Technological ~~A~~analysis and experimental reproduction of the techniques of perforation of quartz ~~and amethyst~~ beads from the Ceramic period in the Antilles

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Abstract

Personal ornaments are a very specific kind of material production in human societies and are particularly valuable artifacts for the archaeologist seeking to understand past societies. In the Caribbean, Early Ceramic Age sites have yielded a highly diverse production both in terms of raw materials and typology. In recent years they have been the subject of renewed interest, mainly based on the diversity and provenance of raw materials, and on typological similarity, used as proxies for exchange networks, social interactions and the evolution of these phenomena through the Ceramic Age. Meanwhile, the *chaîne opératoire* for lithic beads and pendants has not been investigated in detail, including the process of creating narrow perforations in quartz beads several centimeters long. This hard material (7 on the Mohs scale), represented as rock crystal and amethyst in the collections, is indeed very difficult to perforate without the use of metal drills or harder minerals used as drill-bits or abrasives such as diamond or emery. In this work we demonstrate that it is possible to produce these perforations with cactus thorns and crushed quartz as abrasive powder. We also show that the wear created by our experimental work is fully comparable to the wear visible on the archaeological artifacts. This process, using only materials available to Ceramic Age people, also accounts for the absence of both adequate drills and production wastes of quartz beads in the archaeological record. The investment of Ceramic Age inhabitants of the Lesser Antilles in the production of the many beads made of very hard material recovered in archaeological excavations is once again highlighted. The perforation process, not investigated in detail so far in this archaeological context, has to be taken into account in the value of these highly symbolic artifacts, in addition to the exotic provenance of the raw material.

INTRODUCTION

Personal ornaments are found in many human cultures around the world and is considered as one of the oldest forms of symbolic expression, appearing in the Middle Paleolithic (Bar-Yosef Mayer et al., 2020; Peresani et al., 2013; Radovčić et al., 2015; Vanhaeren et al., 2006) and diversifying in the Upper Paleolithic in the form of durable, archaeologically identifiable remains (Kuhn, 2014). Such ornaments are non-utilitarian artifacts, often attached to a symbolic function, taking ~~its~~their value mainly in what ~~it~~they embody~~ies~~: social distinction according to gender or a particular status, embellishment of the individual, social links, etc. (e.g. Heizer and Fogelson, 1978; Munan, 1995; Nguru and Maina, 2020; Nobayashi, 2020; Wiessner, 1982). They are~~It is~~ also the marker of common concepts and symbolic thought among an ancient society (Bérard, 2013; Carter and Helmer, 2015; d'Errico et al., 2003; Kenoyer, 1997, 1991; Vanhaeren and d'Errico, 2006). ~~It~~They can also be valued because of the often associated complex craftmanship necessary to ~~its~~their production, which is acquired only after many years of practice (Roux et al., 1995).

Early~~First~~ Ceramic communities are known in the Lesser Antilles since~~for~~ about ~~2~~500 ~~years~~ B.C. thanks to numerous radiocarbon dates (Fitzpatrick, 2006; Napolitano et al., 2019) and occupied the whole archipelago. T~~t~~hey grew locally into ~~complex societies~~ chiefdoms in the Late Ceramic Age (ca. 750-1100 A.D.), and into the complex societies of the Final Ceramic that were encountered by~~until~~ the European colonization at the end of the 15th century (Bérard, 2019; Hofman, 2013; Siegel, 2010). During the Early Ceramic Age,~~is period~~, a population of pioneering horticulturists and ceramists, known as being part of Saladoid tradition, occupied the entire Lesser Antilles ~~from -400 cal. B.C. to about 500/750 cal A.D. depending on the regions of the archipelago~~ (Bérard, 2013)~~(Bérard, 2019)~~. Their economy was based on shellfish harvesting, fishing, hunting, and slash-and-burn cultivation of various plants imported from the mainland (Bérard and Giraud, 2006; Giovas, 2019; Pagan-Jimenez, 2011; Serrand and Bonnissent, 2018). In addition to a complex and diversified ceramic production (zoomorphic effigy vessels, incense burners, dishes, pots, bowls and bell-shaped vessels), displaying very elaborate decorations (painted, incised), most of the tools were produced from~~on~~ shell~~,~~ and ~~from~~ diverse rocks, locally available or imported from other islands and even from the continent (Bérard, 2004; Knaf et al., 2021; Knippenberg, 2007; Queffelec et al., 2018)~~(Bérard, 2004; Knippenberg, 2007)~~. At the very heart of their material culture, personal ornaments ha~~d~~ve a special place: made of shells (Falci, 2020; Haviser, 1990; Serrand, 2007, 2002) or gemstones, they are very diverse.

Raw material~~s~~ acquisition from as far away as the isthmo-colombian area, the Northeastern part of South America, or the Greater Antilles, and the variety of shapes, demonstrate the important investment in this craft, and the expertise of the craftspeople~~men~~ (Bérard, 2013; Cody, 1993, 1990;

Falci et al., 2020; Haviser, 1991; Hofman et al., 2008; Knippenberg, 2007; Murphy et al., 2000; Narganes Storde, 1999, 1995; Queffelec et al., 2020, 2018). Indeed, if many of these ornaments we~~a~~re ~~designed in~~made from soft minerals or rocks, the numerous, much harder ~~and~~ long quartz beads[1]~~,~~ ~~much harder,~~ raised an undeniable interest around their ~~question of~~ perforations since the first observations of th~~ese~~is ~~material~~ production~~s~~ (Harrington, 1924). ~~It~~Quartz is a mineral with a hardness of 7 on the Mohs scale, and it can therefore theoretically only be perforated by materials at least as hard as it. Metal drills, particularly hard rocks, or the use of diamond are described in numerous works dealing with lithic adornment as indispensable tools for the narrow perforation of hard objects (Gwinnett and Gorelick, 1998, 1987; Kenoyer, 1997, 1986; Kenoyer and Vidale, 1992; Ludvik et al., 2015). If such studies exist for some archaeological contexts, the perforation techniques used for quartz in the Antilles during the Ceramic period are particularly difficult to imagine. Indeed, no production of metal for utilitarian purposes is known for this period, metal being introduced in the archipelago only with the arrival of the inhabitants from the Greater Antilles around 750 cal A.D., in the form of an alloy of copper, silver and gold called guanin, which was~~is~~ used exclusively for ornamentation (Siegel and Severin, 1993). Descriptions of perforations and associated tools remain very limited and poorly documented in the Caribbean context (de Mille et al., 2008; Falci et al., 2020). A fragment of a lithic point interpreted as a drill of less than a centimeter associated with a broken amethyst bead was found in Pearls (Grenada) and is very briefly described (Cody, 1991). The works on two Puerto Rican sites mention, without description, drills in hyaline quartz and flint (Narganes Storde, 1999, 1995), while the flint drills found at Gare Maritime (Guadeloupe) are too wide compared to the narrow perforations observed on the hard rock beads found in Antillean sites (Fouéré, 2006). The only drills of the ~~Ceramic~~Precolumbian period that can correspond to the ~~restricted~~small dimensions of the perforations are found in Mexico, outside the Saladoid context (Hirth et al., 2009), and do not appear to have been suitable to produce perforations several centimeters long. Finally, several historical sources indicate the use of plants (leaf stem or palm wood) and fine sand to perforate hyaline quartz beads~~,~~ with a simple hand drill~~,~~ in Central American communities in the early 20th century (Koch-Grünberg, 1910 cited by Cody 1990; Wallace, 1889). A. R. Wallace (1889, p. 191-192), returning from a trip to South America, writes that "*Indians*" wore ornaments "*which is really quartz imperfectly crystalllized. These stones are from four to eight inches long, and about an inch in diameter*" and that drilling them "*is said to be a labour of years*" and "*for the largest size, […] [he] was informed [it] sometimes occupies two lives*". His work has been ~~resumed~~summarized by W~~V~~. E. Roth (1924), the~~n~~ latter then being cited as primary source by ~~W.~~V. Roth (1944) and then by J. Crock and R. Bartone

1 As amethyst is a gem composed of quartz whose color comes from its Fe^{4+} ion content (Fritsch and Rossman, 1988), we will use the term quartz in the remainder of this work, since it is the properties of the mineral that are of interest to us here and not its color, while the term amethyst will be retained when describing archaeological objects which do indeed have a clearly visible purple or mauve coloration

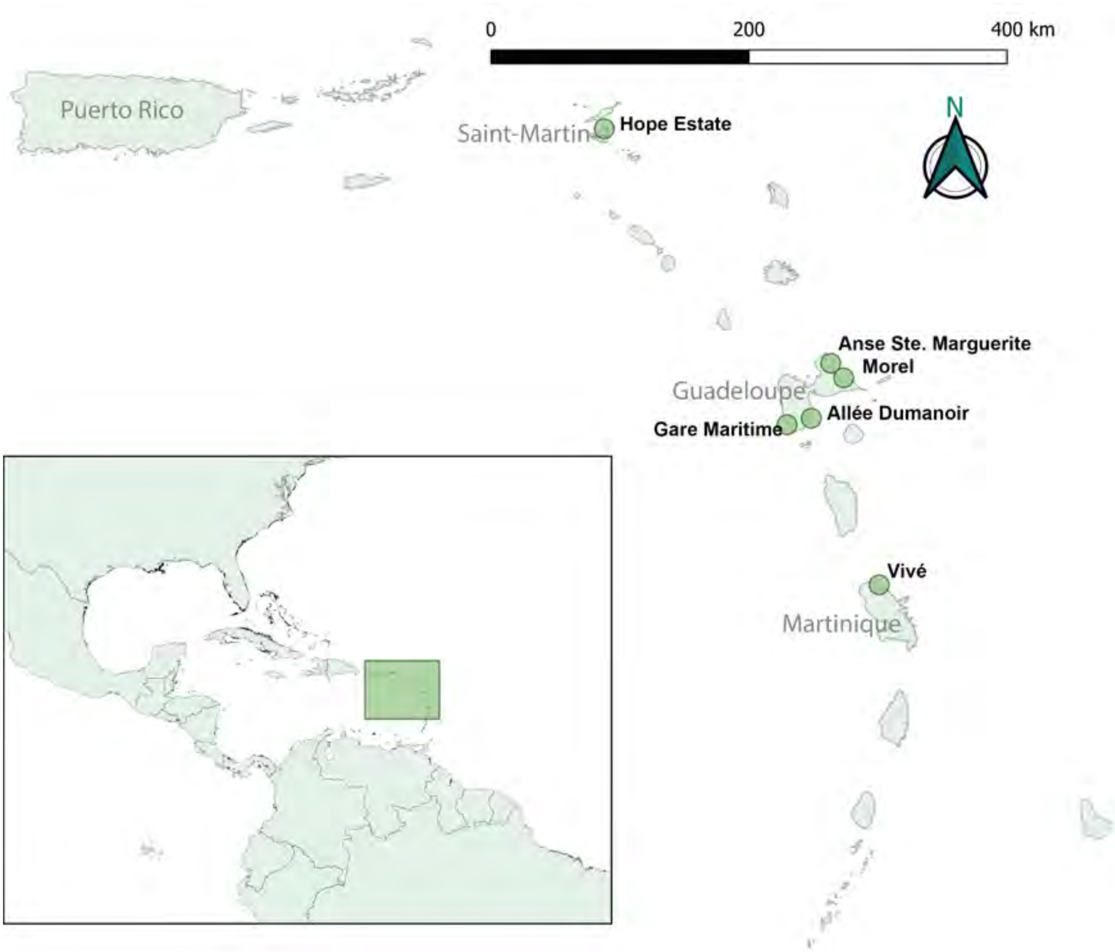
(1998)~~ describes that it takes two to three human generations to perforate a cylindrical quartz bead~~. This somewhat incredible investment is based on the narrative saying that the perforation is made with *"large wide plantain, triturating with fine sand and a little water"*~~large plant stems, fine sand (of unspecified nature) and a little water~~. In the ~~ethnographic~~archaeological cases, the lubrication of the perforation is attested but the drills are made of materials harder~~ materials~~ than the one to be perforated or, in the cases where this difference in hardness is weak, coupled with a harder abrasive (Gurova et al., 2017; Gwinnett and Gorelick, 1998; Kenoyer, 1991, 1986; Kenoyer and Vidale, 1992; Ludvik et al., 2015). Observations on archaeological Saladoid objects are limited to the mention without photography, of unfinished quartz beads with cones at the bottom of the perforation, ~~without photography,~~ which ~~would~~ indicates the use of a ~~hollow (~~tubular~~)~~ drill bit ~~without specifying its nature~~ (Cody, 1991; Crock and Bartone, 1998). Observations of ~~stigmata~~microwear on the inner surface of the perforations~~ would~~ also confirm the use of an abrasive (Falci et al., 2020).

In order to understand the techniques used and ~~to~~ measure the investment in time and resources devoted to this particular production by the Precolumbian~~Amerindian~~ groups of the Early Ceramic Age in the Antilles~~of this period~~, this work will focus on the *chaîne opératoire* and, more particularly, on the question of quartz perforation. For this, a study of beads from several Caribbean archaeological sites ~~will be~~was conducted, and these results ~~will be~~have been compared with those from an experiment specifically focused on perforation techniques.

MATERIAL & METHODS

Material

The regional inventory of lapidary ornaments from the Ceramic period recently completed (Queffelec et al., 2021), and the systematic stud~~y~~ies of these objects found in the archaeological sites of Guadeloupe, Martinique, and Saint-Martin (Queffelec et al., 2020, 2018) have~~s~~ allowed the identification of numerous beads made of quartz or amethyst.~~ It is this last corpus that could be studied in this work.~~ A total of 32 amethyst beads and 27 ~~quartz~~rock crystal beads, found on the three islands (Figure 1), in Early Ceramic Age midden layers and burials, ~~are~~were therefore available for study, but none were found with an unfinished perforation (Table 1 ;~~;~~ Figures ~~1~~2, ~~2~~3, ~~3~~4 and~~et~~ ~~5~~4). ~~Also of note~~Noteworthy is the scarcity of elements from the *chaîne opératoire* of the quartz beads, represented only by ~~only 6~~six small amethyst flakes and ~~5~~five rock crystal flakes and crystals.



105 Figure 1. Map showing the location of the archaeological sites from which the beads were recovered.

Gem material	Type	State	Guadeloupe				St. Martin	Martinique
			Gare Maritime	Allée Dumanoir	Morel	Anse Ste Marguerite	Hope Estate	Vivé
Amethyst	Barrel-shaped	Blank						
		Finished	2		6			1
		Broken		1	2		1	
	Cylindrical	Blank						
		Finished	1		1		2	
		Broken	1				1	
	Discoid	Blank						
		Finished					1	
		Broken						
	Biconical	Blank						
		Finished			3	1		4
		Broken						
	Spherical	Blank						
		Finished			1			1
		Broken						
	Button	Blank						
		Finished		1				
		Broken						
	Undetermined	Blank	1					
		Finished						
		Broken					1	
	Total		5	2	13	1	6	6
Rock crystal	Barrel-shaped	Blank						
		Finished						
		Broken						
	Cylindrical	Blank						
		Finished	1		11		3	1
		Broken			2		2	
	Discoid	Blank						
		Finished	1				2	
		Broken	1				1	
	Biconical	Blank						
		Finished						
		Broken					1	
	Spherical	Blank						
		Finished						
		Broken						
	Total		3	0	13	0	9	1

Table 1: Distribution of the types of amethyst and rock crystal beads in the different Early Ceramic sites studied.

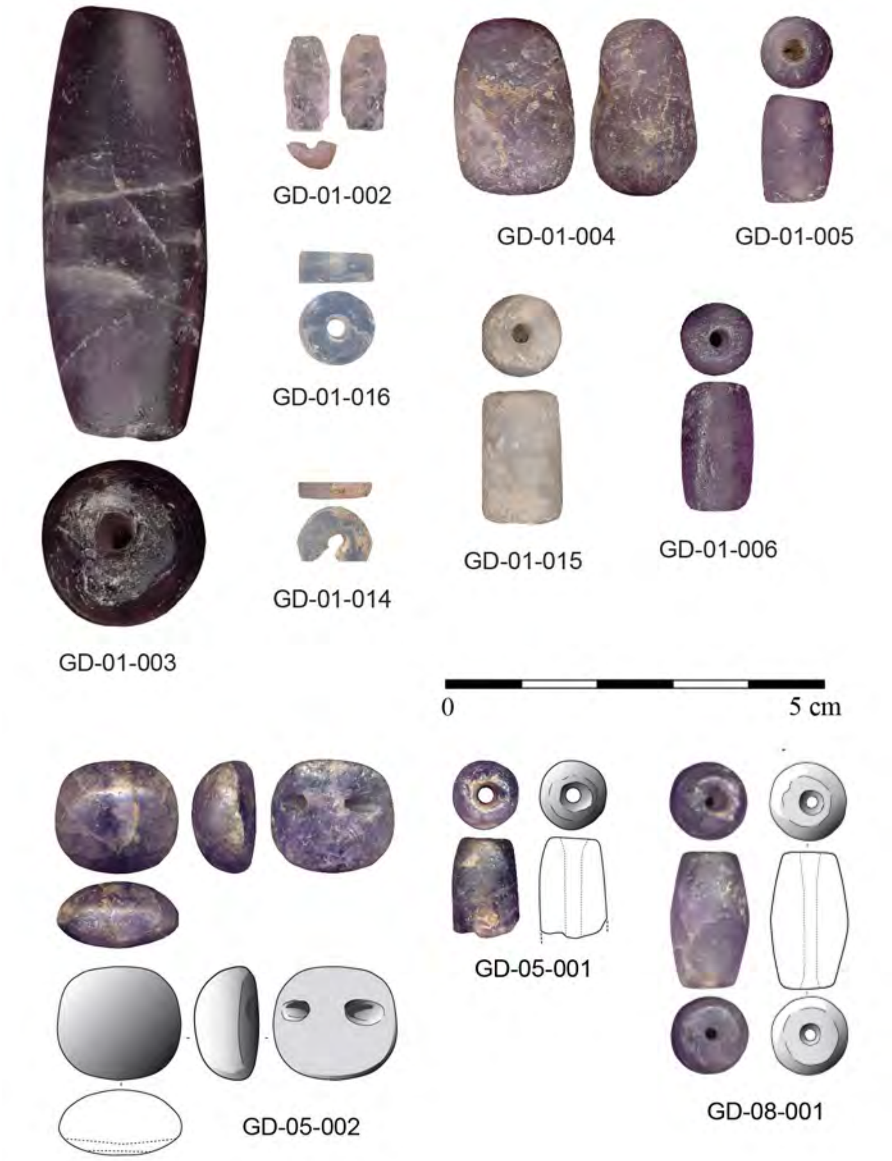


Figure ~~1~~2: Photographs and drawings of beads from Gare Maritime (GD-01), Allée Dumanoir (GD-05), and Anse Ste Marguerite (GD-08), Guadeloupe.

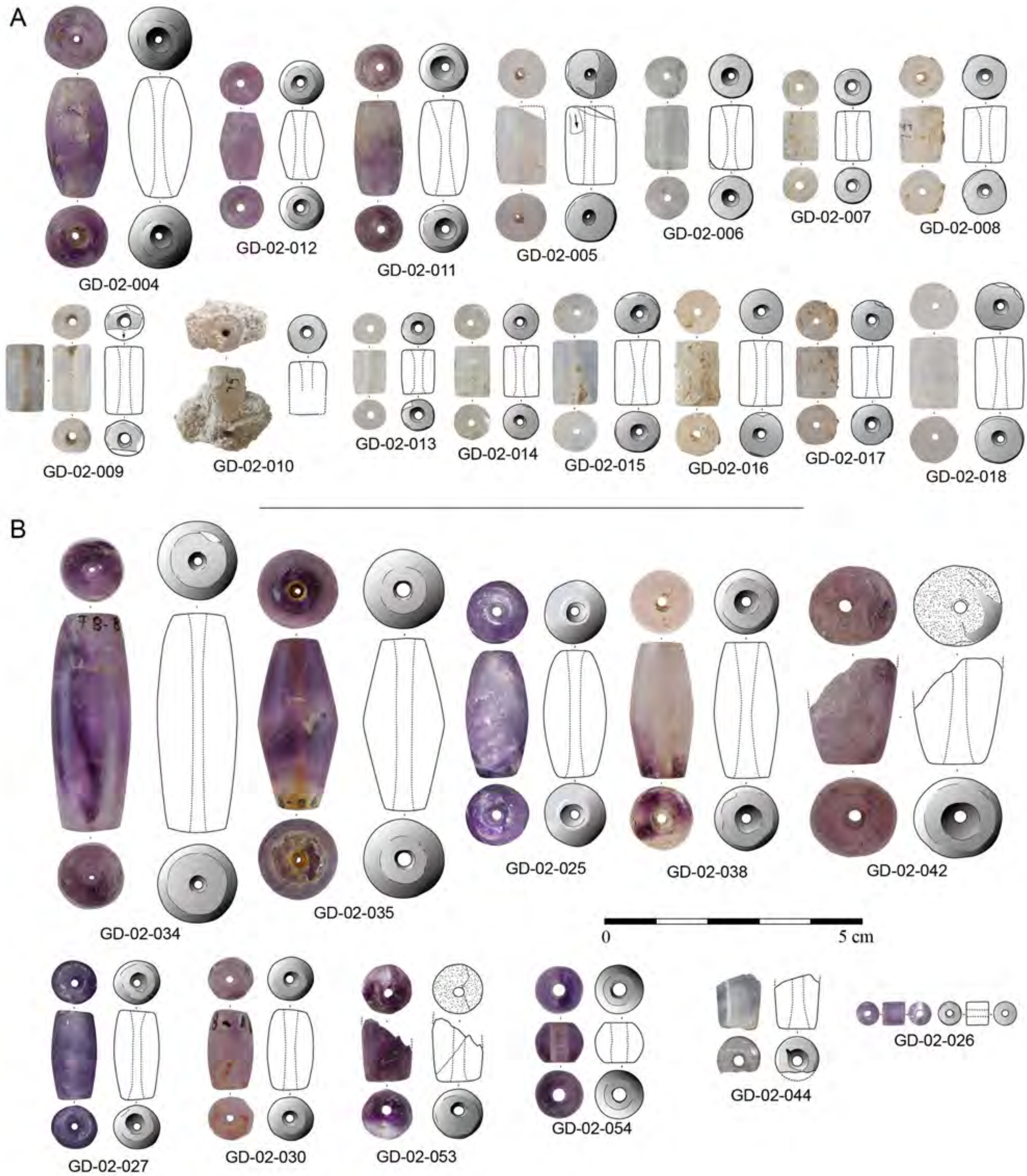


Figure ~~2~~3: Photographs and drawings of beads from the collar (A) and the other parts of Morel (GD-02) site (B), Guadeloupe.

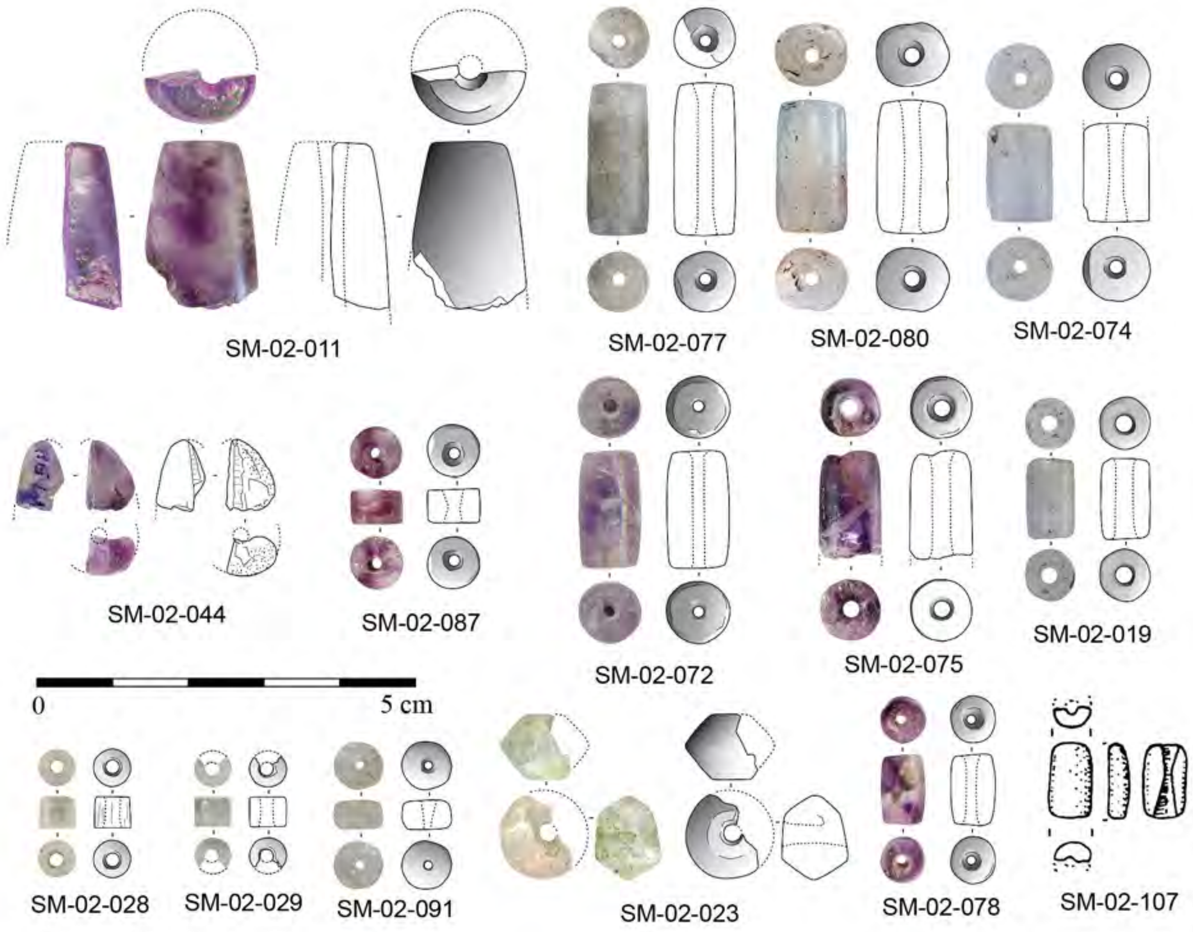


Figure ~~3~~4: Photographs and drawings of the beads and manufacturing debris~~products~~ from the site of ~~the~~ Hope Estate ~~*chaîne opératoire*~~ (SM-02), Saint-Martin.

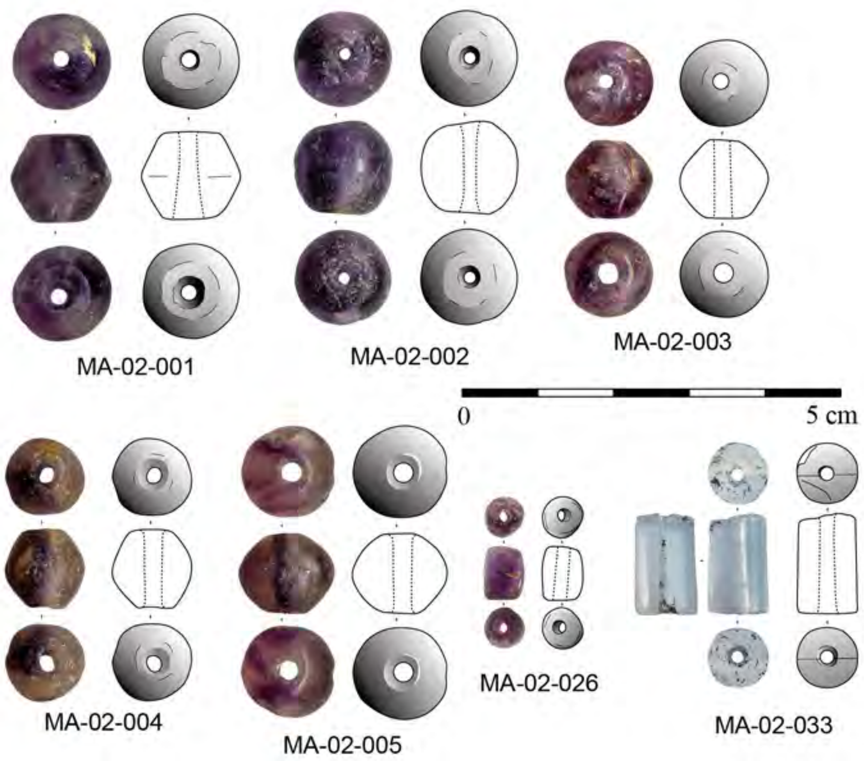


Figure ~~4~~5: Photographs and drawings of the ~~pearl~~beads of Vivé (MA-02), Martinique.

Methods

Imaging Archaeological Beads

Perforations were first observed with the hand lens, and for most of them, an elastomer imprint of the interior of the hole was made with a dispenser gun for more advanced observations. For this purpose, the beads are first cleaned with a fine bamboo rod and wet cotton, and three successive imprints are made to clean the perforation. The last imprint is observed and photographed at low magnification (Leica Z16APO Macroscope and Canon EOS 350D digital camera), then under ~~a~~ scanning electron microscope (SEM) at 30X and 100X magnification, after being coated with carbon to ensure electron conductivity. These observations were made with a JEOL IT 500 HR equipped with a Field Electron Gun. SEM ~~observations~~ allows to observe the fine structures on the surface of the elastomer which are the negatives of the surface of the perforation. It is also the only method that allows ~~a~~ comparison with the literature (Kenoyer, 2017; Ludvik et al., 2015; Raad and Makarewicz, 2019).

X-ray microtomography is a technique aiming at 3D-scanning an object in a totally non-invasive way, and providing access to both internal and external features. ~~It also allows to overcome the constraints of 2D images while avoiding the taking of elastomer impressions~~This technique overcomes the constraints of 2D while eliminating the need for elastomer casts. (sometimes impossible if the bead is too narrow or broken). It has already been used, albeit rarely, for studies of archaeological beads, with highly technical focus on the scanning method (Yang et al., 2011).and to look at the shape of the perforation, especially of double perforated beads, with no specifics on the details of the surface of the hole (Falci et al., 2020). In this study four archaeological amethyst beads (GD-02-038, GD-02-026, GD-02-025 and GD-08-001) were 3D-scanned using a GE V|tome|x s microtomograph, at a cubic resolution of 7 µm per voxel.

Experimentation

Numerous perforation techniques exist in the ethnographic record. They fall into two categories: manual perforation systems and mechanical systems (Leroi-Gourhan, 1971). For the hardest materials, mechanical systems are necessary to optimize the applied force and rotational movements. One of t~~T~~he most effective systems for our experiments is the ~~archer~~bow drill (Figure ~~5~~6), which we used. Other mechanical drills can be effective, like the pump drill, but we did not test it. This system allows a greater vertical force to be exerted, which is essential when the hardness of the rocks to be drilled exceeds 5 or 6 on the Mohs scale (Kenoyer, comm. pers.). However, the force applied to the handle must not be too high or the drill will break. The bow~~archer~~ is made of a piece of green wood (for flexibility) about 85 cm long and slightly curved for a better grip. The diameter is about 1.5 cm along the whole length. A leather cord attached to both ends of the ~~archer~~bow induces the rotation of the shaft or rod. This rod is held in a vertical position by one of the hands via any object that allows its rotation.

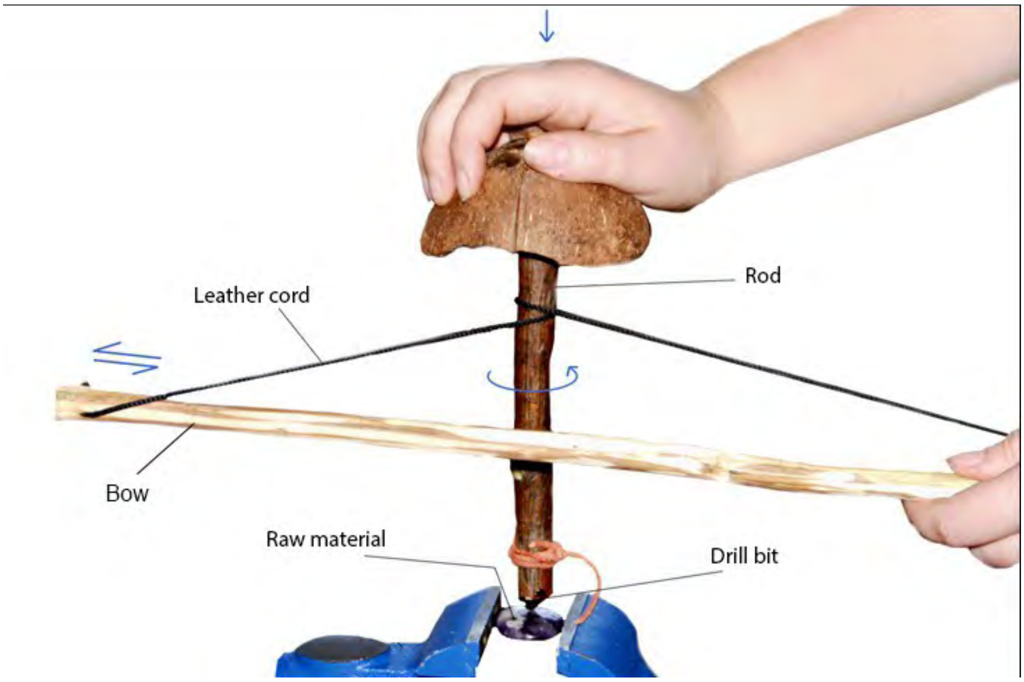


Figure ~~5~~6. Experimental bow drill device used in this work.

The drills are inserted and attached to the end of the handle with shellac (insect resin) and held firmly in place with a leather lace tie. The drills must be ~~both~~ narrow and strong enough not to wear out too much under the action of the abrasive.

Most ~~ethnographic~~archaeological examples indicate that perforations of hard materials ~~is~~are achieved by using an abrasive, which can be combined with water or oil as a lubricant, considerably increasing the perforation ~~performance~~effectiveness (Gwinnett and Gorelick, 1979). From a mechanical point of view, the volume loss of the future bead, per unit length, during a perforation, depends on three main physical factors of the drilled material: toughness (ability of a material to resist fracturing), hardness (resistance of a sample surface to penetration) and abrasion resistance (Sela and Roux, 2000). ~~The drill bits and abrasives were selected according to two criteria: their hardness, which must be at least equal to that of amethyst, and their compatibility with the archaeological record.~~The drill bits and abrasives were selected according to two criteria: their hardness, which must be at least equal to that of quartz for one of them, and their compatibility with the archaeological record. One obsidian and one flint drill were pressure shaped to maintain straightness along a ridge. These proved too large to make long perforations, so 4 additional pressure-worked flint flake drills were made. These flake drills have a triangular cross-section, to allow for more efficient drilling (Kenoyer, pers. comm.). As for the~~For~~ the organic drills to be used with the hard abrasives, we used bone, wood and vegetable thorns. The bone is a fragment of horse rib already shaped into a point and measuring less than 2 mm in diameter. Two types of wood were tested: Lignum vitae, or guayacan (found in the Antilles), which is known for its extreme hardness and resistance (Friedrich et al., 2021), and oak wood, which is less hard but has well-known physical properties. The thorns of selected plants are the tips of agave leaves and thorns of *Melocactus intortus,* also called « cactus tête à l'anglais », a species of cactus endemic to the Caribbean. Its thorns have a density, and thus a hardness, much higher than that of wood (2280 kg/m^3 for thorns of *Melocactus intortus (S.I. 2) versus* 1142 kg/m^3 for fresh oak for example (Shmulsky and Jones, 2019).

Preliminary tests have been made with different abrasives: fine amethyst powder ground using a ball mill (Fritsch brand Pulverisette 23, with a bowl and ball made of zirconium oxide), fine almandine garnet powder (up to 7.5 on the Mohs scale) made by the same process, and industrial silicon carbide (hardness of 9-9.5) used only for tests with wood drill. The final and complete perforation was done using hammered and sieved amethyst to get as close as possible to the archaeological context. To ensure lubrication, drops of water and small amounts of abrasive are deposited at regular intervals (every minute) on the depression. It was necessary to often push back the sand towards the active part. Movements called push and up (applied by making vertical gestures with the handle of the drill), necessary for the perforation, allow the abrasive to stay at the bottom of the depression, avoiding the digging on the edges and thus the enlargement of the cavity in the active area (pushing marks). The surface of the polished amethyst pebbles bought for experiments was previously frosted by abrading it on a diamond wheel, in order to obtain a surface closer to those observed on the preforms of the archaeological record and to guarantee a better grip of the drill on the surface at the beginning of the process.

RESULTS

Chaînes opératoires

Rock crystal and amethyst are two gems ubiquitously employed by Saladoid people (Cody, 1993; Falci et al., 2020; Queffelec et al., 2020, 2018; Watters, 1997). Unfortunately, this material, although widely distributed in the region, does not allow ~~us~~ to trace its origin, despite some ~~unfortunately~~ unfounded hypotheses summarized by Queffelec (2018).

The blanks seem to be processed by flake shaping and then pecking and polishing (Falci et al., 2020), as observed in other parts of the region and world (Falci, 2015; Kenoyer, 1997; Sela and Roux, 2000). They are then perforated with different profiles: some beads have tapered perforations while others have particularly straight and narrow perforations. Except for some discoid beads, the perforations are made from both ends. Once the perforation is complete, the surface of the bead is finely polished, probably on "grooved polishers", such as those found at the Gare Maritime site in Guadeloupe (Figure ~~6~~7). Their use for the manufacture of shell beads, which are very common at many sites (Serrand, 2002), is also likely. The reuse of broken objects, when the location of the break allows it, is quite recurrent. Some broken beads are roughly repolished at the break. More precise descriptions and drawing can be found in previous works (Queffelec et al., 2018, Queffelec et al., 2020).

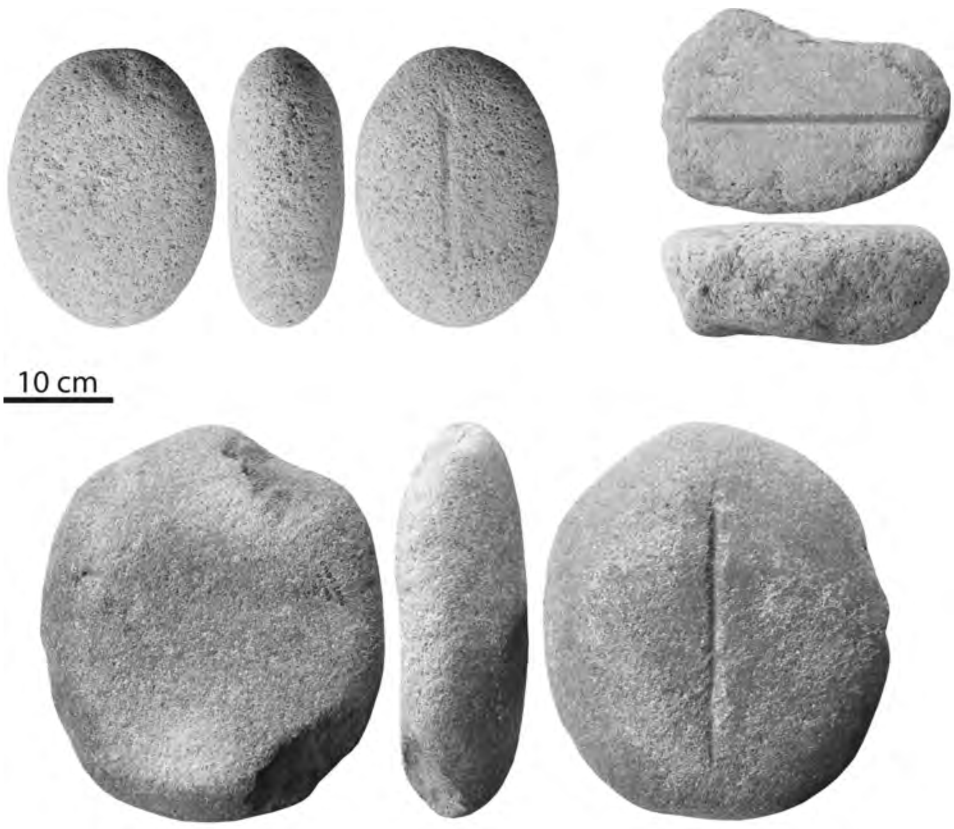


Figure ~~6~~7: Grooved polishers recovered during excavations at the Gare Maritime site (modified after Fouéré, 2006).

Observations and experimental results

Types of perforations in the archaeological record

No bead in the process of being perforated has been identified in our studies. Four types of perforations are observed in the assemblages: ~~rectilinear~~cylindrical, chamfered (cylindrical with a larger diameter at the beginning), biconical and conical perforations. With the exception of the last type, they are made by perforating from both ends. The blanks in other materials than quartz do not allow us to define a clear order of perforation: some present a start of perforation on one end only, while others are perforated from both sides~~ at the same time~~. As it can be observed for other hard material which may probably share the perforation technique,~~T~~ the surfaces to be perforated are prepared either by percussion, as shown by centripetal microremovals on carnelian blanks, or by pecking as observed on diorite blanks.

Perforations are often asymmetrical, sometimes with different perforation axes. The type of perforation does not appear to be related to the shape of the bead (Figure ~~7~~8 and Appendix 1). The rock crystal beads from the Morel site ~~greatly influence the results because they~~ make up a significant portion of the rock crystal sample and allow to make an interesting observation:~~. A~~although homogeneous in their typology and found within the same burial (Durand and Petitjean Roget, 1991), their perforations differ: one is ~~rectilinear~~cylindrical, 8 are chamfered and 3 are biconical.

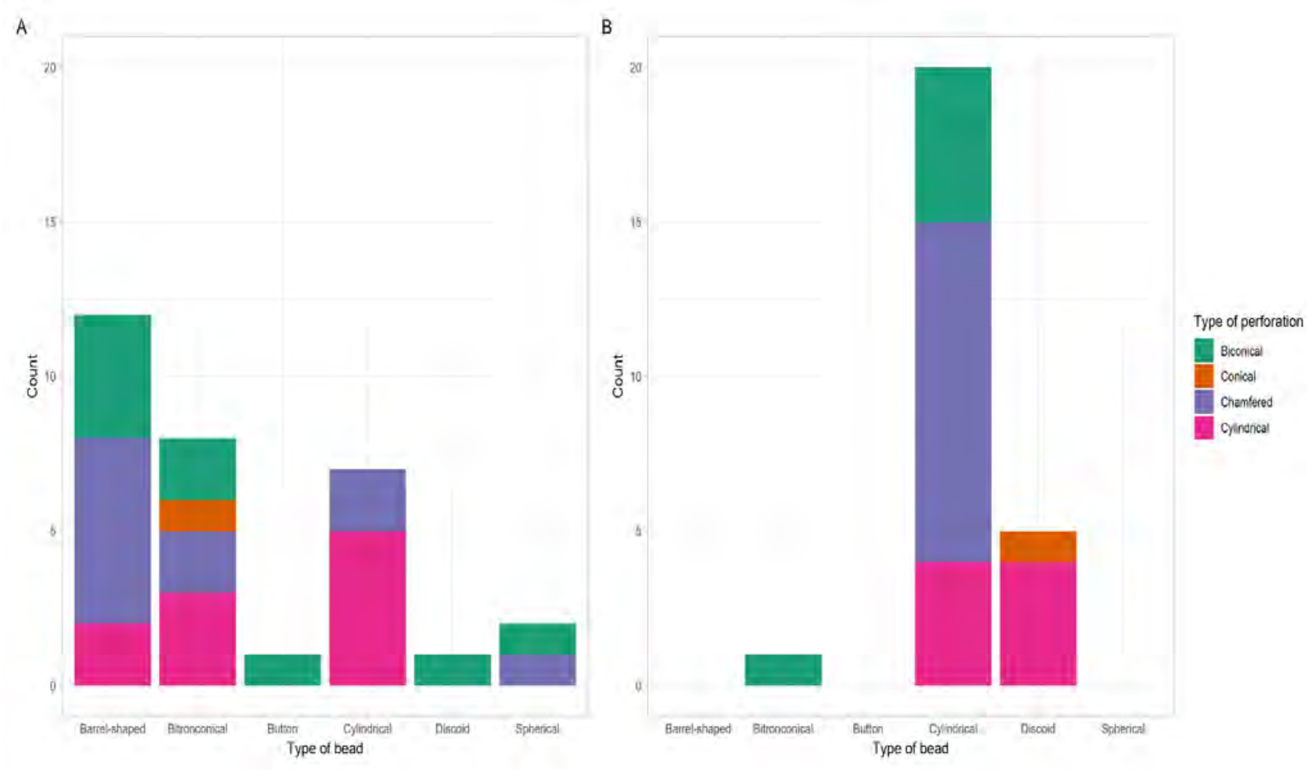


Figure ~~7~~8 : Types of perforation according to the type of amethyst (A) and rock crystal (B) beads.

X-ray microtomography images of the selected amethyst beads from Morel and Anse à la

Gourde ~~archaeological sites~~ (~~GD-02-026,~~ GD-02-038, GD-02-025 and GD-08-001) demonstrate how efficient and useful is this method to highlight the morphology of the perforations. The perforation of the selected beads~~They~~ are all biconical and ~~two of them~~ join in the center of the bead with a slight offset (Figure ~~8~~9). The perforations are narrow and not very tapered. The junction of the two sides of the perforation shows a smaller diameter for two beads (GD-02-038 and GD-02-025) indicating that the final few millimeters of drilling was made with a thinner drill bit. The remaining tip of the perforation at the junction allows to observe only the edges of the hole, not the center unfortunately. The shape of the bottom of the perforation would have been “nipple” shaped, with a rather flat terminal surface, but we cannot know if there would have been an inverted cone or not. The resolution of the 3D model of these full beads is sufficient to observe the internal ~~S~~striations ~~are clearly visible even with these full bead acquisitions~~ ~~when one zoom into the figure~~, because these beads are not ~~being~~ the biggest ones. Long scanning times~~acquisitions~~ centered on the perforation are required to obtain 3D models with sufficient resolution to observe them on big beads like GD-01-003 (Figure 10~~9~~), since the resolution automatically drops when one wants to ~~have~~ scan a bigger volume. It is also possible to see on the surface of the beads GD-08-001 and GD-02-025 the pecking marks under the coarse polish., and that striations have been erased from some parts of the perforation, probably due to the hanging of the bead.

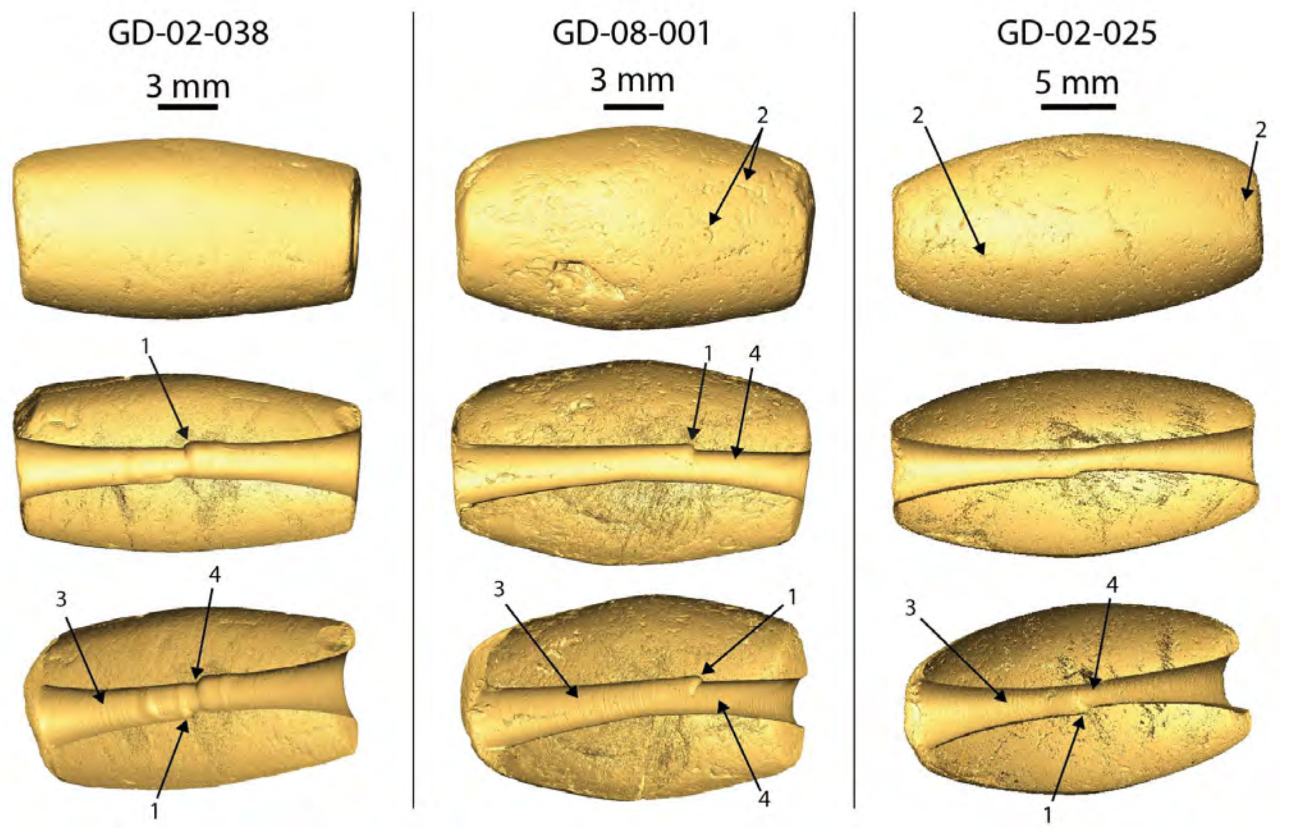


Figure 9~~8~~: X-ray microtomography images of amethyst beads GD-02-038, GD-02-001, and GD-02-025 ~~and GD-08-026~~. The tip of the perforations are “nipple” shaped with a rather flat temrinal surface~~one perforation has a rounded shape~~ (1) ~~indicating the use of a plain drill bit~~. Traces of surface staking are visible (2). Abrasive striations (3) and their absence in some parts (4) can ~~only~~ be distinguished in the~~on~~ three perforations thanks to the high resolution reached for these 3D models. ~~(3) with the resolution reached for the scan of a~~

complete bead.

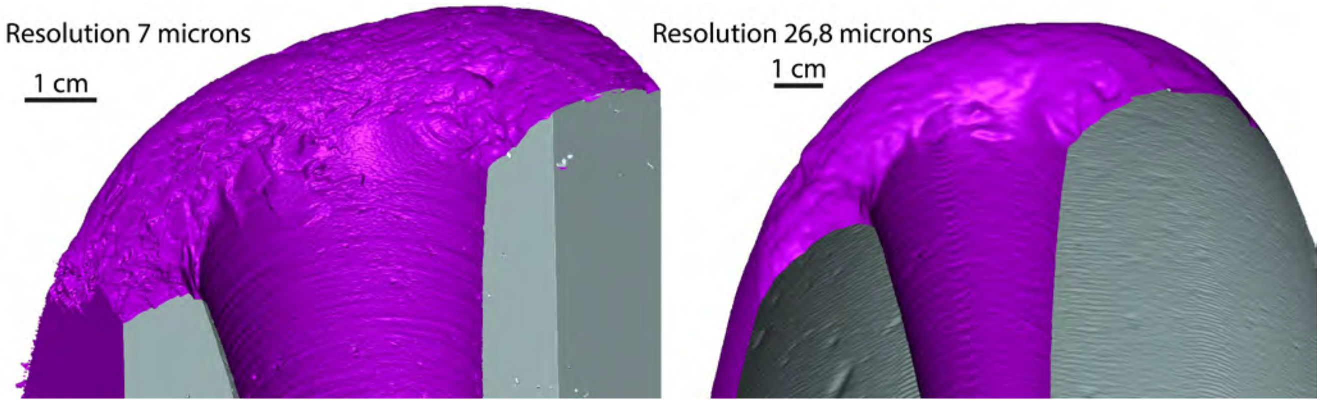


Figure 910: Comparison of visibility of perforation details with two microtomography resolutions on GD-01-003. The resolution with 7 microns per voxels on the left allows to observe the striae, while the resolution of 26.8 microns per voxel on the right allows only to imagine them.

Observations of the elastomer ~~impressions~~casts of the beads' perforations with a Scanning Electron Microscope (SEM) reveal deep, discontinuous striations on the Gare Maritime amethyst beads (GD-01-002 and GD-01-005; Figure 1~~0~~1, A et B). The striations on the Vivé bead ~~impressions~~cast (MA-02-033 and MA-02-006; Figure 1~~1~~2) are more faded,. The very smooth surfaces of the St. Martin beads still show very slight striations (Figure 1~~2~~3). This ~~erasure~~smoothing of striations is caused by string rubbing that can cause abrasion of the perforation on the long-term. The resulting smooth surfaces are also visible on the ~~impression~~casts of GD-01-003 (Figure 1~~0~~1, C) and MA-02-033 (Figure 1~~1~~2), as well as a long stripe on MA-02-033 cast (Figure 12). The pushing marks are also well preserved. They are visible as slightly larger diameter rings in GD-01-002, GD-01-005, and MA-02-006.

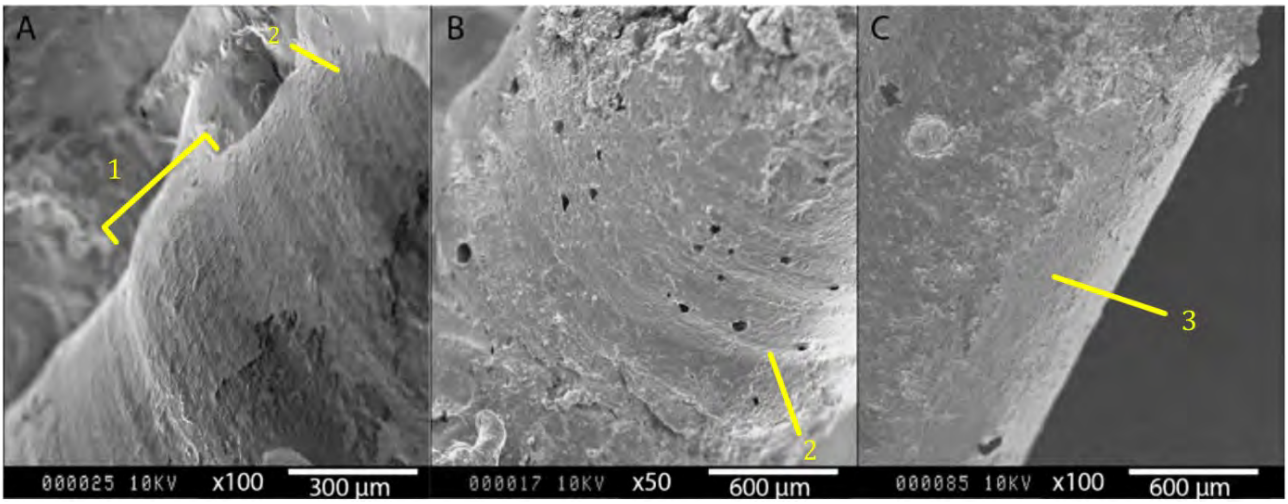


Figure 1~~0~~1: SEM images of the elastomer ~~impression~~casts of the GD-01-002 (A), GD-01-005 (B) and GD-01-003 (C) perforations. The pushing marks (1), striations (2) and polished surfaces (3) are shown.

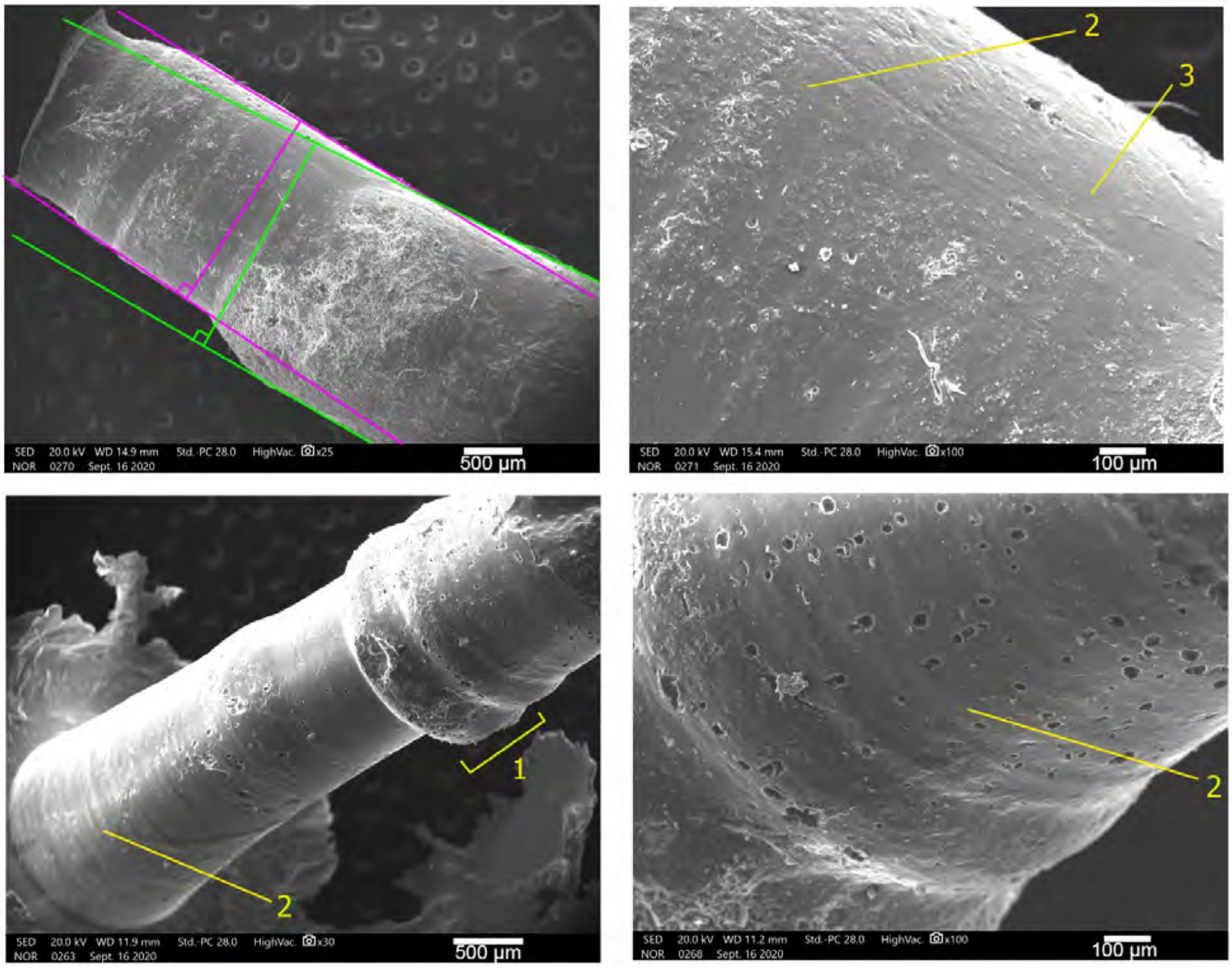


Figure 1~~1~~2: SEM images of perforation i~~mpression~~casts of beads from the Vivé site (Martinique): MA-02-033 made of amethyst (top) and MA-02-006 made of rock crystal (bottom). The bead MA-022-33 shows two axes of perforation and we can guess striations (2), probably partly erased by the wear due to the use of the object (3). The cast~~impression~~ of the perforation of bead MA-02-006 shows striations related to the perforation process (2), as well as very marked pushing marks (1).

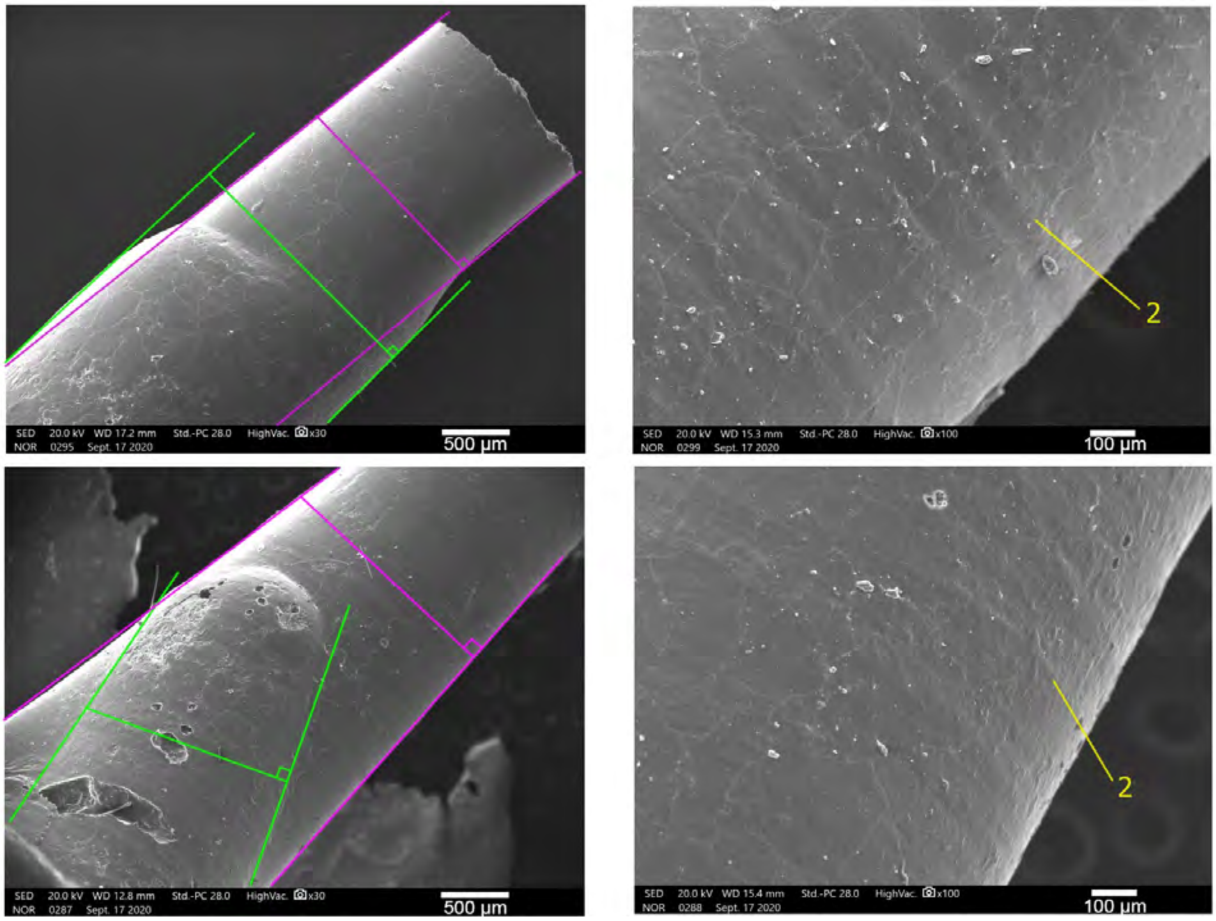


Figure 1~~2~~3: SEM images of the perforation ~~impressions~~casts of Hope Estate rock crystal beads SM-02-77 (top) and SM-02-80 (bottom). The perforation of SM-02-077 is highly polished where its diameter is smallest. The perforation of SM-02-080 clearly shows an error in the angle at the beginning of the perforation, which was later corrected by the craftsman. Although the surface of the perforations is very smooth, the striations are still visible (2).

The orientation of the perforation has sometimes changed during the work, as it is obvious from the observation of the imprint of bead SM-02-080, from the Hope Estate archaeological site, which shows no less than ten different perforation angles (Figure 14~~3~~). The second rock crystal bead from the same site has only two perforation angles but of different diameters, creating a pretty regular perforation pattern.

The two imaging techniques allowed for the observation of internal microwear, the shape of the drill hole, but we can also note that of course SEM images have higher resolution and allow to observe the surface of the hole at higher magnifications. It also allow to observe the different axes of perforation better. On the contrary, the 3D model could allow to acces the variation of diameter, circularity of the perforation etc., but this remain a perspective of the method since we did not apply it in this first attempt. X-Ray microtomography also needs the archaeological beads to be moved from their museum or other curation place, while making an elastomer cast is feasible in any place.

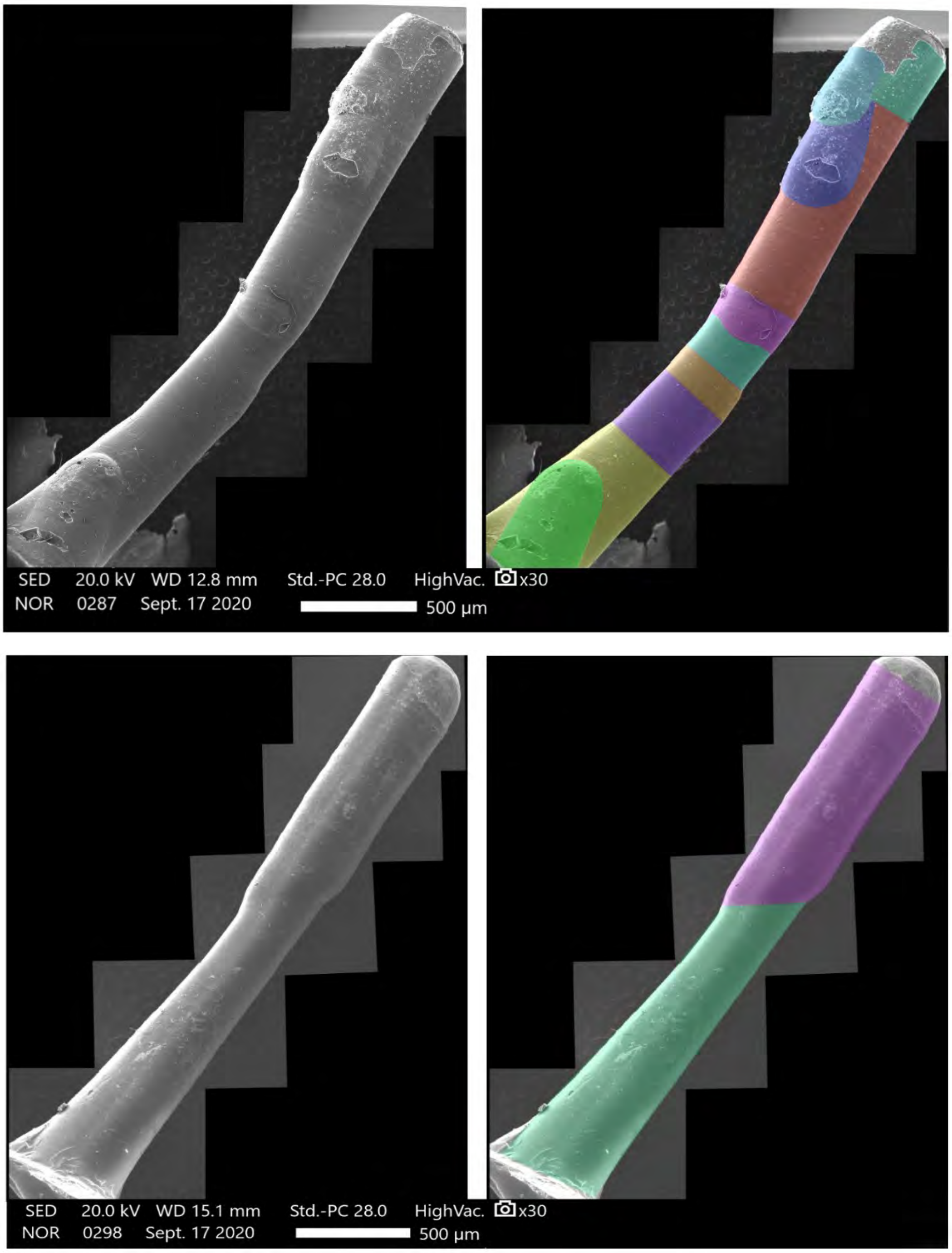


Figure 14~~3~~: Montage of SEM images of the perforation casts~~impressions~~ of rock crystal beads SM-02-77 (top) and SM-02-80 (bottom). The perforation of SM-02-77 shows ten different perforation ~~angles~~axes, some of which show a strong offset from the perforation axis (green and light blue). The bead SM-02-80 shows only two perforation angles.

Experimental perforations

The preliminary tests have implemented the different combinations of drill bits and abrasive, in order to verify the effectiveness of the bow drill, as well as the parameters allowing to perforate quartz. It was obviously possible to drill a hole with a solid copper drill and abrasives harder than quartz (silicon carbide, rutile), and also by substituting these very hard abrasives with ground quartz: quartz powder can be used to produce a perforation in quartz.

On the contrary, using long and narrow diameter drill bits made of lithic materials, which could be compatible with the observed perforations, has not been successful since they are too brittle (Figure 1~~4~~5). These drill bits are not found in the archaeological record. Bead drill holes made with experimental chert and obsidian drills create wide, conical and short perforation, unlike the archaeological ones (Figure 16).~~Other shapes of drill bits, found in the archaeological record, have been tested (Figure 15), but they produce large and short perforations~~.

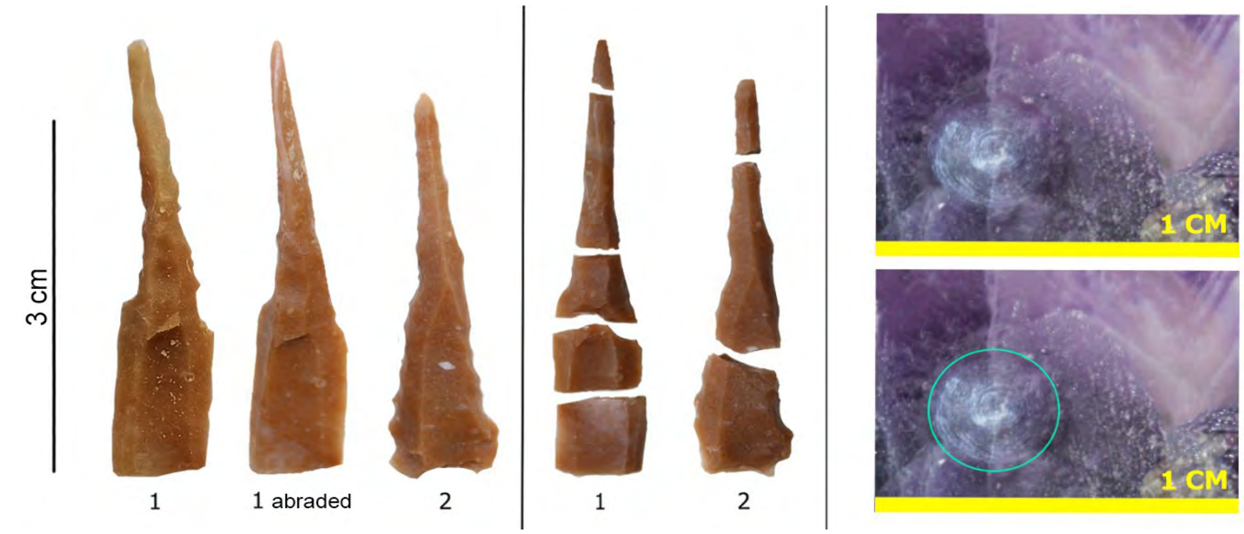


Figure 1~~5~~4: Photographs of the two flint drill bits (one of which has been abraded to reduce its diameter), before and after use, as well as of the perforation created. The diameter of the perforation is almost compatible with the archaeological record but these drills are very fragile.

Figure 1~~6~~5: Flint (left) and obsidian (right) drill bits, before and after use. They allowed to produce the beginnings of perforation, but too large compared to the archaeological record.

The use of bone or wood drills, whether made of oak or Lignum vitae, did not allow us to make a perforation in quartz, even using silicon carbide as an abrasive. Indeed, under these conditions, it is the drill that wears out or breaks, while the support does not undergo a significant removal of material. The palm leaf stalk and the agave thorn did not allow the realization of a perforation into ~~on the surface of~~ quartz either, because ~~their flexibility is too important~~they were too flexible to impose a sufficient vertical force. The only organic material that allowed the realization of a beginning of perforation are the thorns of cactus: *Melocactus intortus* in our experiment. The casts of the experimental perforations made with cactus thorns and garnet abrasive show striations due to the abrasive (Figure 17~~6~~). Residual frustums are observed at the end of both casts ~~(i.e., at the bottom of the hole~~i.e., point at which the cactus drill tip was drilling into the amethyst) for the perforations made with the ~~*Melocactus intortus*~~ *cactus* thorn drill and the ~~amethyst~~quartz abrasive. In addition, this perforation shows two different perforation diameters, clearly visible in the macroscope images. The shape of the beginning of the perforation is oval, due to the back and forth movements that impacted the verticality of the drill during perforation.

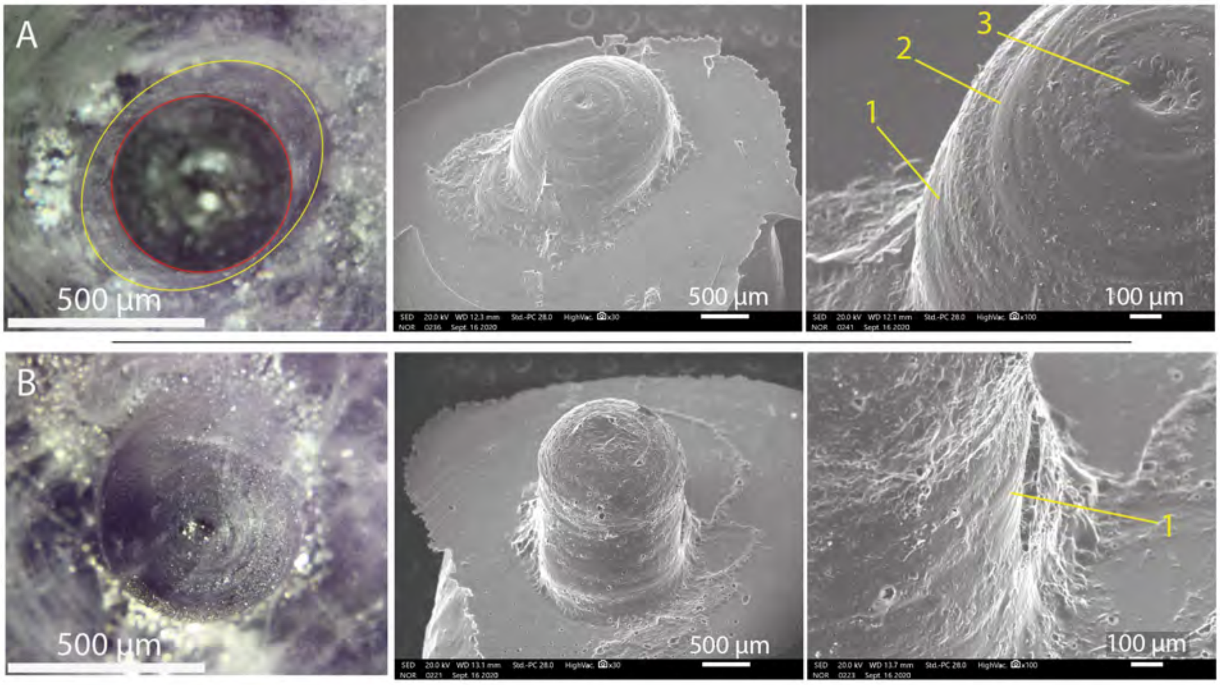


Figure 16~~7~~: Microphotographies of experimental drillings and SEM image of the elastomer ~~impression~~cast (20kV HV SS28 SED x30 et x100). A : amethyst with quartz abrasive and drill made of *Melocactus intortus* thorns*, B* : amethyst with garnet abrasive and drill made of *Melocactus intortus* thorns. *Fine s*triae created by the abrasive are visible (1), and also thicker stria of unknown origin (2), as well as ~~inverted cone~~a frustum at the end of each perforation (3). Perforation in B shows two different diameters of perforation.

A through-hole in an amethyst pebble was made with a total of 28 long *Melocactus intortus* thorns (Figure 1~~7~~8) and crushed amethyst as the abrasive. The perforation was bipolar and~~It~~ is 10.2 mm long and has a widest diameter of 2.5 mm at one of the beginning. This represents 43 days of work, 5 hours per day, for a total of 215 hours.

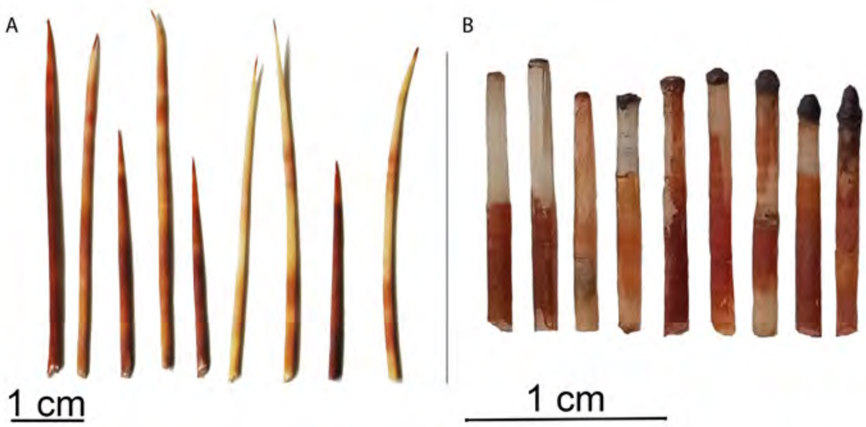


Figure 1~~7~~8: Sample of *Melocactus intortus* thorn drills before and after use. We can observe the change of the shape of the active part according to the wear of the drill, which very often burned because of the friction.

The darker, older thorns were found to be more resistant than the lighter thorns which are younger and softer. The active part~~, blunt,~~ quickly became blunt and sometimes burnt due to insufficient water inflow. The deeper the perforation, the more difficult it was to bring water to the active part (creation of a bubble, less contact with the surface of the thorn, thinner at this point). The thorns wore out in a rather heterogeneous way, between 30 minutes and one hour, depending on the vertical force exerted and the moment when the burning was noticed. Once the active part was burnt, the drill became unusable and sometimes left carbonaceous residues at the bottom of the perforation.

Concerning the whole perforation, on the first half of the ~~impression~~cast (the elastomer always broke while being pulled out of the perforation), which represents almost the entirety of the biconical perforation created, the striations are well ~~present~~visible and the pushing marks quite weak. Four perforation axes are observed, their offset angles are very small (Figure 1~~8~~9). The end of the perforation is "nipple" shaped. On the second part of this perforation (not shown), we also noticed the striations due to the abrasive, and high angles between axes of perforation implied by the need to ~~due to the will to~~ join the ~~end of the~~ first perforation.

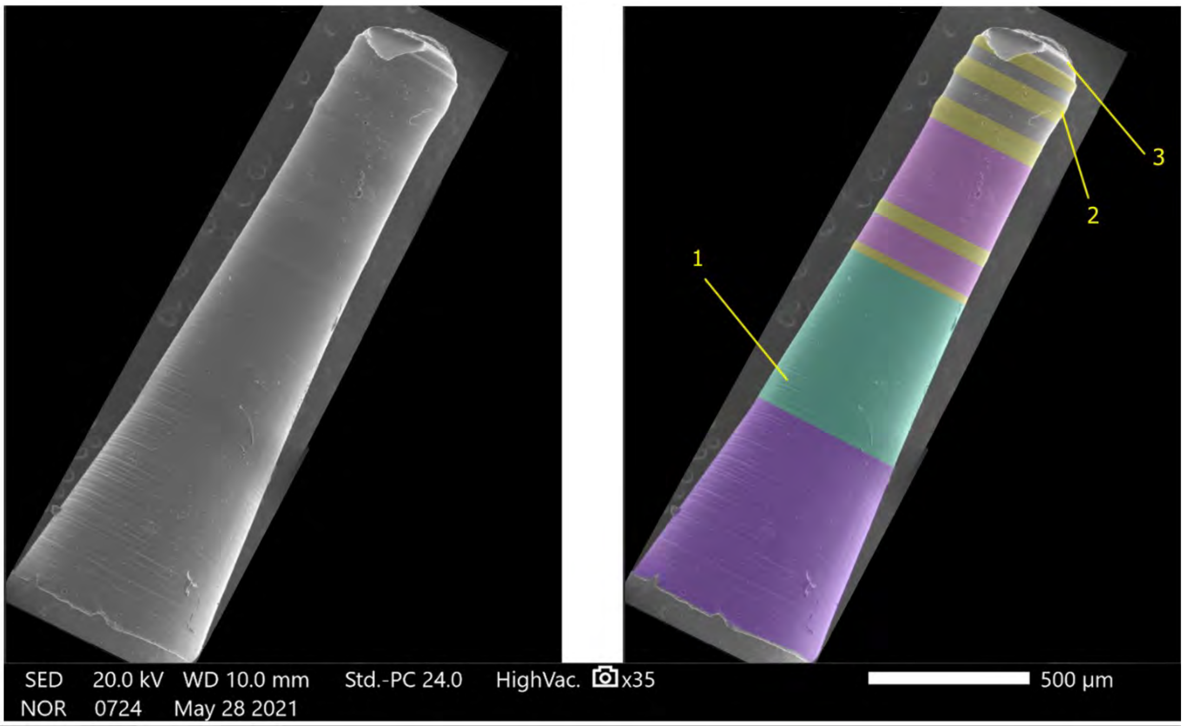


Figure 1~~8~~9: Montage of photographs of one half of the biconical ~~impression~~cast of the experimental perforation in the SEM (20kV SED x35). Four different perforation angles are observed with a small variation amplitude (purple, green, pink and original color). We also observe the striations caused by the abrasive which are very marked (1), and the pushing marks, in yellow, are very small and short (2). The tip of the perforation is "nipple" shaped (3).

DISCUSSION

This work based on both archaeological and experimental material describe in detail one of the crucial steps of beads production in the past: the perforation of hard material without the help of metal.

The observation of a significant number of finished archaeological beads from 6 archaeological sites of the Ceramic Age located on 3 islands of the Lesser Antilles, with complete perforations, has provided a great deal of information. From a typological point of view, the length of the bead seems to influence the ~~shape~~type of the perforation. Indeed, cylindrical~~rectilinear~~ and chamfered perforations are the most common, especially for cylindrical and barrel-shaped beads. On the other hand, conical perforations are relatively rare for these beads and are observed only on short beads. It should be noted that the chamfer may disappear with heavy polishing of the perforation surfaces or wear of the bead. Thus, a bead with a chamfered perforation that is broken and then repolished may look similar to a conical or ~~straight~~cylindrical perforation. It is therefore difficult to establish links between typology and technology on the basis of so few artifacts with so much variability.

Imaging techniques, by SEM on elastomer ~~impressions~~casts and by microtomography, allowed the observation at high magnification of ~~a~~the internal surface invisible to the naked eye~~ because located inside the pearl~~. The images of the ~~impressions~~casts of the perforations of the Antillean beads reveal the abrasive striations and the pushing marks already described in the literature for other contexts (Gurova et al., 2017; Gwinnett and Gorelick, 1979; Kenoyer, 2017; Kenoyer and Vidale, 1992; Ludvik et al., 2015). Similarly, changes in perforation angles could be identified on the SEM image montages as well as through microtomography. The ~~stigmata~~microwear observed in this study confirm the use of abrasive for all the archaeological perforations studied here, and to a great diversity in the technical gesture of perforation, highlighted by a great diversity in terms of frequency of pushing marks and multiple perforation angles.

On the experimental perforation, the striae are very prominent, most likely due to the fact that it did not undergo post perforation wear. The perforation is also quite short compared to the perforations of long beads, which induces less wear of the abrasive particles on the walls near the end of the bead, when perforating the more internal part of the bead. Our experiment also replicated pushing marks, reinforcing the interpretation of their presence due to abrasive use (Gurova et al., 2017; Gwinnett and Gorelick, 1998, 1979; Ludvik et al., 2015). Here they appear to be related to where the drills burned. Indeed, they are located primarily in the innermost part of the experimental perforation (about 5 mm from the external surface of the bead)~~10.2 mm long~~), where the drills were wearing and burning the fastest. The pushing marks visible on the archaeological beads are located in the central part of the perforation, which confirms the use of abrasive with a resistant drill whose active part wears away. The pushing marks in the context of a perforation with a vegetal drill bit could therefore be reinforced by this specific wear phenomenon combining drill bit wear and accumulation of coals in the active part and then the accumulation of abrasive on the edges of the active part.

The reasons for the irregularities in the alignment of the perforation axes are not yet determined. They can be caused by a changing dexterity of the person(s) performing the perforation or by the position of the blank, especially concerning the shapes whose holding is the most delicate (spherical beads for example). In view of our own experimental work, the regularity of the profile seems to have little to do with technical mastery, contrary to what is claimed in the literature, especially concerning materials exceeding a hardness of 5.5 on the Mohs scale (Gurova et al., 2017). Indeed, although we are novices in this craftsmanship, the entire experimental perforation is rather regular, with ~~4~~four identified perforation axes, ~~whose~~ differences in orientation of which are very small. This may be due to our maintenance system (industrial vice), not compatible with the archaeological context. Only the error in estimating the ideal location of the second part of the perforation could represent the lack of experience. Thus, perforation habit is not clearly identifiable in our experimental study. Intra- and inter-experimental reproducibility tests would be relevant to identify the parameters governing the regularity of perforation, but given the time required to perform this experimental work, it seems difficult to implement.

Worldwide, ~~T~~the use of metal to perforate materials as hard as quartz or carnelian, especially with small diameters of perforation, has always been the preferred hypothesis ~~by the authors~~ (Gwinnett and Gorelick, 1998, 1987; Kenoyer, 1997, 1986; Kenoyer and Vidale, 1992; Ludvik et al., 2015), ~~and~~but for the Caribbean islands, Harrington (1924) already indicated that « *Most of the stones used are very hard, and it must have taken a long time to peck and grind them into shape; the nature of the tools available to the workman of that day and place, and capable of drilling such small holes through such obdurate materials as amethyst and quartz crystal, remains a mystery* ». Pinchon (1952) also noted, about a cylindrical bead made of rock crystal found in Martinique, that « *The polishing and even more the drilling had to be a considerable task, given the primitive the artist must have had at his disposal. He undertook to drill the stone, first by one end, then by the other, and the holes met with a small shift that reveals the method used. It is difficult to imagine the hours and days of labour that such a work must have required, and this single bead was perhaps part of a necklace made up of multiple similar pieces!* (our translation from French) ». We demonstrate in this work that it is possible to do so with a vegetal drill, in this case made of cactus thorn, a material available in large quantities to the Amerindians, and the~~whose~~ perishable nature of which ~~helps to~~ explains their absence in the archaeological record.

The use of abrasives harder than the material to be drilled has also been widely put forward in the literature (Gurova et al., 2017; Gwinnett and Gorelick, 1979; Kenoyer, 2017, 1986; Ludvik et al., 2015; Sela and Roux, 2000) while we can confirm that it is possible to use an abrasive of the same hardness as the object to be perforated. It is also interesting to note that the use of bead shaping ~~residues~~debitage could be crushed to be used as an abrasive, thus explaining their rarity in the archaeological record.

Finally, several aspects of the experiment remain to be explored. First, the system for holding the drill bit in the handle has not been addressed. The use of tar for the shank is attested in the Lesser Antilles for the recent ceramic periods (Serrand et al., 2018), so its use for fixing the drill bit is a significant possibility. Also, the impact of the shape and size of the abrasive grains are parameters to be characterized, from a qualitative point of view and also to see if there can be an influence on the striations created. Then, the bead holding system remains to be determined even if it can be as simple as two pieces of wood held together with strings at both ends, especially concerning its position in relation to the person who drills. Indeed, although exhausting, the use of an ~~archery~~bow drill in a standing position is also impractical because it constantly solicits both arms. The joints of the upper limbs, especially the shoulders, are heavily strained. A more elevated position in relation to the vice or a seated practice, already observed in the works of description of the productions of carnelian beads ~~in the Indus Valley,~~ in India (Sela and Roux, 2000) are aspects to be explored if we want to take into account the comfort of the craftsman. Finally, the efficiency and ease of the experimental perforation depend on the appreciation of the experimenter, and therefore remain quite subjective. More precise criteria than simply obtaining a perforation after a given time to determine efficiency could be established.

It should be noted that, despite the fact that the analyses of the perforation angles are very instructive concerning the characterization of the regularity of the perforation, they are however carried out on images in 2D despite the ~~E~~3D nature of the artifacts. The ~~angles~~axes are then only those readily apparent ~~angles~~ and further analysis based on a three-dimensional work would allow to evaluate with precision these shifts between the axes of perforation.

CONCLUSION

The *chaîne opératoire* ~~of~~for the production of quartz beads (and other hard materials) is still very poorly understood in ~~the~~ various archaeological ~~records~~contexts. ~~If~~Although this ~~work~~topic has been ~~carried out~~exhaustively adressed by a few authors in particular contexts, such as the Bronze Age cultures of the Indus Valley, it is clear that many other ~~chronological~~ periods or ~~other~~ regions of the world have not benefited from such studies. This work, by combining observation of archaeological objects and experimentation, makes it possible to remedy this for the Ceramic period in the Antilles.

Very few blanks or shaping wastes are known in the Antillean archaeological record for quartz materials, and observation of finished objects can only point to a shaping technique by pecking before beginning the perforation. A significant variability is observed in the type of perforation of quartz beads from the Ceramic period in the Antilles, preventing any strong link between bead typology and perforation shape to be highlighted. On the contrary, the observation of the ~~stigmata~~striae persisting inside the perforations indicates that the technique used is always the same.

The study of the ~~impressions~~elastomer casts of experimentally created perforations, highlighting numerous concordances with the ~~stigmata~~usewear preserved by the archaeological objects, allows us to explain some of them, confirming the knowledge previously produced in other archaeological contexts and providing explanations in accordance with the archaeological record devoid of drills compatible with the perforations observed. First of all, we can affirm that the use of metal was not necessary for their perforation: it is possible to perforate quartz beads using cactus thorns as a drill bit, widely available in the Caribbean islands. Secondly, it is possible to make very fine and long perforations by combining with this vegetable drill a free abrasive of the same hardness as the material to be perforated. Thus we have been able to demonstrate that it is possible to use crushed quartz to perforate quartz, which could explain the near absence of waste from the shaping of these beads in archaeological sites, if the beads were shaped on site. This possibility to crush rock to use it as abrasive has been already evidenced (Gazzola, 2007). It adds to other potential uses of these wastes, which can make it disappear from the archaeological record, as homeopathic powder for example, as demonstrated in other context (Vidale and Shar, 1990).

Such a manufacturing process implies a significant investment in time, but does not require extremely advanced know-how, nor the search for particularly rare materials. It could be implemented directly in the archaeological sites found throughout the Caribbean arc. This investment in lapidary production, already noted by the diversity and distant origin of some of the materials used, confirms the importance of this material culture in these pioneering populations of the Caribbean islands.

ACKNOWLEDGEMENTS

The authors of this article wish to thank Jonathan M. Kenoyer for his invaluable assistance in the initial stages of the development of this research project and for the many tips he provided. We also thank Michel Lenoir and Michel Brenet for making the experimental lithic drills. Finally, we thank Benoît Bérard for taking elastomer ~~impressions~~casts of the Vivé bead perforations. The study of the archaeological artifacts would not have been possible without the help of Christian Stouvenot ~~et~~ andGwenola Robert (DAC Guadeloupe), Susana Guimaraes, Katarina Jacobson (Musée Edgar Clerc), Thierry Dorival (DAC Martinique), ~~et~~and François Petit (owner of Hope Estate).

FUNDING

This work was carried out within the framework of the Programme Collectif de Recherche Parures Amérindiennes dans les Antilles Françaises, funded by the Ministry of Culture (DAC Guadeloupe and DAC Martinique) and the Region of Guadeloupe. This work benefited from the environment of the GPR Human Past.

CONFLICT OF INTEREST

The authors declare there is no financial conflict of interest. Alain Queffelec is manager of PCI Archaeology.

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SUPPLEMENTARY MATERIAL

Appendix 1 :

Site	Gem material	Type	Inventory number	State	Perforation
Gare Maritime	Amethyst	Barrel-shaped	GD-01-003	finished	biconical
			GD-01-005	finished	straight
		Cylindrical	GD-01-002	broken	straight
			GD-01-006	finished	straight
			GD-01-004	blank	-
	Rock crystal	Discoid	GD-01-014	broken	straight
			GD-01-016	finished	straight
		Cylindrical	GD-01-015	finished	straight
Allée Dumanoir	Amethyst	Barrel-shaped	GD-05-001	finished	chamfered
		Button	GD-05-002	finished	biconical
Morel	Amethyst	Barrel-shaped	GD-02-004*	finished	chamfered
			GD-02-011*	finished	biconical
			GD-02-025	finished	chamfered
			GD-02-027	finished	chamfered
			GD-02-034	finished	chamfered
			GD-02-053	broken	chamfered ?
			GD-02-042	broken	biconical ?
			GD-02-030	finished	biconical
		Bitronconical	GD-02-012*	finished	biconical
			GD-02-035	finished	chamfered
			GD-02-038	finished	biconical
		Spherical	GD-02-054	finished	biconical
		Cylindrical	GD-02-026	finished	straight
	Rock crystal	Cylindrical	GD-02-015*	finished	biconical
			GD-02-017*	finished	biconical
			GD-02-018*	finished	biconical
			GD-02-006*	finished	chamfered
			GD-02-007*	finished	chamfered
			GD-02-008*	finished	chamfered
			GD-02-009*	finished	chamfered
			GD-02-013*	finished	chamfered
			GD-02-014*	finished	chamfered
			GD-02-016*	finished	chamfered
			GD-02-005*	finished	straight
			GD-02-010*	finished ?	chamfered ?
			GD-02-044	broken	chamfered ?
Anse Ste Marguerite	Amethyst	Bitronconical	GD-08-001	finished	chamfered
Hope Estate	Amethyst	Cylindrical	SM-02-072	finished	straight
			SM-02-075	broken	chamfered
			SM-02-078	finished	chamfered
		Discoid	SM-02-087	finished	biconical
		Barrel-shaped	SM-02-011	broken	straight ?
		Undetermined	SM-02-044	broken	-
	Rock crystal	Cylindrical	SM-02-019	finished	straight
			SM-02-074	finished	biconical
			SM-02-080	finished	chamfered
			SM-02-077	broken	chamfered
			SM-02-107	broken	biconical
		Bitronconical	SM-02-023	broken	biconical ?
		Discoid	SM-02-091	finished	conical
			SM-02-028	finished	straight
			SM-02-029	broken	straight
Vivé	Amethyst	Bitronconical	MA-02-001	finished	conical
			MA-02-003	finished	straight
			MA-02-004	finished	straight
			MA-02-005	finished	straight
		Spherical	MA-02-002	finished	chamfered
		Cylindrical	MA-02-026	finished	straight
	Rock crystal	Cylindrical	MA-02-033	finished	straight

Appendix 2 : Specific mass calculation for cactus thorns used in this work

Dimensions of the thorn :

h = 39,61 mm

R = 0,50 mm

Mass: m = 0,071 g

Volume: $V = \pi \times R^2 \times h = \pi \times 0{,}5^2 \times 39{,}6 = 31{,}10\ mm^3$

Specific mass: $\rho = m / V = 71/31{,}10 = 2.28\ mg/mm^3$ ($2280\ kg/m^3$)

Density: $d_{thorn} = \boldsymbol{\rho}_{thorn} / \boldsymbol{\rho}_{\mathbf{water}} = 2280 / 1000 = 2.28$