted?
82	Automorphic	Sinew + adhesive	1	●	●			Point broken in shaft
83	Automorphic	Sinew + adhesive	1					Point de-hafted before impact
84	Automorphic	Sinew + adhesive	1	●	●			Point de-hafted
85	Automorphic	Sinew + adhesive	1	●				Point broken and de-hafted

86	Automorphic	Sinew + adhesive	1	●	●	●		Point broken in shaft
87	Automorphic	Sinew + adhesive	1	●				Point broken in shaft
88	Xenomorphic	Sinew + adhesive	1	●				Point broken in shaft
89	Xenomorphic	Sinew + adhesive	2	●	●	●		Point broken and de-hafted
90	Xenomorphic	Sinew + adhesive	1	●	●	●		Point de-hafted, shaft broken
91	Xenomorphic	Sinew + adhesive	1	●				Point broken and de-hafted
92	Xenomorphic	Sinew + adhesive	1	●				Point damaged, moved in shaft
93	Xenomorphic	Sinew + adhesive	2	●	●			Point broken in shaft

Table 3 Outcome of the transverse point experiment

Exp. 86/ID	Quartz type	Hafting	Nr of shots	Contact material				Outcome
				skin	gel	bone	wall	
94	Automorphic	Adhesive	1	●	●	●		Point damaged in shaft
95	Automorphic	Sinew + adhesive	1	●	●	●		Point broken in shaft
96	Automorphic	Adhesive	1	●	●	●		Point broken in shaft
97	Automorphic	Sinew + adhesive	1	●	●	●		Point damaged in shaft
98	Automorphic	Adhesive	1	●	●	●		Point lost
99	Xenomorphic	Adhesive	1	●				Point de-hafted
100	Xenomorphic	Sinew + adhesive	2	●	●	●		Point broken in shaft
101	Xenomorphic	Sinew + adhesive	3	●	●	●		Point broken in shaft
102	Xenomorphic	Adhesive	1	●		●		Point broken in shaft
103	Xenomorphic	Sinew + adhesive	1	●	●	●		Point broken in shaft

Table 4 Outcome of the tip experiment

It appears that for the transverse arrows, the morphology of the lithic armature affected success rate more than it did for the barbs. In the case of arrows mounted with barbs, the wooden point pierced the skin first, whereas for arrows tipped with transverse points, the properties of the cutting edge and other morphological aspects were crucial for success. Some points that failed to pierce the skin displayed clear morphological disadvantages, such as relatively thick portions right behind the cutting edge due to the proximity of the butt and the bulb of the blank. In some cases, however, these disadvantages could be overcome, and the arrow was shot deep into the target despite the less-than-ideal distal morphology. This probably has to do with the angle of impact and the variation in the thickness of the skin stretched over the target.

While acknowledging that the morphometric variability within the projectile categories is quite substantial (Fig. 2), and that the division of the transverse points into segments and Mesolithic points is somewhat artificial due to limited amount of retouch and high variability in blank shapes, it is interesting to note that the small sample examined here may suggest differences among success rates of these general morphologies. The success rate is highest for the barbs, suggesting that this hafting mode allows for the largest variability in blank morphometrics without significant influence on the outcome. It has to be stressed, however, that the basic functioning of these arrows significantly differs from the other three categories: the sharpened wooden tip is the part that first pierces the skin, making these arrows somewhat more standardised in design in comparison to the rest of the sample. While the sample remains small, it seems obvious that the arrows on which the barbs were fixed with only sinew performed worse than those where adhesive was used. The sinew-bound barbs detached from their shafts in several cases upon impact and thus did not contribute to the size of the wound.

When the special case of barbed arrows is left aside, the rest of the sample shows the highest success rate for tips (8/9), second highest for segment-shaped transverse points (9/12), and the lowest for the remaining transverse arrows (8/16). The samples are small, but these observations seem to suggest that as far as unmodified or minimally retouched blanks go, selecting flakes with convergent distal morphologies is a safer choice than selecting ones with a transverse cutting edge. While these results are preliminary and can partly be attributed to other variables than point morphology, they may have interesting implications for blank selection and projectile design. It seems that in the case of transverse arrowheads, the morphology of the blank has to be more carefully selected for and/or adjusted than in the case of tips with convergent distal extremities. This may in part explain the observation that Mesolithic transverse and oblique points are a relatively standardised artefact category in quartz assemblages where the proportion of formal tools is otherwise low (see Manninen and Knutsson 2011; Manninen and Tallavaara 2011).

6.2 Trace formation and identification: general observations

As expected, xenomorphic quartz in particular is somewhat unique in terms of trace formation and analysis. Impurities that may affect fracture patterns can be sizeable and frequent. This is illustrated by a barb where a longitudinal break ("burination") propagated along an impurity in the material (Fig. 5a), and by a transverse point where the proximal end shattered along impurities, cracks, and recrystallization planes (Fig. 5b).

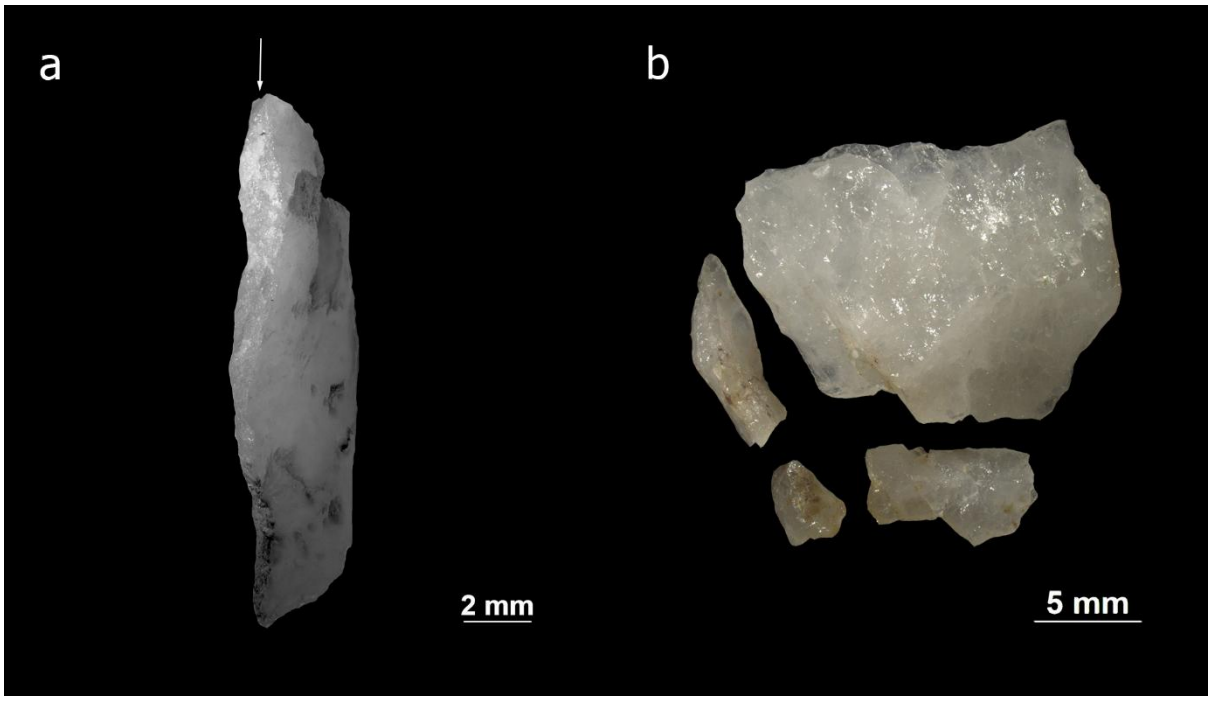

Fig. 5 a. A longitudinal break ("burination") that followed an impurity in the raw material (barb 86/55a, xenomorphic quartz). Original magnification 10×. b. An experimental transverse arrowhead (86/70, xenomorphic quartz) showing breakage along flaws and irregularities in the material

SEM analysis offers further evidence of the idiosyncratic behaviour of quartz under mechanical stress. For instance, on one of the pieces (86/88), possible deep step-terminating spin-offs were recorded, but their initiations were judged either very diffuse or absent, and it was unclear whether they were truly secondary damage associated with the break and not simply surface irregularities formed during knapping and cut by the subsequent impact break. The SEM image of the area

suggests that the observed features do initiate from the break surface, but the area seems to show a combination of flaw-controlled fracture propagation and fully developed conchoidal fracturing on microscale (Fig. 6). These features, although small and not highly relevant for projectile identification, emphasise the importance of understanding the dual nature of break and scar formation in xenomorphic quartz that is likely to affect the formation and appearance of larger features as well.

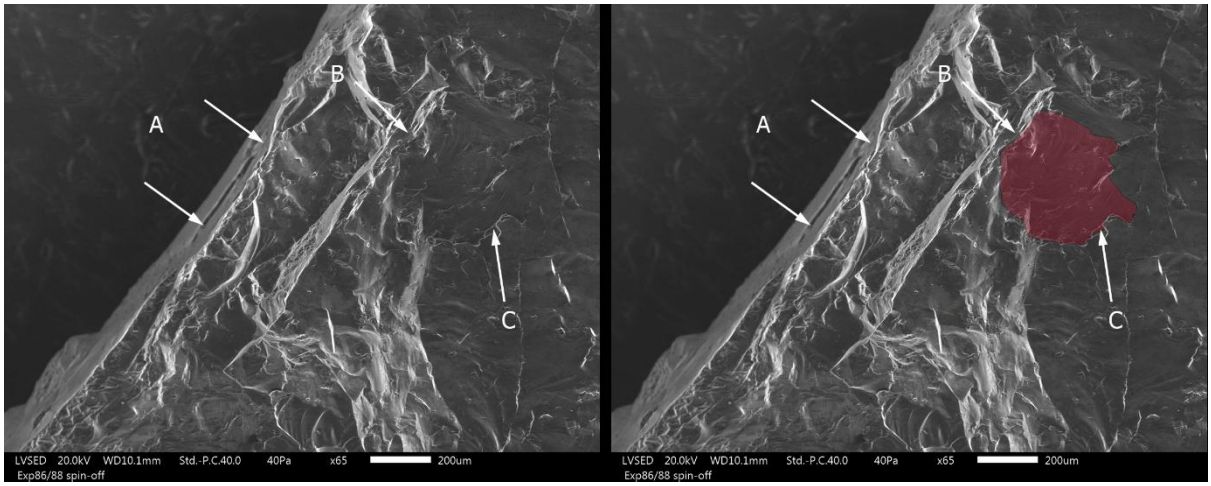

Fig. 6 Spin-offs on Exp. 86/88 (xenomorphic quartz) imaged with SEM. Their initiations (A) are not obvious cones, and the removals are thus more representative of cleaving than of conchoidal fracture. A shallow tertiary scar (highlighted with red in the image on the right) with a well-developed cone initiation (B) and a step termination (C), located at the right extremity of the spin-off, witnesses a combination of conchoidal and flaw-controlled fracturing in this area. The larger of the spin-offs shows the pronounced step termination already visible under low magnification. It is clearly caused by a plane of weakness intersecting the fracture path, cutting the propagating crack short and resulting in a spin-off less than half a millimetre in length. Original magnification 65×, scale bar 200µm

Another transverse point in xenomorphic quartz (Exp. 86/91) appears to show a combination of fragmentation (sensu Callahan et al. 1992; Tallavaara et al. 2010) and formation of secondary damage. Here, macroscopic examination of the piece shows that a significant amount of material has been removed from the ventral aspect of the distal fragment of the piece that was snapped in two by a non-characteristic proximal break (Fig. 7a). The termination for this supposedly large removal is not visible under reflected light, nor are its outer edges. Its initiation and termination could not be pinpointed with the SEM, either, but smaller removals within it could be detected (Fig. 7b-c). Again, it seems that a combination of different fracture phenomena is responsible for the formation of these features, with fragmentation along a plane oriented roughly parallel to the ventral surface being responsible for the removal of the majority of the lost volume. This kind of (secondary) fragmentation is not included in the original schematic description of flake fragmentation (Callahan et al. 1992; Rankama 2002; Tallavaara et al. 2010), but Tallavaara and colleagues mention a number of secondary fragments that could not be refitted during the experiments (Tallavaara et al. 2010). It is probable that the phenomenon described here corresponds to or at least overlaps with what happens when quartz is knapped.

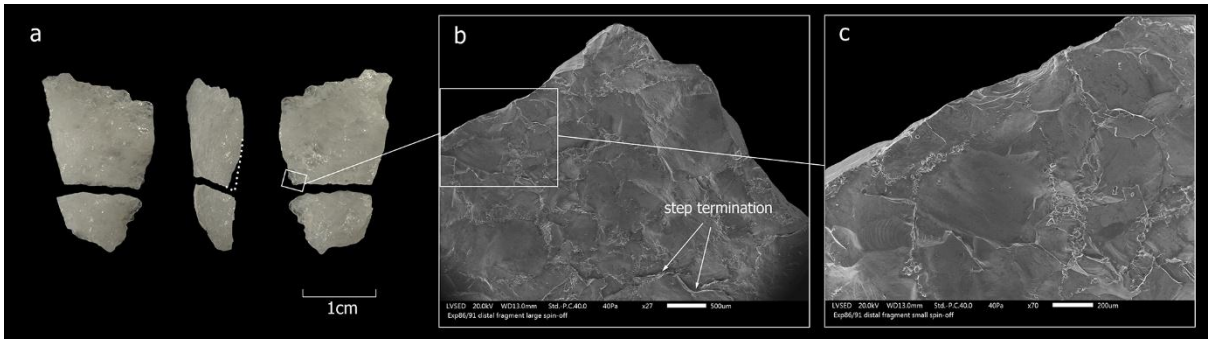

Fig. 7 Transverse point Exp. 86/91 (xenomorphic quartz) with a large secondary removal. a. Refitted artefact showing the loss of volume on the distal fragment. b. No clear termination for the large removal was detected in the SEM analysis, but smaller, shallow step-terminating removal without a clear point of initiation or outline is visible within it. It appears that part of the surface has split off starting from the break through a sequence of secondary removals. Original magnification 27×, scale bar 500µm. c. A small conchoidal scar with minuscule scars at its initiation, not detectable with the stereomicroscope. Original magnification 70×, scale bar 200µm

Further, a small tip break on one of the barbs made of xenomorphic quartz illustrates that while some of the features can be diffuse and hard to interpret, others can be easily misinterpreted. This break was originally classified as a bending-initiated step-terminating removal with its initiation on dorsal surface on the right side of the tip, but is in fact a snap/feather-terminating removal oriented at right angles to its originally assumed direction. What looks like a step termination is actually an irregularity on the break surface, running parallel to the direction of impact (Fig. 8). This tip break is thus another example of fracture propagation partly controlled by the existing flaws in the material, giving rise to irregular break surfaces. It shows that care is needed when interpreting small features in xenomorphic quartz.

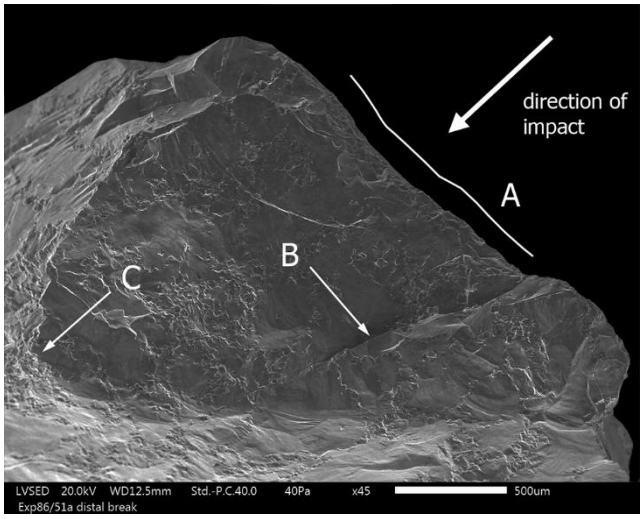

Fig. 8 A small tip break the type and direction of which were misidentified in the low magnification analysis. In addition to the break, crushing (A) was also observed, running perpendicular to the supposed orientation of the small break and leading to a contradictory damage pattern. The SEM image shows that the assumed step-termination (B) is in fact a structural irregularity, and the break actually reality terminates in a snap (C). Its direction is thus exactly the same as that of the crushing (small conchoidal scars) formed at its initiation. Original magnification 45×, scale bar 500µm

High magnification results show that some of the possibly impact-related removals were not identified during low magnification analysis. While these removals are usually small, and only one patch of scarring could be identified as impact damage with certainty thanks to the MLITs found in association with it, these observations together suggest that the frequent use of high magnifications in confirming or challenging what is seen under low magnification is a recommendable approach (see also Rots and Plisson 2014; de la Peña et al. 2018).

While the majority of observations made in this section concern xenomorphic quartz, certain recurrent features also appear in automorphic varieties. Under high magnification, projectiles in both raw materials commonly show incipient cracks in the areas that came into contact with the target. These cracks are dominantly oriented in the direction of impact (Fig. 9), but also several cases where these longitudinal cracks occurred in combination with transverse ones were encountered. The cracks thus seem to have formed as the result of compression and bending forces that occur at the moment of impact. They cannot, however, be considered diagnostic of impact by themselves, since similar cracks were found on fragmented bipolar flakes, usually oriented in the direction of the blow.

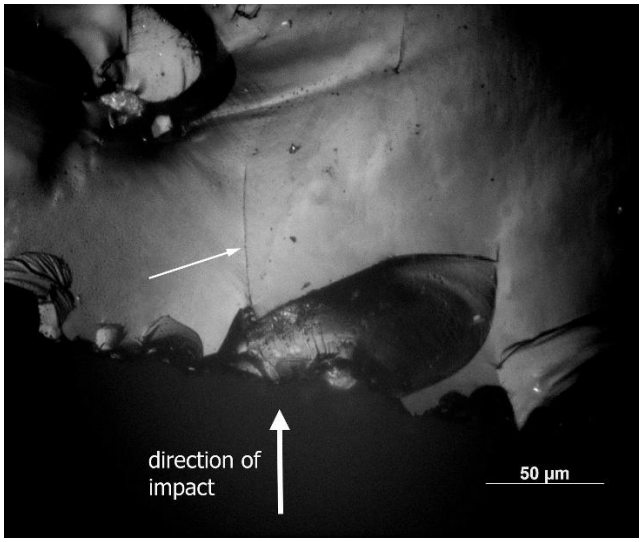

Fig. 9 A crack oriented in the direction of impact (arrow), associated with small scarring. Exp. 86/57b (xenomorphic quartz), original magnification 500×, scale bar 50µm

Among the linear features (MLITs) that formed on our experimental armatures upon impact, different types are represented. Using Knutsson's (1988) terminology, irregular and regular striations dominate heavily, whereas sleeks are extremely rare and basically only occur as one component of larger features that are best characterised as very large irregular striations or abrasion tracks. This suggests that the MLITs are mostly formed through brittle fracture wear and only rarely through plastic deformation (see Knutsson 1988; Derndarsky and Ocklind 2001).

A particular type of striation occurs repeatedly in our sample. It can be characterised as an unusually broad straight-sided (regular) striation. It seems to cut if not deeply, at least relatively harshly into the surface, and has an even, flat bottom (Fig. 10). We interpret it as a special case of a series of subsurface cracks (see Knutsson 1988; Derndarsky and Ocklind 2001). These striations occur on both xenomorphic and automorphic quartz. We therefore tentatively propose that they may be the result of a specific type of load situation caused when a quartz particle stuck in the target scratches the surface of the projectile (cf. Kamminga 1982; Knutsson 1988).

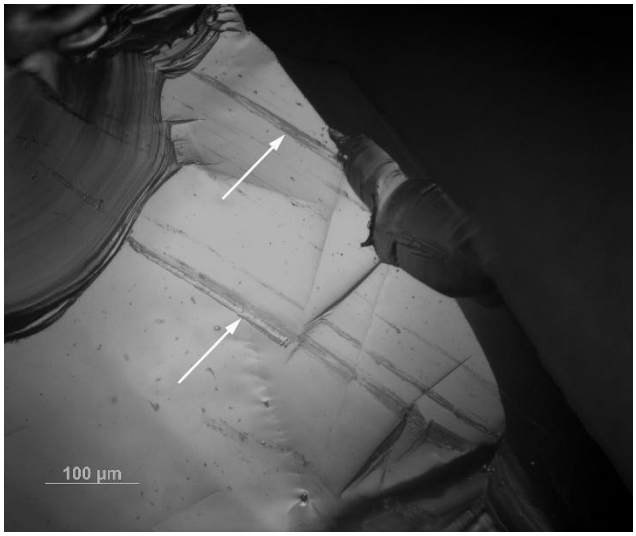

Fig. 10 An example of broad regular MLITs described in the text. Transverse point Exp. 86/86, automorphic quartz, original magnification 200×

6.3 Possible sources of confusion in projectile identification

6.3.1 Macroscopic features

When analysing quartz, care should be taken to not confuse production-related features with impact wear. The bipolar method in particular creates breaks with pronounced secondary damage (spin-offs). These secondary scars are most pronounced in automorphic quartz, but microscopic spin-offs occur along break edges also in xenomorphic quartz, even though the majority of them are too small to be easily visible under low magnification.

Several experimental armatures in the studied sample have pronounced longitudinal breaks or removals along lateral edges ("burinations") that were formed during production (Fig. 11a). These features may be associated with other forms of damage (e.g. abruptly terminating removals and crushing) that can also be confused with impact wear (Fig. 11b). In addition to these challenges, some pieces in automorphic quartz show more ambiguous facets that could be confused with so-called impact burinations. The latter problem is similar to erroneously identifying flakes split longitudinally during knapping as burins (*burin de siret*, Bordes 1961; for quartz, see Siiriäinen 1981). On the other hand, actual impact-related longitudinal removals along one edge can be very diffuse and almost impossible to distinguish from a break facet of a longitudinally split flake (Fig. 11c).

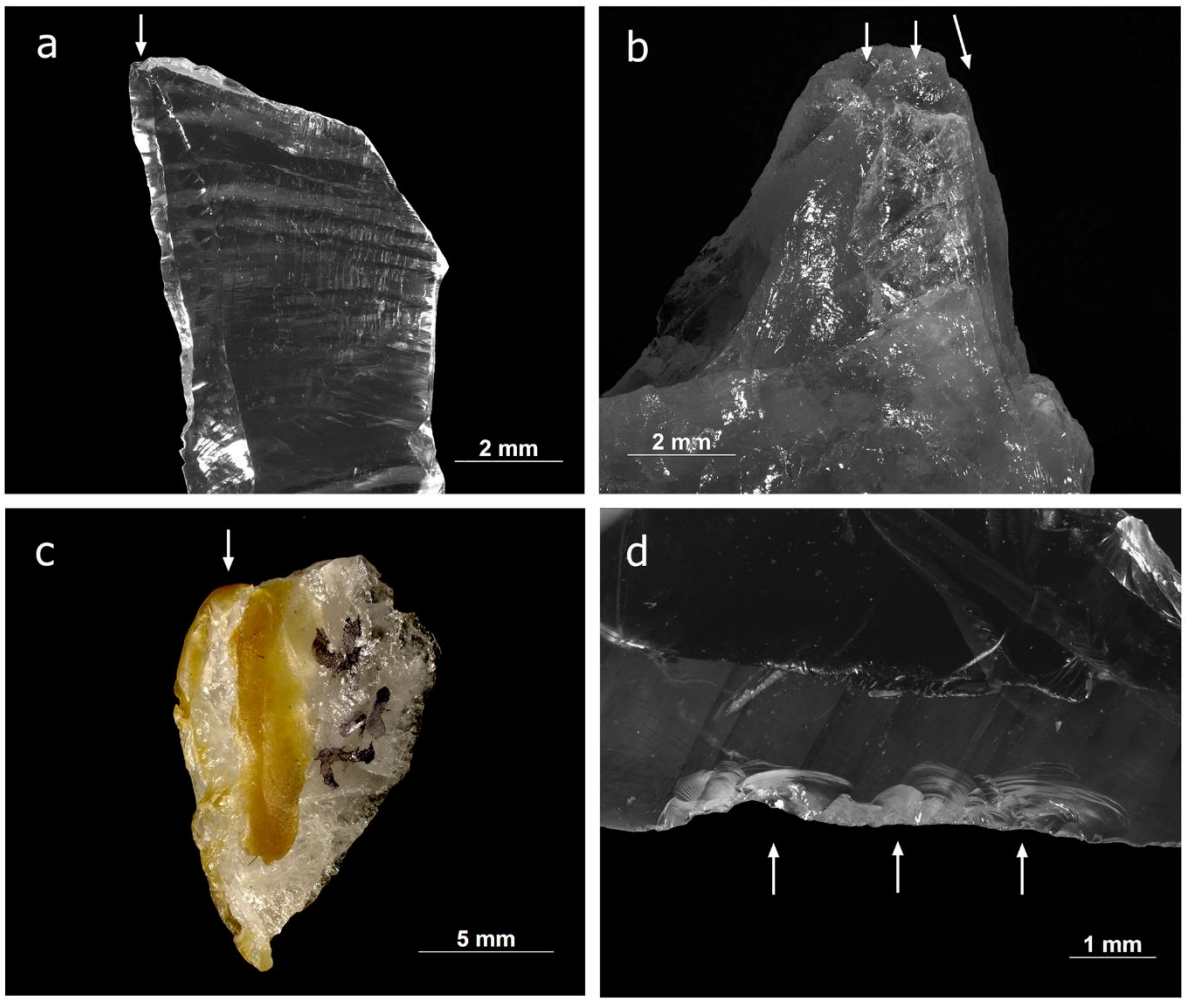

Fig. 11 a. An elongated removal ("burination") formed during knapping (flake 86/59-4 from the bipolar knapping control sample, automorphic quartz, original magnification 20×) (de la Peña et al. 2018: fig 10e). b. A feature resembling an impact burination associated with tip damage (step-terminating removals and crushing), both resulting from knapping (Exp. 24 in Taipale 2012). Original magnification 20×. c. Example of a longitudinal break (burination) on a barb. The long removal (still stuck on the shaft) was easy to detect before the removal of the resin, but very difficult to tell apart from a facet formed in knapping after the piece was cleaned. d. Retouch-like scarring from contact with another barb on 86/48b, automorphic quartz. Original magnification 32× (de la Peña et al. 2018: fig. 15b)

While production-related features can easily be confused with impact damage, impact damage can in rare cases be confused with intentional retouch. This is the case with the unusually regular and continuous scarring on the lateral edge of an experimental barb (Fig. 11d), caused by contact with another barb upon impact. Notches form a specific case of edge damage that can sometimes result from impact but also from a variety of other causes including knapping and trampling. These features are discussed in detail elsewhere (de la Peña et al. 2018).

6.3.2 Microscopic features

The occurrence of impact-like features on freshly knapped flakes and flake fragments is a strong argument for an approach that integrates low and high magnification analysis with a good understanding of technological aspects of quartz industries. Our experimental sample shows that MLITs form on quartz, and can in several cases help to confirm projectile function (see below).

A word of caution is, however, needed when it comes to identifying these features. A bipolar flake fragment from knapping experiments is an example of a case where secondary scarring associated with a break is accompanied by striations (Fig. 12). While it is possible to tell such coincidental combinations of features apart from impact traces, a much more secure approach is one that takes into account the overall morphology of the piece as well as the location and orientation of different features, and combines observations made under low and high magnifications. Linear features on quartz are frequent, and only some of them are functionally relevant.

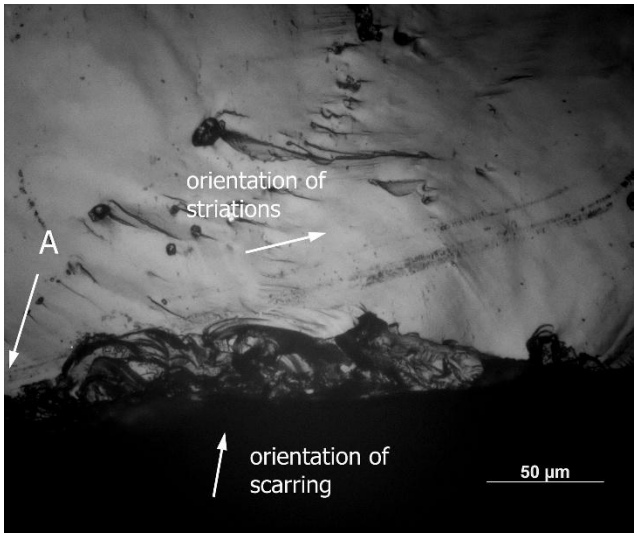

Fig. 12 An example of coincidental link between edge damage and striations, potentially confusable with MLITs. Here, a careful examination of the traces helps to separate them from impact wear. The striations initiate on the left side of the damaged zone (A) instead of right at the scars' edges, and the orientations of the features differ

6.4 Damage patterns and microscopic features on barbs

Altogether four barbs were lost in the target during the experiment, and one detached from its shaft in flight before impact, and was therefore not analysed. On the remaining 40 barbs, damage is abundant, with 31 barbs showing macroscopic traces (see Table 5). Tip fractures are quite common: fourteen of the recovered barbs have breaks at their distal extremities. Five of these pieces also show a second break. One additional piece has a medial break, bringing the total number of fractured pieces to 15. Of the pieces with their tips preserved, only four show other damage on them, and when it occurs, it is generally light scarring or, in one case, crushing that is relatively subtle and difficult to characterise.

Feature type	**Automorphic**		**Xenomorphic**		**Combined**	
	n (N=14)	**% (N=14)**	**n (N=26)**	**% (N=26)**	**n (N=40)**	**% (N=40)**
Bending-initiated step-terminating surface-to-surface breaks	1	7.1%	0	0.0%	1	2.5%
Other surface-to-surface breaks	3	21.4%	8	30.8%	11	27.5%
Bending-initiated step-terminating edge-to-edge breaks	0	0.0%	0	0.0%	0	0.0%
Other edge-to-edge breaks	2	14.3%	2	7.7%	4	10.0%
Indeterminate breaks	0	0.0%	0	0.0%	0	0.0%
Several breaks on same piece	2	14.3%	3	11.5%	5	12.5%
Spin-offs	4	28.6%	1	3.8%	5	12.5%

Burinations*	3	21.4%	2	7.7%	5	12.5%
Distal scarring	1	7.1%	3	11.5%	4	10.0%
Lateral scarring (cutting edge)	13	92.9%	9	34.6%	22	55.0%
Basal scarring	3	21.4%	3	11.5%	6	15.0%
MLITs	5	35.7%	5	19.2%	10	25.0%
Other striations	6	42.9%	8	30.8%	14	35.0%
Other microwear possibly from impact	8	57.1%	18	69.2%	26	65.0%
No macroscopic damage	1	7.1%	8	30.8%	9	22.5%

Table 5 Frequency of different types of features on experimental quartz barbs in each raw material category and in the whole sample (for break categories, see Fig. 4). *Category "burinations" includes both longitudinal breaks and smaller removals; these features are also included in the counts in their appropriate categories (here, edge-to-edge breaks and basal scarring)

It seems that the breaks that can be considered classically diagnostic of impact, that is, the ones showing secondary scarring (spin-offs) (Fig. 13a) or a bending initiation and a step termination, are dominantly caused by the collision of two barbs, or two fragments of a single barb, against each other. This may imply that the number of diagnostic breaks on barbs increases when the hafting system allows them to detach and collide on impact. The breaks originating from contact with the target (most often skin and ballistic gel) are in general snaps, although in one case contact with skin and ballistic gel produced a complex break on the thin and fragile distal extremity of the first barb (Fig. 13b).

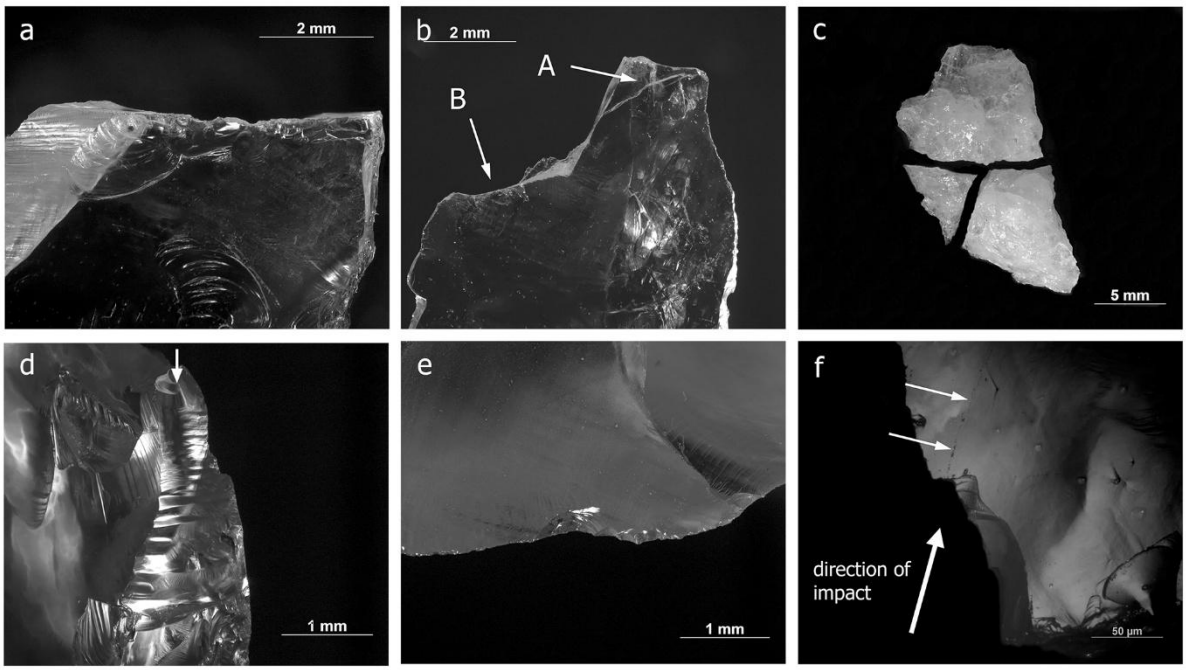

Fig. 13 a. Spin-offs on barb 86/48a, automorphic quartz, original magnification 32× (de la Peña et al. 2018: fig. 15c). b. A complex break at the distal extremity of barb 86/45b (automorphic quartz), showing a bending-initiated step-terminating component (A) and a snap component (B). Original magnification 25×. c. Barb 86/52a (xenomorphic quartz) exploded into three fragments through snap breaks on impact (de la Peña 2018: fig. 16a). d. Elongated removal ("burination") on barb 86/48b (automorphic quartz), caused by counter-pressure from shaft. Original magnification 50×. e. Patch of scars forming a small notch on Exp. 86/47c

(automorphic quartz). Original magnification 50×. f. A MLIT associated with a microscopic burin-like removal, indicating the direction of impact on 86/57a (xenomorphic quartz). Original magnification 500×

One of the barbs made of xenomorphic quartz exploded into three fragments upon impact as a result of contact with skin and ballistic gel (Fig. 13c). The two breaks on this piece are clean transverse and longitudinal snaps and are not accompanied with MLITs. The fragmentation of this barb can be considered comparable to fragmentation of flakes during knapping (see Callahan et al. 1992; Tallavaara et al. 2010). While other striations were found that probably formed at the moment of impact when the fragments moved against each other, these are not directly linked with the break edges, are oriented in two different directions, and could easily be confused with taphonomic or production-related striations if this was an archaeological piece.

Features traditionally termed burinations (but see Coppe and Rots 2017 for critical review of the use of the term) include longitudinally or obliquely oriented breaks as well as shorter removals in our sample of barbs (see Fig. 4). They seem dominantly caused by counter-pressure from the shaft upon impact since they are most often located on the edge that was against the shaft (Fig. 13d).

Lateral scarring is the most common type of impact damage on the barbs and takes various forms. Twenty-two out of 40 barbs that could be examined after the experiment show lateral edge damage. Barbs coming into contact with each other on impact can cause intense edge damage, such as the long stretch of retouch-like scarring observed on barb 86/48b (Fig. 11d). In most cases, however, the damage is more limited and consists of small groups of scars or isolated scars. It is sometimes notch-like (Fig. 13e) (de la Peña et al. 2018). The orientation of the scars is often oblique to the edge and thus indicative of the position of the piece in the shaft, but also scars with a more perpendicular orientation occur, making it sometimes difficult to determine the angle at which the armature hit the target by looking at edge damage alone, especially in cases where the scars are few in number.

Interestingly, considerable proportion of the lateral damage observed on the barbs (29%, or 15 out of 52 recorded scars or groups of scars) has been caused when they have been pressed against the bindings upon impact. With the exception of two minor cone-initiated scars, all of this damage is bending-initiated, whereas the scars formed through contact with the wooden shaft, the target or the adhesive show both cone and bending initiations, with cone initiations dominating slightly.

The relatively frequent detachment of barbs and their subsequent collision with each other is a major cause for damage in the sample, and obscures any possible pattern in damage frequencies introduced by barb position in the shaft (first, second, or third counting from the distal end of the arrow). It also makes it difficult to evaluate the influence of contact material (skin, gel and/or bone) on damage attributes.

Microscopic features on barbs consist of true MLITs (Moss 1983; Fischer et al. 1984), other striations, and microscopic scarring, cracking, and abrasion. Exactly one fourth of the barbs (10/40) have MLITs. Five of them are made of automorphic quartz and five of xenomorphic quartz. The linear features are always parallel or slightly oblique to the cutting edge of the barb and serve as an indication of the alignment of the armature with its shaft (Fig 13f).

The lower frequency of MLITs on xenomorphic quartz (5/26 pieces) as opposed to automorphic quartz (5/14 pieces) may be partly due to observational difficulties in analysing xenomorphic quartz, but more probably due to differences in the rates of edge damage formation in the two raw materials. Especially the rates of lateral scarring differ greatly from one raw material to the other (see Table 5). Our experimental dataset thus demonstrates the more fragile nature of automorphic quartz edges, and suggests a link between the amount of macroscopic damage (especially lateral scarring) and the frequency of MLITs.

Microwear from hafting is relatively scarce on the barbs. Twenty-five of 40 barbs showed no features in their hafted portions. Of the remaining barbs, one has striations clearly formed under the bindings. On several others, striations behind the rim of the hafted edge running parallel to it were occasionally recorded, and one of the pieces displayed an abraded ridge. The most prominent hafting-related features in our sample of barbs are thus the elongated removals ("burinations") formed by counter-pressure from the shaft, the distinctive bending-initiated scarring caused by sinew bindings, and the striations formed under the bindings.

6.5 Damage patterns and microscopic features on transverse arrowheads

Three transverse points were lost during the experiment, and one of them detached from the shaft before impact and was not analysed. Another point was excluded from analysis since the only fragment that was recovered was too small to manipulate and could therefore not be examined in detail. These pieces excluded, the sample totals 27 transverse points. Out of these, three arrows either ricocheted off the skin and subsequently hit the wall behind the target, or missed the target and hit the wall instead. The wall is made of autoclaved aerated concrete and is not strictly comparable to materials found in nature, and cannot therefore be considered a relevant reference for comparisons with archaeological material. The pieces that came into contact with it are nevertheless included as a special case in the discussion of impact wear to serve as a proxy for contact with hard non-animal material (stone, wood, etc.), but the microwear on them is treated with caution.

Transverse points are characterised by breaks initiating and terminating on a surface ("transverse" breaks) and breaks initiating on the cutting edge and terminating on the opposite or adjacent edge (base or lateral edge; "longitudinal" breaks) (Fig. 4; Table 6). The breaks in the former category are typically oblique but in some cases almost perpendicular to the direction of impact (Fig. 14a). The breaks in the latter category often split the piece in two almost equal parts or at least removed a considerable proportion of its volume, and are oriented parallel or oblique to the axis of the arrow (Fig. 4). Two of these bending-initiated breaks, one in automorphic quartz and one in xenomorphic quartz, terminate in a cascade of steps (Fig. 14b), whereas the rest show snap or feather terminations. In addition, one bending-initiated surface-to-surface break on an automorphic quartz point has a step termination.

Feature type	Automorphic		Xenomorphic		Combined	
	n (N=11)	% (N=11)	n (N=16)	% (N=16)	n (N=27)	% (N=27)
Bending-initiated step-terminating surface-to-surface breaks	1	9.1%	0	0.0%	1	3.7%
Other surface-to-surface breaks	4	36.4%	7	43.8%	11	40.7%
Bending-initiated step-terminating edge-to-edge breaks	1	9.1%	1	6.3%	2	7.4%
Other edge-to-edge breaks	3	27.3%	1	6.3%	4	14.8%
Indeterminate breaks	0	0.0%	4	25.0%	4	14.8%
Several breaks on same piece	4	36.4%	3	18.8%	7	25.9%
Spin-offs	6	54.5%	8	50.0%	14	51.9%
Burinations*	3	27.3%	0	0.0%	3	11.1%
Distal scarring (cutting edge)	8	72.7%	8	50.0%	16	59.3%
Lateral scarring	1	9.1%	0	0.0%	1	3.7%
Basal scarring	0	0.0%	3	18.8%	3	11.1%
MLITs	8	72.7%	10	62.5%	18	66.7%
Other striations	9	81.8%	11	68.8%	20	74.1%
Other microwear possibly from impact	7	63.6%	11	68.8%	18	66.7%
No macroscopic damage	1	9.1%	1	6.3%	2	7.4%

Table 6 Frequency of different types of features on experimental quartz transverse arrowheads in each raw material category and in the whole sample (for break categories, see Fig. 4). *Category “burinations” includes both longitudinal breaks and smaller removals; these features are also included in the counts in their appropriate categories (here, edge-to-edge breaks and spin-offs)

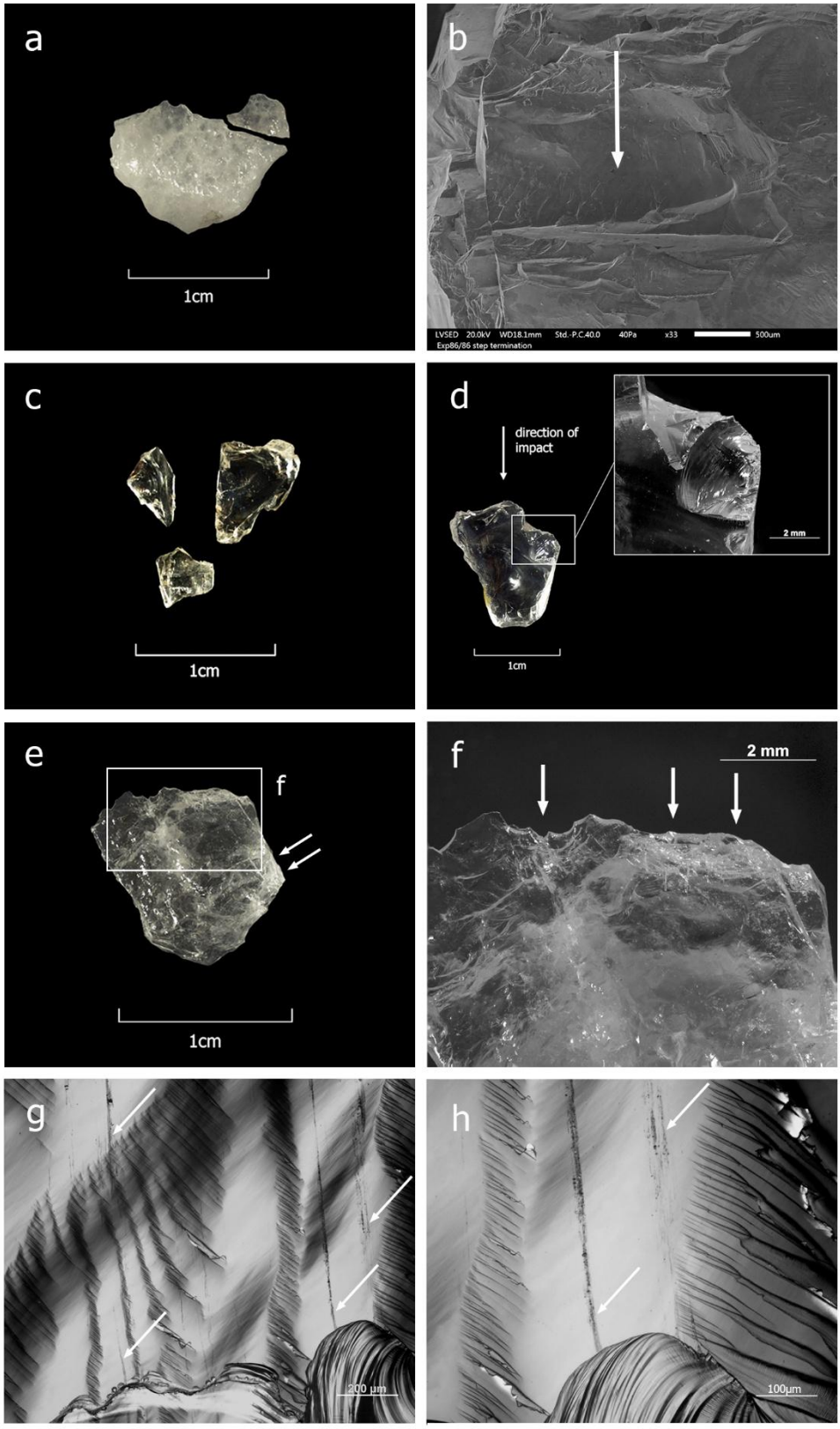

Fig. 14 a. A surface-to-surface break on experimental transverse arrowhead (86/79, xenomorphic quart), oriented almost perpendicular to the direction of impact. b. The termination of an edge-to-edge (longitudinal) break on 86/86 (xenomorphic quartz) consisting of multiple steps. The arrow indicates the general direction. Original magnification 33×. c. Fragmented transverse point (86/85) in automorphic quartz. d. A longitudinal fracture interrupted by zones of weakness in the material on 86/63, associated with another longitudinal break

that has large transverse spin-offs (shown in detail, 25×) and characteristic perpendicular damage on the cutting edge. e. Perpendicular damage on the cutting edge (see also f.) and a longitudinal (oblique) break associated with transverse step-terminating spin-offs (arrows) on 86/86. f. A detail of the typical perpendicular damage on the cutting edge of 86/86 (see also e.). Original magnification 25×. g. MLITs associated with the distal edge damage (visible in the lower part of the image) on 86/64 (automorphic quartz). Original magnification 100×. h. A detail of MLITs shown in g. Original magnification 200×

Two pieces serve as examples of high-degree fragmentation. The first one, a ricochet, exploded into several fragments (Fig 14c) through at least one transverse and two longitudinal breaks. The middle fragment shows a complex fragmentation pattern with heavy secondary scarring, and is therefore suggestive of projectile use, but its original orientation in the shaft cannot be reconstructed, and two small fragments that were recovered cannot be refitted to it. The other piece came into contact with the wall, and also shows a complex fragmentation pattern with two breaks initiating from the distal (cutting) edge. One of the breaks has an angular path (Fig. 14d), caused by the propagation of a longitudinal fracture interrupted by transversal cracks in the material. The breaks are both snap-terminated, but are associated with spin-offs (Fig. 14d). This piece illustrates the brittle and partly erratic behaviour of automorphic quartz on impact with hard material.

While some of the breaks on the transverse points are very characteristic, many others are not informative from the point of view of projectile identification. Altogether four transverse breaks and one longitudinal break, occurring on four pieces, cannot be characterised in detail since there are no features that would allow determining where the fracture initiates and terminates. On two out of these four pieces, however, other features such as spin-offs and MLITs permit identifying them as projectiles and reconstructing their orientation in the shaft. This again shows that when multiple scales of observation are used and the overall patterning of wear is taken into account, the problem of frequent, uncharacteristic fragmentation of quartz projectiles can be partly overcome.

Spin-offs are relatively common on transverse points, especially when compared with barbs (Tables 5 and 6, Figs 6 and 7). In addition to the general rules of spin-off formation discussed above, another observation is of interest here. It concerns secondary removals associated with longitudinal, obliquely oriented breaks. They occur on three fragmentary points. The secondary scars are oriented perpendicular to the break's edge, and thus also (roughly) perpendicular to the direction of impact (Figs 14d and 14e). From the point of view of correctly identifying the armature's orientation in the shaft, these features can be potentially confusing if the overall pattern is not taken into consideration. In the case of 86/86, the break's initiation on the cutting edge is associated with heavy scarring in the direction of impact, and also MLITs roughly perpendicular to the cutting edge can be found under high magnification (Fig. 10). These features confirm that the armature was hafted transversally. Armature 86/63 shows a similar combination of distal edge damage (although lighter than on 86/86) and MLITs.

Scarring on the cutting edges of the transverse points is systematically heavier than the damage found on barbs, and only two of the transverse points do not show any macroscopic scarring or other damage (Table 6). The most distinct damage pattern observed in our sample is a patch of bending-initiated, invasive, large scars with abrupt or fissured terminations easily visible to the naked eye, sometimes associated with a longitudinal break and/or heavy crushing and cracking (Fig. 14f). The orientation of the scars is clearly perpendicular to the cutting edge of the transverse point.

Despite the difference in armature morphologies, this damage pattern bears close resemblance to that reported by Fischer et al. on flint transverse points (Fischer et al. 1984: fig. 15b-c) and by Tomasso and Rots on transversally hafted flint trapezes (Tomasso et al. 2015). The brittle nature of quartz contributes to the additional crushing and cracking of the point's cutting edge.

While this type of damage is more frequent in automorphic quartz, a similar pattern can also be seen in xenomorphic quartz. The orientation of the microscopic linear features – both true MLITs and striations without an obvious connection to the impact damage – leave little doubt about the direction of impact (Fig 14g-h).

Our experiments are not comparable to those of Pargeter et al. (2016) due to obvious differences in the setup (type of bow, shooting distance, their use of a target with no skin and their use of commercial glue in hafting). It is, however, interesting to note here that the bending-initiated breaks and large removals initiating from one surface at the cutting edge (Pargeter et al. 2016) are completely absent in our sample. Two pieces in automorphic (rose) quartz from Seppä's (1995) study, however, show large bending-initiated removals with complex terminations, and one of these also has large spin-offs on the dorsal aspect of both fragments. One of the arrows was shot into paraffin and one into the animal target, suggesting that the type of target alone does not explain the difference between our and Pargeter's data. The bows between our study and Seppä's do not differ significantly (47 vs 51 pounds), so the cause for the different results probably lies in artefact raw material and morphology. In the rest of the sample from Seppä's study, the damage patterns fit well with those in our experimental sample. This suggests that minor differences in armature design (e.g. edge alignment) do not significantly increase variability in damage patterns.

With the exception of the extensive diffuse "spin-off" on 86/91 described earlier (Fig. 7), no large spin-offs comparable to those reported by Pargeter et al. (2016) were encountered. Instead, majority of the breaks recorded in our sample are transverse and longitudinal snaps, and the spin-offs are usually very small in size, measuring only around 1mm. The clearest overlap between our sample and that of Pargeter et al.'s are longitudinal breaks initiating on the cutting edge ("impact burinations", Pargeter et al. 2016).

Hafting wear is not particularly common on transverse points, but the proportion of pieces with definite hafting wear is still clearly higher than among the barbs. Five out of 27 transverse points show traces obviously formed within the shaft. These include striations linked with edge damage and other striations caused by contact with the shaft, striations associated with damaged ridges, and, on one piece, basal damage associated with incipient cracks in the direction of impact. Of special interest here is Exp. 86/66 which shows an oblique dorsally initiated snap exactly along the haft limit. Under high magnification, the fragment that was inside the shaft shows a somewhat messy pattern of striations, part of which qualify as MLITs, with two main orientations, one parallel and one perpendicular to the edge of the break. A further three pieces show more ambiguous striations for which other origin (production) cannot be excluded.

6.6 Damage patterns and microscopic features on tips

The current small sample of unmodified and minimally retouched convergent flakes hafted as tips does not by any means give a comprehensive view of impact damage on this armature type. It does, however, suggest certain trends that may be interesting to test through further experimentation.

One tip was lost during the experiment, leaving nine for analysis. Two of them show a break at the tip. Both breaks, one in xenomorphic quartz and one in automorphic quartz, initiated from a surface and propagated along cracks or other fragile zones in the material, and their appearance is thus more characteristic of the flaw patterns in the quartz than specific forces at play during breakage. One of them is associated with a second, longitudinal step-terminating break.

The other breaks (n=6) are typically bending-initiated snaps, in most cases clearly initiated and terminated on a surface but lacking clear features that would allow determining the direction. While the breaks themselves in this sample are undistinctive, four of them (three in automorphic and one in xenomorphic quartz) have spin-offs, two of them on both surfaces. On automorphic quartz these secondary scars can be relatively large (2–3mm; Fig. 15a), while on xenomorphic quartz

they are again very small, measuring less than 1mm. A further two xenomorphic quartz points have possible step-terminating spin-offs that under low magnification are roughly comparable to the ones documented on 86/88 (Fig. 6). Ventral spin-offs on one piece were imaged with SEM. Part of them are clearly conchoidal scars (Fig. 15b) while the others, located at the opposite end of the fragment, seem to be the result of the removal of microscopic blocks of quartz through cleaving (Fig. 15c).

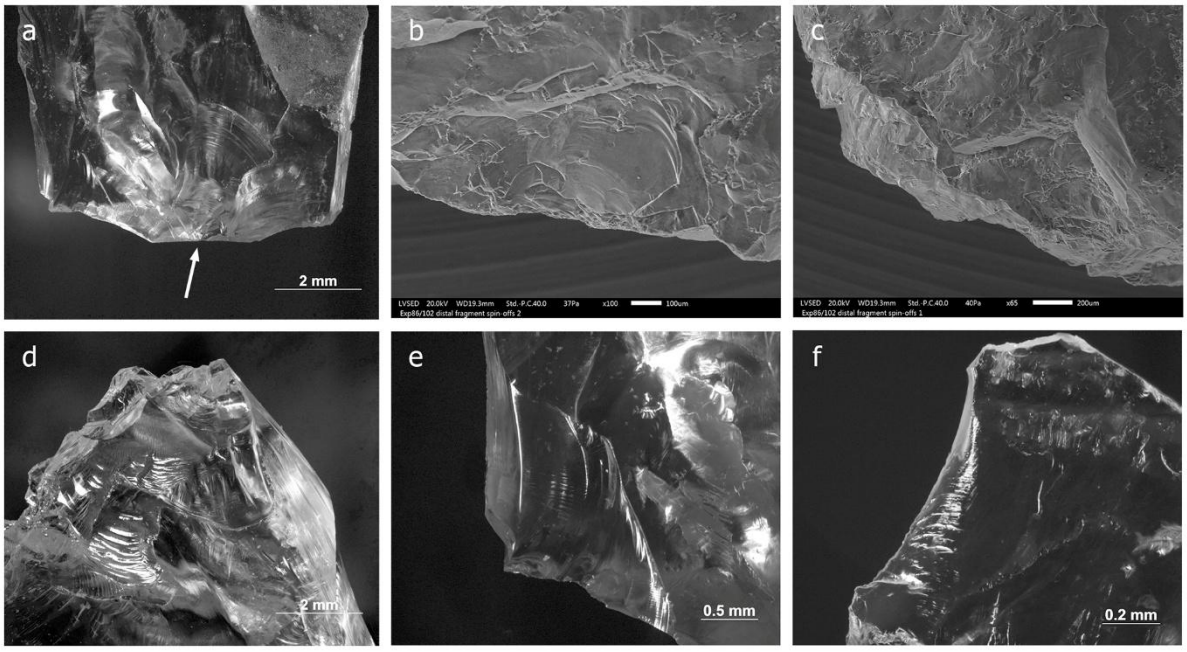

Fig. 15 a. Spin-offs on tip 86/95, automorphic quartz. Original magnification 25×. b. Small spin-offs with cone initiations on 86/102 (xenomorphic quartz). Original magnification 100×, scale bar 100µm. c. Small spin-offs without distinct initiations on 86/102 (xenomorphic quartz), formed through the removal of microscopic blocks of quartz probably through cleaving. Original magnification 65×, scale bar 200µm. d. Dominantly step-terminating invasive scars, with their initiations largely removed by crushing, on ventral surface of the tip of 86/97 (automorphic quartz). These are associated with a large step-terminating scar on the dorsal side. Original magnification 25×. e. A lateral scar on tip 86/95 (automorphic quartz). Original magnification 63×. f. A lateral scar on barb 86/48 (automorphic quartz). Original magnification 160×

In purely qualitative terms, spin-offs on the tips seem somewhat more pronounced and easier to identify than those on transverse points and barbs. The block-like removals on 86/102 suggest that this is not solely a question of the quality of the raw material in this sample, and can thus perhaps be attributed to the fact that unlike on transverse points (where breaks are often oblique), the spin-offs here are formed exactly in the direction of impact, leading on average to longer and deeper, and also more numerous, scars (see Table 7).

Feature type	Automorphic	Xenomorphic	Combined
	n (N=4)	n (N=5)	n (N=9)
Bending-initiated step-terminating surface-to-surface breaks	0	0	0
Other surface-to-surface breaks	2	2	4
Bending-initiated step-terminating edge-to-edge breaks	0	1	1
Other edge-to-edge breaks	0	1	1
Indeterminate breaks	0	3	3
Several breaks on same piece	0	2	2
Spin-offs	3	3	6
Burinations*	0	2	2
Distal scarring (cutting edge)	2	0	2
Lateral scarring	3	2	5
Basal scarring	2	1	3
MLITs	2	1	3
Other striations	3	2	5
Other microwear possibly from impact	3	3	6
No macroscopic damage	0	1	1

Table 7 Frequency of different types of features on experimental quartz tips in each raw material category and in the whole sample. *Category "burinations" includes here secondary removals that are also counted in spin-offs

Tip damage is rare in this sample, but when it occurs, it can be extreme (Fig. 15d). What is of special interest here is lateral damage that is both frequent and partly similar to that observed on barbs. However, even though the characteristics of lateral scarring on the two projectile types overlap, with both showing bending-initiated, often invasive scars oriented obliquely to the edge (Fig. 15e-f), the removals on the tips seem to be systematically larger. More importantly, three out of five of the pieces showing lateral damage also have a break associated with spin-offs. This kind of combination is rare on barbs. Even though the tip sample is small, it may well be that focusing on overall wear patterns offers a key to distinguishing between these two types of projectiles.

MLITs occur on three of the nine tips that could be analysed, in two cases associated with a break and in one case associated with the heavy distal damage mentioned above. Hafting wear is practically absent in this sample. Only one piece (86/100) shows tentative wear in the form of microscopic abrasion and cracking on its ventral proximal corner.

7 Discussion

7.1 Do wear patterns allow the identification of barbs, transverse points and convergent points?

In sum, even though the majority of breaks in all projectile categories are not suggestive of impact, and their number is probably increased by the fracturing of xenomorphic quartz along internal discontinuities, impurities and other flaws, certain repetitive patterns seem to emerge that could allow reconstructing the orientation of the armature in its shaft on the condition that the number of damaged pieces in the sample is sufficiently high. In each case, the overall patterning of traces is the key, and any analysis attempting to make these kinds of distinctions should focus on combinations of features instead of searching for one specific trait (see Rots and Plisson 2014; Rots 2016).

The wear on transverse points is clearly distinct from that on the other two armature types. Features that are limited to this category include invasive bending-initiated abruptly terminating damage oriented perpendicular to the cutting edge (often accompanied by MLITs), bending-initiated step-terminating longitudinal breaks initiated from the cutting edge, and oblique breaks associated with spin-offs oriented roughly perpendicular to the direction of impact (Fig. 16a). While for Mesolithic transverse points, the morphology is often by itself enough to determine the hafting orientation, this is not necessarily the case for all morphologies (for competing hypotheses on Howiesons Poort segments, see e.g. Lombard 2011; de la Peña et al. 2018), in which case these criteria can help to distinguish between lateral and transverse hafting.

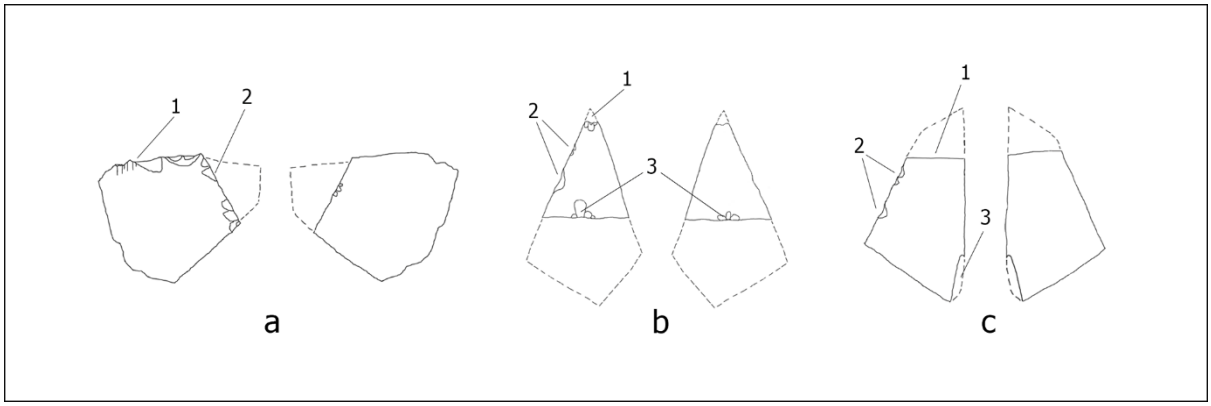

Fig. 16 Idealised drawings of typical wear patterns on different projectile types. a. Transverse points. 1: invasive bending-initiated abruptly terminating edge damage associated with MLITs, 2: oblique break associated with perpendicular spin-offs. b. Convergent tips. 1: scarring responsible for the removal of the outermost tip, 2: lateral obliquely or perpendicularly oriented damage, 3: break with spin-offs. c. Barbs. 1: tip break (in the experimental sample, typically a non-characteristic snap), 2: lateral obliquely or perpendicularly oriented damage, 3: an elongated removal on the non-active edge caused by counter-pressure from the shaft

Convergent tips and barbs share certain features such as bending-initiated lateral scarring oriented obliquely to the edge (Fig. 16b-c: 2). It is obvious that the chances of reliably telling apart these two armature types can only be evaluated through further experimentation involving tips. Yet, the small sample examined here allows the formulation of preliminary hypotheses about potentially useful criteria for identifying convergent points archaeologically.

While the breaks on tips are typically as undiagnostic as in the other two groups, spin-offs are more frequent and easily identifiable than on barbs and transverse points, not least because tips are the only category that recurrently shows bifacial spin-offs. The contrast with barbs is particularly clear. Also heavy distal damage (Fig. 16b: 1) is absent on barbs, although it has to be noted that it is not extremely frequent on tips, either.

Table 8 shows the proportion of experimental pieces with convincing evidence of projectile use within each raw material category and projectile type. Here, macroscopic and microscopic evidence were combined, and strict criteria were applied. Only armatures that showed a combination of impact damage and MLITs or a combination of macroscopic features indicative of projectile use are included in the counts. When the tip sample, which is too small for meaningful comparisons, is excluded, the identification rate is highest for transverse points, and lowest for barbs in xenomorphic quartz. A breakdown of MLITs per projectile and feature type (Table 9) offers an explanation: linear impact features are particularly frequently associated with distal damage on transverse points.

	Automorphic quartz			Xenomorphic quartz		
	certain	total	% certain	certain	total	% certain
Barbs	5	14	35.7%	4	26	15.4%
Transverse	7	13	53.8%	8	16	50.0%
Tips	3	4	75.0%	1	5	20.0%

Table 8 Number of pieces showing convincing evidence of projectile use (a combination of impact damage and MLITs or a combination of macroscopic features) in the experimental samples, divided by raw material and projectile type. These numbers represent pieces that could be confidently identified as projectiles in an archaeological setting

Feature type	Barbs				Transverse				Tips			
	MLITs			Total	MLITs			Total	MLITs			Total
	yes	no	NA		yes	no	NA		yes	no	NA	
Bending-in. step-term. surface-to-surface breaks	2	0	0	2	0	1	0	1	0	0	0	0
Other surface-to-surface breaks	2	9	0	11	4	7	0	12	2	1	1	4
Edge-to-edge breaks (incl. burinations)	0	3	1	5	3	3	0	6	0	1	0	1
Indeterminate breaks	0	0	0	0	2	2	0	4	0	3	0	3
Spin-offs	0	3	1	3	3	11	0	14	2	4	0	6
Distal damage	0	4	0	4	10	5	1	16	1	0	1	2
Lateral damage	4	18	0	22	0	1	0	1	0	4	1	5
Basal damage	0	6	0	6	0	3	0	3	0	3	0	3
No macroscopic damage	0	9	0	9	1	1	0	2	0	1	0	1

Table 9 Occurrence of MLITs (microscopic linear impact traces) in association with different types of impact features in the experimental sample. Distal damage refers to damage on the distal tip for convergent tips and barbs, and damage on the cutting edge for transverse points

These results suggest that the archaeological visibility of quartz barbs in general, and barbs in xenomorphic quartz in particular, may be low in comparison to other armature types. They have, however, been recently identified in different archaeological contexts (Knutsson et al. 2015a; de la Peña et al. 2018), which suggests that this problem can be partly overcome with a techno-functional approach and appropriate sampling strategies.

7.2 Quartz and flint

When our barb data are compared to the results of a recent study that involved flint barbs (Rots 2016), certain similarities and differences emerge. Tip breaks on flint barbs in Rots's study are rarely step-terminating, which is also the case for both of our raw material samples, where the only step-terminating break (on automorphic quartz) occurred as the result of barb collision. It is clear that the proportion of automorphic quartz pieces with lateral edge damage (92.9%; Table 5) is in the same range with that of flint barbs, all of which showed lateral scarring of some type (calculated from Rots, 2016, table 12.3), while the frequency of lateral damage is considerably lower in xenomorphic quartz (34.6%; Table 45). This suggests that while general patterns of damage formation within a projectile type may overlap between flint and quartz, certain qualities of xenomorphic quartz will introduce variability that can lead to lower success rates in projectile identification.

Our transverse points show damage patterns that are partly similar to those documented in previous studies on flint (Fig. 16a; Fischer et al. 1984; Tomasso et al. 2015). In addition to the invasive scarring on cutting edge (Fig. 17a-b and 14f, Fischer et al. 1984: fig. 15b-c), the point discussed in the context of unusual spin-offs (Fig. 7) is relevant here because it is morphologically roughly similar to the points used by Fischer and colleagues. It shows a proximal break like the point depicted by Fischer et al. (1984). The difference is in the quality of the ventral "spin-offs" on the distal fragment: our point shows a combination of fragmentation (cleaving) and minuscule conchoidal scars (Figs 17c-d). This illustrates that while there are indications that some damage patterns are analogous on flint and quartz, they can become difficult to detect due to the idiosyncratic behaviour of the less homogenous raw material. This example also warns against the use of spin-off measurements as diagnostic criteria without a careful consideration of the effect of raw material properties.

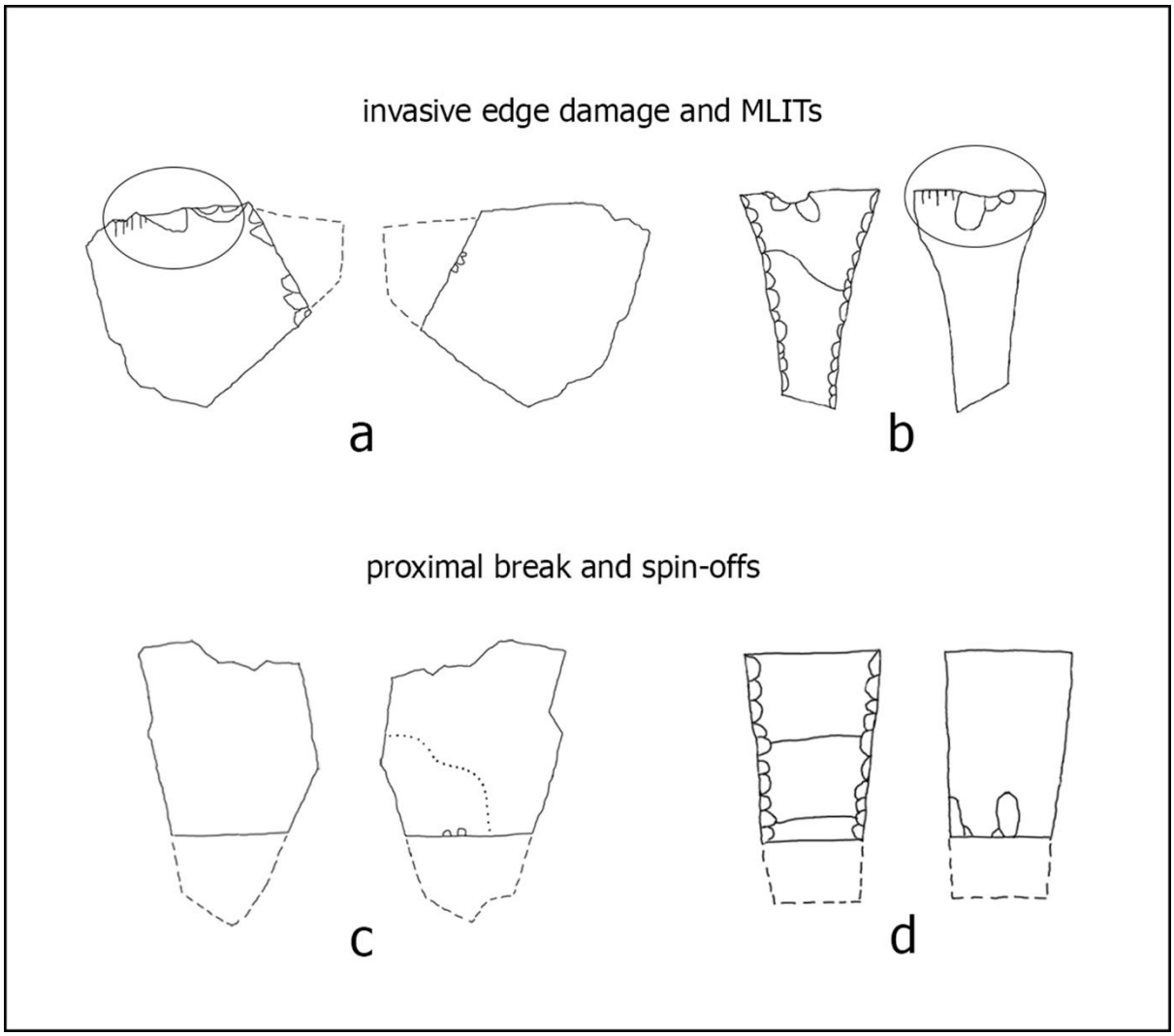

Fig. 17 Idealised drawings of wear patterns on quartz transverse points (a, c) and flint transverse points as described by Fischer et al. (b, d; Fischer et al. 1984: figs 7H and 15). a. Invasive distal scarring oriented perpendicularly to the cutting edge and associated with MLITs. b. Similar pattern in flint depicted by Fischer et al. (redrawn from Fischer et al. 1984: fig. 15). c. Wear pattern involving a proximal transverse break and spin-offs (see also Fig. 6). d. Similar damage on flint transverse point (redrawn from Fischer et al. 1984: fig. 7H)

The applicability of the criteria used for identifying projectiles made of flint and other cryptocrystalline rocks is a complicated matter. Our preliminary identification of certain similarities in the patterning of wear between the two different raw materials seems to speak for Pargeter's (2013) argument that rock type variability is secondary in comparison to tool use in macrofracture formation. Patterns similar to flint *do* exist even in xenomorphic quartz. These patterns are, however, infrequent and often ambiguous. We are therefore not convinced that the relationship between tool use and raw material properties is straightforwardly hierarchical. The frequency of partly or fully flaw-controlled breaks in all projectile categories suggests that the variability in structural properties both between and within different types of quartz is enormous. For this reason, we believe that only rigorous large-scale experimentation – preferably combined with mechanical testing of raw material samples (de Lombera-Hermida and Rodríguez-Rellán 2016; Rodríguez-Rellán 2016) and appropriate quantification of impact features – will allow determining to what extent internal planes and flaws in quartz interfere with the formation of diagnostic wear patterns. Until then, uncritical application of descriptive and analytical criteria developed for flint should preferably be avoided in the analysis of quartz projectiles.

7.3 Quartz and impact damage quantification

We believe that before methods based on quantification of wear features, such as measuring the size (area) of impact-related removals (Pargeter et al. 2016), can be successfully applied, the idiosyncratic behaviour of quartz under mechanical stress needs to be well understood and the rules applied to the specific case of impact fracture formation. In our view, this requires further, controlled experimentation involving large samples, statistical analysis, and ideally collaboration with experts from other relevant disciplines such as geology.

Based on our current dataset, we suggest that the length of impact fracture propagation and the volume of removals in xenomorphic quartz and in more erratic forms of automorphic quartz are controlled not only by the properties of the weapon and the target (point morphology, kinetic energy, angle of impact, resistance of the target) but also, and to a significant extent, by the presence and severeness of internal planes, impurities, and other zones of weakness in the lithic armature.

It seems evident that this variability in raw material qualities does not prevent the formation of impact breaks considered classically diagnostic (compare Pargeter et al. 2016). It leads, however, into the formation of a myriad of more subtle and ambiguous features that will keep the proportion of easily identifiable impact breaks low in comparison to cryptocrystalline rocks. It will also introduce additional variability into the dimensions and other characteristics of the more pronounced features. The ambiguous spin-offs documented with the SEM demonstrate the effects of the co-existence of conchoidal fracture and breakage along cleavage planes and other irregularities in xenomorphic quartz. As a result, most of the spin-offs are either fully formed but microscopic conchoidal scars, or removals with diffuse initiations cut short by flaws in the material. In both cases, they often measure less than 1mm in length, which has clear implications for approaches that search for sizeable, "diagnostic" spin-offs.

These observations call for a methodology that not only acknowledges but also, where possible, takes advantage of the particular behaviour of quartz under mechanical stress.

7.4 Can variables other than raw material be responsible for the observed patterns?

Our experimental material shows a relatively low frequency of easily identifiable impact breaks and several examples of cases where impact-related features are either small in size (e.g. microscopic spin-offs) or unusual in terms of initiation, propagation and termination when compared to cryptocrystalline rocks. We have argued that these characteristics are the result of particular

mechanical properties of quartz that affect fracture formation during projectile impact. An alternative explanation for the observed traits in the experimental sample could, however, lie in the experimental design. The main variables that could affect the frequency and characteristics of macroscopic impact damage are the robustness of the hafting system and armature morphology.

The strength of the hafting arrangement has an influence on breakage patterns in lithic armatures since the weakest element in the projectile (or target) will suffer damage unless the projectile's energy is dissipated through elastic deformation of the target (Plisson and Beyries, 1998; Rots and Plisson, 2014). This means that a failing hafting system will reduce the amount of damage to the lithic component of the projectile by absorbing a significant part of the energy. A brief examination of the cases where the hafting failed (i.e., the armature detached or moved considerably in its shaft) allows evaluating whether one or several of the bonding systems used (sinew, adhesive, and a combination of the two) produced considerable failure rates that would affect the wear patterns and the interpretation of the effects of the properties of the quartz itself on impact damage formation.

Given that the barbs were hafted in sets of three, hafting failure actually increases the frequency of impact breaks for this group of armatures by increasing the chances of contact with hard material (another barb) (see section 6.4). Barbs therefore form a special case and are not considered here. When the remaining projectiles (transverse and convergent tips) are examined, there are altogether four projectiles where the armature detached or considerably moved within its shaft without piercing the skin (see Tables 2–4). These can be considered the cases where there is most reason to suspect that the hafting system was not resistant enough to allow the formation of clear impact traces on the lithic armature. They include one convergent tip hafted with adhesive, and two transverse points hafted with sinew and adhesive. One of the transverse armatures shows a longitudinal break, spin-offs, and distal edge damage, and the other shows distal and basal edge damage. The convergent tip is the only one of the three that does not display macroscopic damage.

In addition to these three arrows, there are 11 cases where the armature de-hafted either inside the target on impact or when removing the projectile from the target. Of these, four show a break, five show edge damage of varying sorts, and only two show no macroscopic damage at all.

These counts indicate that while hafting failure may affect the observed rate of breakage, the matter is not straightforward since some of the most obvious impact breaks actually occur in these two groups due to the fact that some of the armatures came into contact with hard material. The cases where the hafting "failed" are spread over all three types of bonding systems used. This suggests that rather than being simply a question of the raw materials chosen (sinew, adhesive), the robustness of the hafting arrangement is affected also by other factors such as for example armature size and morphology and the amount and location of bindings and/or glue applied. Our current dataset is too varied to allow an accurate evaluation of the combined effect of the hafting arrangement and the contact material(s), and a thorough evaluation of the role of the former would require a different (more controlled) setup. For the purposes of the present study, however, it suffices to say that there is no simple relationship between the robustness of the hafting arrangement and the amount or quality of impact damage formed. This means that the patterns we observe are not significantly affected by failures in hafting.

Armature morphology is a complex variable that cannot be reduced to simple measures of length, width or thickness since other characteristics such as edge angles and surface convexities are crucial for fracture formation. While we acknowledge that the experimental samples are varied with respect to morphology due to the low amount of retouch and the subsequently low degree of standardisation, we assume that the variation that armature morphology introduces into the observed breakage patterns is mostly random and does not result in systematic biases. We therefore consider that the patterns we have described are representative of the behaviour of quartz on impact. It is clear, however, that future experiments that aim at a more detailed registration and

interpretation of impact fracture phenomena should be structured so that the effect of each variable is controlled for and tested using larger samples.

7.5 Impact damage on automorphic vs xenomorphic quartz

When the automorphic quartz armatures in our samples are viewed side by side with their xenomorphic counterparts, it is clear that features are usually much easier to identify and characterise on the former, and that it shows a higher frequency of diagnostic combinations of features. While our samples are too small and varied for evaluating how rare these patterns are in xenomorphic quartz, their presence among a relatively limited number of experimental armatures seems to suggest that when samples (assemblages) are large enough, such patterns should emerge even if they are partly prohibited by the unpredictable behaviour of xenomorphic quartz.

Furthermore, a "blind" division of the sample into automorphic quartz and xenomorphic quartz is not necessarily the best strategy when the goal is to understand the details of wear formation in the quartz family, as the variability within each group can be quite large (de Lombera Hermida 2009; Tardy et al. 2016). In our sample, the angular fracture pattern observed on one of the transverse points in automorphic quartz (Fig. 14d) serves as one example of slightly erratic behaviour of this raw material. While automorphic and xenomorphic varieties *typically* behave differently from one another, the variability within each category is significant enough to propose that employing only a simple division like this may lead into ignoring structural characteristics that can be relevant for impact damage formation. Further experimental work is needed for understanding which structural properties control fracture propagation and how, and whether or not they are visible to the naked eye.

8 Conclusions

Our data supports the hypothesis that the mineralogical properties of quartz, as described in recent archaeological literature, affect impact damage formation. These properties result in breakage along fault planes and other zones of weakness, in removals with irregular or diffuse morphologies, and in the interruption of fracture propagation.

While breaks and damage generally considered as "diagnostic" of impact in flint armatures also occur in quartz, they seem to be less frequent. Further work is needed to understand their relevance for projectile identification and interpretation. In addition to traits considered classically "diagnostic", we documented a number of more ambiguous features that seem to be the consequence of fully or partly flaw-controlled fracture propagation. Also the pronounced brittleness of quartz contributes to the differences between quartz and flint projectiles.

Regardless of these effects, a number of criteria can be proposed for distinguishing among quartz barbs, transversely hafted armatures, and convergent tips on an assemblage level. Barbs tend to show varying combinations of lateral damage, tip breaks (typically snaps), and removals caused by counter-pressure from the shaft. Transversally hafted pieces are characterised by heavy perpendicularly oriented damage at the cutting edge that is often accompanied by MLITs, as well as longitudinal (oblique) breaks that sometimes show spin-offs oriented perpendicularly to the direction of impact. The small sample of tips suggests that while the features on them and on the barbs can overlap, spin-offs are likely to be more pronounced and more frequent on tips, and heavy damage on the outermost tip is also more likely to occur.

These results show that impact wear on quartz is a topic worth further exploration and can significantly contribute to our understanding of past hunting practices. Analytical methods should, however, be adjusted so that they take into consideration the particular behaviour of quartz under mechanical stress. This goal is best reached by systematic large-scale experimentation, mechanical testing, and an analytical strategy that combines different microscopic techniques and scales of observation.

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