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Abstract. Bone flutes make use of a naturally hollow raw-material. As nature does not produce duplicates, each bone has its own inner cavity, and thus its own sound-potential. This morphological variation implies acoustical specificities, thus making it impossible to handcraft a true and exact sound-replica in another bone. This phenomenon has been observed in a handcrafting context and has led us to conduct two series of experiments (the first-one using handcrafting process, the second-one using 3D process) in order to investigate its exact influence on acoustics as well as on sound-interpretation based on replicas. The comparison of the results has shed light upon epistemological and methodological issues that have yet to be fully understood.
This work contributes to assessing the application of digitization, 3D printing and handcrafting to flute-like sound instruments studied in the field of archaeomusicology.

Keywords: Acoustics, Statistics, Handcrafting, Raw-materials, Digitization, 3D printing, Music archaeology

1 Introduction

Elaborating a research project in close collaboration with a craftsman and a research team dedicated to digitization of cultural heritage was the trigger point to different kinds of experiments meant to investigate the morphological variability of bones and its influence on the emitted sounds when carved as flutes. Dealing with this "Sound-morphology" is the main part of a craftsman's work, which is why it was decided to run the project of an apprenticeship that would last for one year [18]. During this time, particular attention was paid to the creation and use of prototypes, i.e. a bone flute manufactured in order to try and understand the sound specificities of a particular bone, and then used as a guide in order

to ease the adaptation process. Indeed, each bone has its own morphology and needs to be considered as an individual. The flute-maker proceeds then with a precise observation of each individual and takes every morphological specificity into consideration in order to craft series of bone flutes with similar sounds and identical tuning, even if this has to result in objects that do not look the same. Otherwise, he would risk to create an inefficient object, or a completely different flute.
These observations have raised specific issues regarding the use of bone flute's replicas for tone scales interpretations in archaeological surveys, as their manufacture never seems to take into consideration the bone's morphology as part of its acoustical specificities ([8], [6] and [16]). They have also led us to conduct "twin experiments" in the hope of reaching consistent results that would spare no methodological tracks (past, actual and yet-to-come sound-reconstruction methods) in order to explore their limitations as well as their potential. This way, we hope to contribute to better the epistemological landscape of archaeological flute's research.
The work presented in this paper focuses on the comparison of the sound results given by both series of experiments.

2 Context of the work

2.1 Approach

Flutes are not all the same. They are grouped into several kinds which are distinguished by the way the air stream is directed toward the edge. Each kind has its own sound aesthetics, but gives also more or less freedom to the flute-player in choosing the pitch and the sound's characteristics, thanks to the blowing angle variability (Fig. 1). Oblique-, pan-, vessel- and transverse-flutes are amongst the most malleable kinds of flutes. We chose duct-flutes as they are the opposite.
In term of organology, these objects can be mentioned as 421.221.12 in the S/H classification system (Sachs/Hornbostel), which means: Internal duct-flute (straight and single) with finger holes and an open end.

Fig. 1: Blowing angle variations regarding two different organological kinds of flutes: a) oblique flute, b) duct-flute

2.2 Partnership

This "two-front approach" demands to assemble a consistent amount of knowledge, which can only be achieved through partnership.

- **Handcrafting process:** the work gathered a traditional flute-maker and a statistician in computational biology.
- **3D process:** the work was based on an existing collaboration between archaeologists and computer scientists on advanced imaging for archaeology, the CNPAO [2]

2.3 Terminology

This paper will use the following terminology according to the acoustical specificities of bone flutes:

- **Morphology:** refers to the natural inner and outer shapes of the bone.
- **Geometry:** refers to the handcrafted inner and outer shapes carved deliberately or not onto the bone's surface.
- **Sound-morphology:** refers to the acoustical sections of the morphology, which define the sound potential of the bone (i.e. the inner cavity). By definition, each bone has a different sound-morphology.
- **Sound-geometry:** refers to the acoustical sections of the geometry, which are involved in the definition of the instrument's final sound, whether they were meant (deliberately carved) or not (unintentional and/or unconscious geometry). As an example: the shapes of the internal duct, of the edge, of the finger holes, etc. By definition, the sound-geometry rules out the outer shaping as long as it does not change the finger holes depth.
- **T0, T1, T2, etc.:** refers to the finger holes' combination. T0 means all holes closed. T1 means that the lower finger hole (the first one) is open. T2 means that the two lower finger holes (the first and the second one) are open, etc.
- **F0, F1, F2, etc.:** systematic identification numbers of the experimental flutes. F0 refers to the control flute, whereas F1, F2, F3, etc. refers to each replica copying the control flute.

2.4 Related works

Nowadays, 3D technologies allow outer and inner contact-free investigation on complex geometries [15]. As such they contribute to answer both preservation and sound studies issues and are more and more used in the actual archaeo-musicological research. If their consequences on our interpretations are still to be defined, they allow different kind of approaches and studies that aim to get a better understanding of ancient sounds. They can be applied to any organological material [10], such as string instruments ([4], [13], [20] and [21]) but also aerophones ([3], [8], [9] and [11]), among which archaeological "flutes", and objects presumed to be flutes, figure ([1], [22], [14], and [23]).
Eventually, the music-archaeology research may even explore new possibilities in sound reconstruction studies, as its data can be applied to sound simulators and sound-scape reconstructions ([24], [12] and [7]).

3 The sound-morphology principle

Naturally hollow rawmaterials, such as bones, hornes, shells or reeds, present a morphological variability between one individual and another. Those variations can be observed both regarding their shapes, their scale and their volumetric and spatial configuration (Fig. 2). Some of them are involved in the sound-morphology. For example, a larger bone will produce a lower pitch for the same length. Likewise, an important and sudden increase or decrease of the bone's conicity tends to distort the efficiency of a close-range finger-hole.

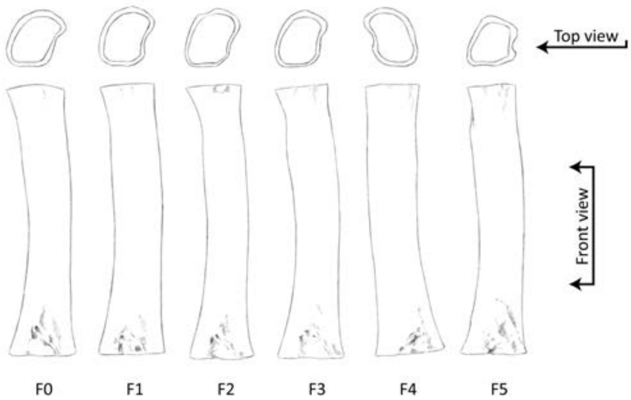

Fig. 2: Morphological variations between bones used for crafting F0 to F5 in the Handcrafting process experiments explained below. Deer femurs show several constants, such as a bulge characterizing the distal part of the epiphysis, a triangular and irregular depression characterizing its proximal part, and a slimming zone in the concave area of the bone's bean-like cross-section. Despite those constants, there never are two identical bones.

In order to illustrate this phenomenon, we chose to handcraft a unique replica of a bone flute in another similar bone (Fig. 3).
The control flute was made in a goat's tibia. It was made very simply, using only steel knife and file, evoking archaeological flutes found in northern Europe for medieval period [5]. The handmade replica was made very carefully, using several measurement tools (caliper, compass, etc.). Also, as the depth of the block changes the pitch, we chose depth 0 (Fig. 4). This calibration is easier to reproduce. We also tried our best to give both blocks a similar soil angle. As a result, the two flutes gave different sounds, with a deviation going from half a tone to more than one tone, increasing as we open the finger holes (Fig. 9 and 10).
This replication test shows how much the sound of a bone flute replica may be deviant from the sound of the control flute it's related to. This phenomenon

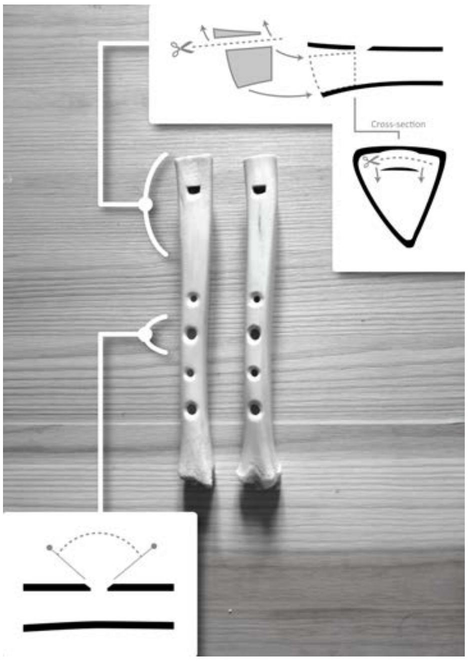

Fig. 3: The control flute (left) and its replica (right) both made out of goat's tibias.

illustrates the notion of "sound-morphology" as it reveals that every bone has a sound-potential of its own.

4 Handcrafting experiments

4.1 Handcrafting replication process and technical specifications

- **Objectives:** those experiments aim to define the extent of the limitation caused by sound-morphology, as well as to explore the acoustical specificities of this phenomenon. The approach is then different from what we can see in experimental archaeology, as we need here a well-known, functional and replicable bone flute in order to compare its actual sounds with our interpretations.
- **Control and sample:** we chose 6 similar deer femurs with morphological variations. 5 replicas is the minimum sample required for statistical analysis.
- **Chosen sound-geometry:** inner duct-flute with rectangular opening and straight edge (Fig. 5). Combined with a straight geometry, this configuration creates powerful blowing constraints and is easier to reproduce.
- **Manufacture:** handcrafted in January 2016.
- **Sound capture and analysis:** because of lack of means, we had to use a common recording device (smartphone) and a free software (audacity).

Having no mechanical blower nor anechoic chamber available at the time, we had to record the sound using natural blowing (as homogeneous as possible) and the same context (a chosen room). Thankfully, the studied phenomenons are contrasting enough to be well illustrated even with a lack of technical means.

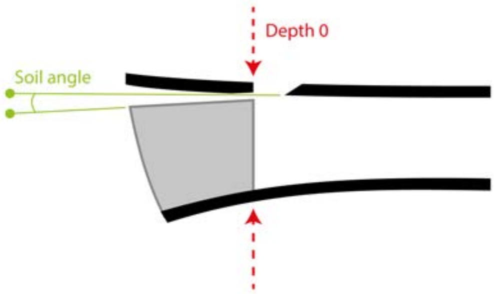

Fig. 4: Illustration of Depth 0 and soil angle

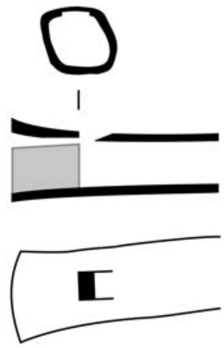

Fig. 5: Depiction of the sound-geometry used for the hand-crafting experiments

4.2 Sound results

The diagrams in Fig. 8 represent the results of basic acoustical analysis of the control flute and its 5 replicas. They obviously show that each individual is different from the control flute.

4.3 Statistics and discussion

The table (Tab. 1) represents statistical analysis made on the recorded frequencies. In order to compare them properly, we had to translate them from Hertz to logarithmic scale (base 2 logarithm).
This table shows heterogeneous frequencies and intervals deviations comparing the sample to the control flute, as well as between each individual from the sample itself. Even if the frequency deviations are mostly non-significant regarding statistics (T0 is the only one being significant), the sound estimation they produce is not satisfying for the ear (about one quarter-tone). However, intervals deviations are really small in comparison (about $1/20^{\text{th}}$ of a tone), which is extremely accurate.
The following facts should also be considered regarding those results:

1. The lower end of the flute was one of the most variable areas and it was then difficult to reproduce an exact geometry in a changing trabecular bone. This could explain T0 deviation.
2. The small sample size is probably involved in those statistical results: a larger sample (20 to 30 replicas) should help us to get better results and thus assess if whether or not this incredibly accurate estimation of intervals is exact. It should also explain the difference between a satisfying intervals reproduction and an unsatisfying frequencies reproduction.
3. The human blow should be ruled out and replaced by a mechanical blower in order to ensure the accuracy of the sound-capture.

objet	hz T0	log2 T0	Diff. 1/2 ton	hz T1	log2 T1	Diff. 1/2 ton	hz T2	log2 T2	Diff. 1/2 ton	T0-T1	Diff. 1/2	T1-T2	Diff. 1/2
Flute 0	1051	10,03755		1176	10,19967		1322	10,36851		-0,162125	-1,945505	-0,168834	-2,026009
Flute 1	1004	9,971544	-0,792041	1133	10,14593	-0,644882	1269	10,30948	-0,708361	-0,174389	-2,092663	-0,163544	-1,96253
Flute 2	1048	10,03342	-0,049487	1194	10,22159	0,262977	1350	10,39874	0,362847	-0,188164	-2,257969	-0,177157	-2,125879
Flute 3	1011	9,981567	-0,671756	1132	10,14466	-0,660169	1269	10,30948	-0,708361	-0,163091	-1,957092	-0,164818	-1,977817
Flute 4	995	9,958553	-0,947931	1115	10,12283	-0,922132	1247	10,28425	-1,011129	-0,164275	-1,971303	-0,161418	-1,937013
Flute 5	1027	10,00422	-0,399918	1145	10,16113	-0,462486	1290	10,33316	-0,424213	-0,156911	-1,882937	-0,172023	-2,064282
Average		9,989861			10,15923			10,32702		-0,169366	-2,032393	-0,167792	-2,013504
Standard deviation		0,029531			0,037438			0,043667		0,012237	0,146847	0,006579	0,078945
table student n=5 & alpha=0,05		2,571			2,571			2,571		2,571	2,571	2,571	2,571
Confidence interval 95 %		0,033955			0,043045			0,050207		0,01407	0,168843	0,007564	0,09077
minimum confidence interval		9,955907			10,11618			10,27681		-0,183436	-2,201236	-0,175356	-2,104274
maximum confidence interval		10,02382			10,20227			10,37723		-0,155296	-1,86355	-0,160228	-1,922735
Flute 0 in the confidence interval range ?		NO			YES			YES			YES		YES
deviation comparing to Flute 0 (Log2)		-0,047686			-0,040445			-0,041487					
deviation comparing to Flute 0 (semi-tone)		-0,572227			-0,485338			-0,497844			0,086888		-0,012505

Table 1: Statistical analysis of frequencies emitted by F0 to F5 while playing successively T0, T1 and T2. Differences are expressed in semi-tones ("-1" equals "1 semi-tone lower"). The right columns show intervals deviations (T0-T1 and T1-T2).

5 3D experiments

5.1 CT-scanning

There exist several possibilities in matter of 3D image acquisition, but CT-scanning was the only viable option because of the very nature of flutes: inner shapes are drastically important and their acoustical properties are extremely sensitive. We needed then a technology that would be able to capture high resolution images both inside and outside of the objects. µ-tomography, also known as µCT, was then the perfect tool. This technology uses X-rays in order to recreate high resolution 3D internal views of an object by compiling the acquired images and is mainly used in medical imaging and industries.

5.2 3D replication process and technical specifications

- **Objectives:** those experiments aim to question the sound-replication capability of 3D technologies in order to define whether or not they may allow us to pass beyond the sound-morphology limitation endured by handcrafting process. They also aim to assess their own limitations and potential as a sound-reconstruction method.

- **Technologies used:**
  1. **µCT-scanning:** the machine is an X-ray microfocus CT system General Electric (formerly Phoenix) v—tome—x 240D from CRT Morlaix, a resources center dedicated to metrology (http://www.crt-morlaix.com/). In the set-up, the sample is placed on a rotating table, and the X-ray source and detector are stationary.
  2. **3D wire and resin printing:** the machines are a MakerBotReplicator2 from IUT Le Creusot, and a Stratasys Mojo from ENS Rennes. The resin model was printed on a 3D Objet by a contractor.
- **Scanned object:** we chose to scan the control flute used in the sound-morphology principle (the one made from a goat's tibia) in order to compare the 3D results to the handmade replica. The flute was scanned in three parts in order to get a precision of less than 50µ. The reassembly was processed with the software Autodesk Meshmixer. Also, as the trabecular bone renders through µ-CT scanning as a cloud of 600+ tiny objects, it cannot be directly printed (Fig. 6). We chose to explore two possibilities: simply removing the objects in one case, and integrating them as a 3D sculpted "patch" in the other (Fig. 7). We used Meshlab and Blender in order to get ready-to-print 3D models.

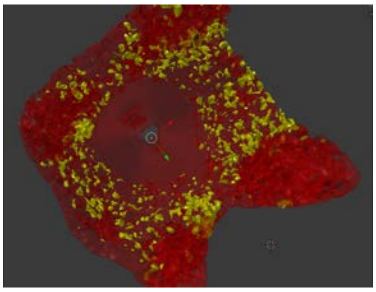

Fig. 6: Disconnected objects (yellow) in the area of the trabecular bone.

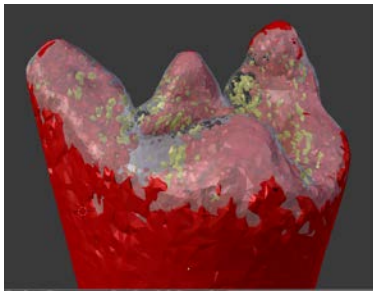

Fig. 7: 3D sculpted patch (transparent gray) on Blender (based on the geometry of the cloud).

- **Replicas:** F1 refers to the handmade replica. F2 refers to the 3D orange wire replica (with 3D sculpted "patch", no post-printing treatments). F3 refers to the 3D white wire replica (without the trabecular bone, acetone bath and ultrasounds post-printing treatment). F4 refers to the 3D white resin replica (better printing resolution, with 3D sculpted "patch", no post-printing treatments).
- **Printings:** printed between January and May 2016.
- **Sound capture and analysis:** same context than for the handcrafting process.

5.3 Sound results

The diagrams in Fig. 9 represent the results of basic acoustical analysis of the control flute and its four replicas.

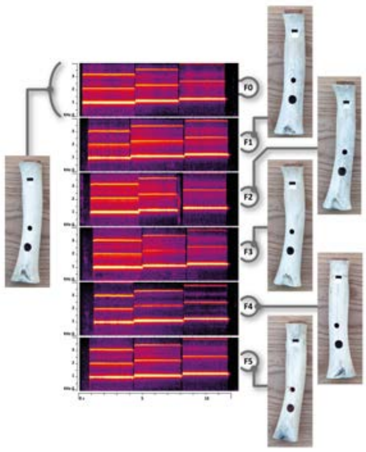

Fig. 8: Diagrams analysis of F0 to F5

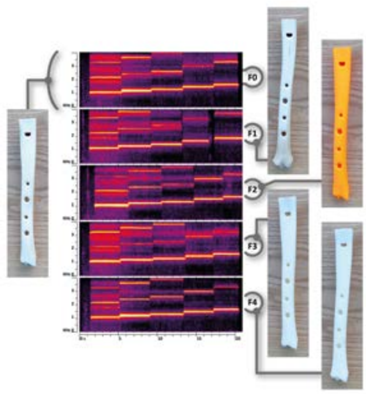

Fig. 9: Diagrams analysis of F0 to F4

5.4 Analysis and discussion

The following tables represent sound-comparisons between the control flute and its replicas using the recorded frequencies translated from Hertz to base 2 logarithm.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	objet	hz T0	log2 T0	Diff. 1/2	hz T1	log2 T1	Diff. 1/2	hz T2	log2 T2	Diff. 1/2	hz T3	log2 T3	Diff. 1/2	hz T4	log2 T4	Diff. 1/2
2	Flute 0	1088	10,087		1208	10,238		1300	10,344		1489	10,54		1649	10,687	
3	Flute 1 (hand-made)	1124	10,134	0,56	1277	10,319	0,96	1401	10,452	1,30	1659	10,696	1,87	1854	10,856	2,03
4	Flute 2 (orange wire)	1055	10,043	-0,53	1176	10,2	-0,46	1287	10,33	-0,17	1497	10,548	0,09	1658	10,695	0,09
5	Flute 3 (white wire)	1083	10,081	-0,08	1187	10,213	-0,30	1271	10,312	-0,39	1455	10,507	-0,40	1624	10,665	-0,26
6	Flute 4 (white resin)	1084	10,082	-0,06	1203	10,232	-0,07	1296	10,34	-0,05	1491	10,542	0,02	1656	10,693	0,07

	A	R	S	T	U	V	W	X	Y	Z	AA	AB	AC
1	objet	T0-T1	1/2 ton	Diff. 1/2	T1-T2	1/2 ton	Diff. 1/2	T2-T3	1/2 ton	Diff. 1/2	T3-T4	1/2 ton	Diff. 1/2
2	Flute 0	0,15	1,81		0,11	1,27		0,20	2,35		0,15	1,77	
3	Flute 1 (hand-made)	0,18	2,21	0,40	0,13	1,60	0,33	0,24	2,93	0,58	0,16	1,92	0,16
4	Flute 2 (orange wire)	0,16	1,88	0,07	0,13	1,56	0,29	0,22	2,62	0,27	0,15	1,77	0,00
5	Flute 3 (white wire)	0,13	1,59	-0,22	0,10	1,18	-0,09	0,20	2,34	-0,01	0,16	1,90	0,14
6	Flute 4 (white resin)	0,15	1,80	-0,01	0,11	1,29	0,02	0,20	2,43	0,08	0,15	1,82	0,05

Table 2: Comparison between frequencies (top) / intervals (bottom) emitted by F0 to F4 while playing successively T0, T1, T2, T3 and T4. Green cells indicate a sound-reproduction precision of $1/20^{th}$ of a tone or less.

As we expected, this table shows that 3D printed replicas are globally closest to the original than the handmade one. This is due to the absence of the bone's morphological variability that would occur from using several bones. However, they are not identical between each other (Fig. 10).

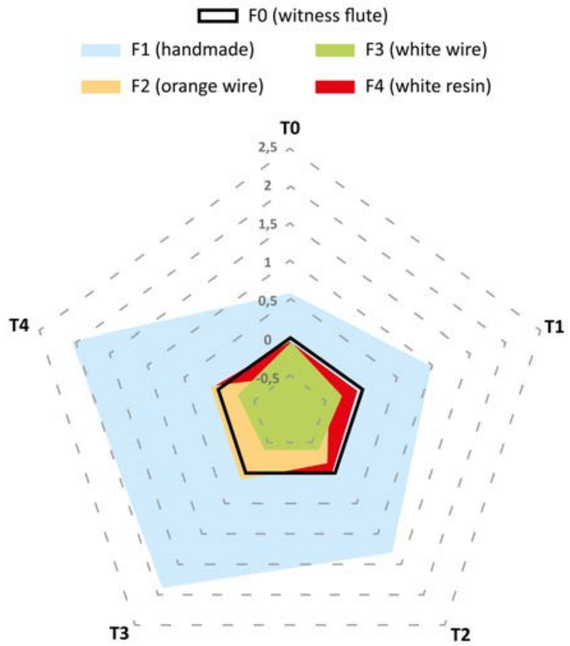

Fig. 10: Diagram representing the sound proximity of each replica comparing to the control flute, for each finger hole (numeric scale in semi-tones). The 0 line represents the control flute. The colored areas represent the replicas' sounds. The more the colored area fills the 0 line, the closest the replica is to the control flute.

In Fig. 10, both orange and white wire flutes present a significant but different deviation regarding their emitted frequencies, whereas the resin flute is the most accurate of them all. Indeed, it reaches the sounds of the original with a precision of less than $1/20^{\text{th}}$ of a tone.

As it appears, acoustical phenomenons related to 3D printed replicas seem to be quite intricate. The following facts should thus be considered regarding those results:

1. 3D wire-printing is processed by fusing a plastic filament which is then deposited by layers, and finally cools down and solidifies. The cooling process comes with a shrinking phenomenon which extent depends on the wire itself as well as on the cooling context (hygrometry and temperature) [17]. Furthermore, these deformations may occur in an irregular way. In other words, 3D wire-printing has a morphological variability of its own.
2. 3D resin-printing on the other hand does not work the same and thus does not have the same sources of error [19]: it uses a laser impact which solidifies a gelatinous resin. This technology is more accurate than 3D wire-printing and gives different physical results (smoother state of surface, solid 3D printings). That explains why this replica is much more accurate than the other ones.
3. Once again, human blow should be replaced by a mechanical blower.

6 Conclusion

Handcrafting and 3D replication processes illustrate the acoustical complexity of bone flutes, as well as they raise most important epistemological and methodological issues. Succinctly, these results advise of the dangers of sound-interpretations regarding ancient flutes when dealing with replicas. They demonstrate the complexity of the acoustical phenomenons related to naturally hollow raw-materials. They also demonstrate that 3D imagery is not as precise and trustworthy as we would think it would be. However, the use of statistics and of high-precision 3D printers seems to offer a promising track to continue this research. Although there is still much work to do in order to reach a better understanding of this situation, at least we now know that archaeological bone flutes sounds should always be interpreted with caution. In any case, this research will try and go deeper in the epistemological and methodological issues.

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