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Chapter 9

Topographic multi-scale surface analysis for the study of stone celts' polishing techniques

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Abstract

This paper presents applied tribological surface analysis for the study of polishing techniques for manufacturing stone celts. A comparative study of archaeological and experimental data has been conducted applying observation under low magnification with a microscope and a digital camera (microscope), interferometry and finally, a multi-scale analysis of surfaces using a mathematical tool developed in the field of tribology, the method of continuous wavelets transform (CWT). These methods of analysis have been applied to diasporite celts from late Neolithic and Early Bronze Age Aegean contexts. Comparative analysis aimed more precisely at evaluating abrasives' performance, isolating their morphological signature on polished surfaces and in this way, identifying their use. The first results showed that multi-scale analysis by CWT is an efficient tool and can successfully contribute at reconstituting prehistoric polishing techniques and evaluating parameters involved.

Keywords: diasporite, emery, corundum, abrasives, axes, adzes, chisels, Aegean, Cyclades, Anatolia, Late Neolithic, Early Bronze Age, interferometry, continuous wavelets transform, experimentation, technical skills

Introduction

The aim of this paper is to present applied tribological surface analysis for the study of polishing techniques, in other words, abrasion mechanisms activated for manufacturing stone celts (axes, adzes) and chisels. These are in the main distinctive tools of Neolithic societies worldwide prevailing in some cases in much more recent periods, as ethnographic data show (e.g. from Iria Jaya: Pétrequin & Pétrequin 2000). Our study aims at reconstituting manufacturing (polishing) techniques and at providing tools for evaluating technical skills and defining technical, functional, aesthetic or symbolic criteria involved in this process. Results could enhance further research on these issues and contribute in the long term at better understanding production systems in question.

Methodology

In the absence of written sources and complete archaeological series, a comparative study of archaeological and experimental data, a method established by S. A. Semenov in the 1940s, remains the most appropriate approach for such technical issues alongside residue analysis applied to ground stone tools (e.g. Kealhofer *et al.* 1999). Use-wear traces on archaeological and experimentally replicated surfaces bearing witness of manufacturing and/or consumption techniques are being compared. Besides observation under low magnification with a microscope and a digital

camera (microscope), we measured the surface topography of polish with an interferometer. Finally, we applied a multi-scale analysis of surfaces using a mathematical tool, the method of continuous wavelets transform (CWT). These methods have been developed in the field of tribology, the science of friction, wear, lubrication and adhesion. Applied to other ancient stone artefacts (e.g. vases, grinding stones), they have allowed to define manufacturing parameters and function through a qualitative and quantitative characterisation of polished surfaces on a microscale (e.g. Morero *et al.* 2013; Procopiou *et al.* 2013).

Interferometry

In order to measure polish, we applied interferometry which uses phase detection. Light reflected by the surface to be analysed is compared with a reference surface. The resulting interference phenomenon is recorded with a digital camera, which produces a map $z(x, y)$ of the measured surface. The dimension of the surfaces measured (x, y) was 2×2 mm. We thus obtained three-dimensional views $z(x, y)$ of polished surfaces. Statistical parameters can be calculated from the analysis of $z(x, y)$ maps obtained: the Local Normal and Sz, mean peak-to-valley height over the assessment surface area (Fig. 1). Polished surfaces are classified according to the values of Sz and the Local Normal. We showed elsewhere (Vargiolu *et al.* 2007; Procopiou *et al.* 2011 & 2013;

Bofill *et al.* 2013) that this quantitative classification can reveal the impact of lubricants and abrasives on shine formation on stone surfaces.

Multi-scale analysis: the method of the continuous wavelets transform

The surfaces of archaeological objects can bear at the same time traces corresponding to the phase of shaping as well as to the final phase of polishing and use. In order to distinguish between these different use-wear patterns and to identify the morphological signature of polishing techniques, we applied a multi-scale analysis. The three-dimensional signal $z(x, y)$ that corresponds to the distribution of heights of a surface generally contains a wide range of wavelengths and amplitudes: $z(x, y) = f(\lambda_i, \lambda_j)$. In fact, the different wavelengths of roughness and waviness of a solid are conventionally classified according to four wavelength bands: shape (flat surface, cylinder, sphere: $\lambda > 2500 \mu\text{m}$), waviness ($500 < \lambda < 2500 \mu\text{m}$), microscopic roughness ($1 < \lambda < 500 \mu\text{m}$) and submicronic roughness (a few nanometers $< \lambda$) (Raja and Radhakrishnan 1979; Zahouani 1995, 1998). The limits of the analysis of wear signature of archaeological surfaces according to classical parameters of roughness are actually well-known, especially as far as abrasive wear mechanisms, which generate wear features in different wavelengths, are concerned (Vargiolu 2008). Despite its reliability, the Fourier transform is limited to the analysis of frequency bands or wavelengths and does not allow one to isolate and extract information without creating disturbing overlapped frequencies. We have, thus, developed the theory of continuous wavelets transform, a system of mathematical tools that allow the study of the multi-scale signature of use-wear according to different factors: the petrographic nature of the artefact, the type of abrasive and lubricant. These mathematical tools allow comparison and classification of archaeological surfaces (Lee 1987; Lee *et al.* 1998; Mezghani 2005). The method is based on the use of analysis windows of various sizes enabling a multi-resolution study of the signal and a local quantification of all the surface components. This mathematical tool examines the signal under a rough resolution with the help of wide wavelets and of a small number of coefficients. For a local analysis, it uses a large number of small wavelets allowing a finer analysis. By analogy, analysis by wavelets is equivalent to observation with an optical microscope whose magnifications are the analysing wavelets at different widths or scales. The compression of analysing wavelets increases the digital microscope's magnification and reveals progressively more subtle details of the surface conditions. In comparison with a Fourier analysis, analysis by wavelets allows a better localisation in the field of high frequencies thanks to the property of wavelets' contraction and the sampling of wavelengths on a dyadic scale.

Mathematical background of the continuous wavelet transform and space-frequency

In order to analyse the multi-scale property of roughness,

which is due to its fixed resolution in the space and frequency domains, the wavelet transform can be used as flexible time-frequency resolution by trading resolution in time for resolution in frequency, where the basic functions are obtained from a single wavelet or mother wavelet $\psi(t)$ by translation and dilation (or compression) (Lee 1997; Lee *et al.* 1998; Mezghani 2005):

$$\psi(b, a) = \frac{1}{\sqrt{a}} \psi\left(\frac{x-b}{a}\right) \quad (1)$$

where a is the contraction coefficient and b is the translation coefficient, a and b are both real numbers quantifying the scaling and translation operations. The wavelet is a finite energy which is a square-integrable function over the range of its independent variable: $\psi(b, a) \in L^2(\mathcal{R})$.

We have defined the wavelets which are set at a fixed function, $\psi(x)$, called "mother wavelet" in Eq. (1). The continuous wavelet transform can be defined by the form:

$$W_{b,a}(x) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(x) \psi^* \left(\frac{x-b}{a} \right) dx \quad (2)$$

This scale transformation can be considered by utilizing the bank filtering theory (Vetterie 1992). The function $f(x)$ passes through the set of dilating and contracting wavelets. The wavelet coefficient $W_{b,a}(x)$ is a function with one variable x , but depends on the two coefficients b, a . One can obtain the plane which is composed of the set of coefficients translation- b , and contraction- a . This plane allows 2D visualization with the axis of frequency or scale a , and axis of space b .

The SMA coefficient and the morphological signature of prehistoric polishing techniques

The spectrum of multi-scale decomposition of a surface is obtained by the coefficient SMA (Fig. 2) representing the arithmetic mean value of all the scales of the surface expressed as follows:

$$SMA(a) = \frac{\sum_{x=1}^M \sum_{y=1}^N |f_a(x, y)|}{MN}$$

We used the SMA parameter to calculate a Multiscale Index Signature (M.I.S.), expressed as follows:

$$M.I.S(a) = \frac{[SMA(a)_{\text{Archaeological_surface}}] - [SMA(a)_{\text{Experimental_polishing}}]}{[SMA(a)_{\text{Archaeological_surface}}]}$$

Ponderation function

The ponderation function $F_T(a)$ is defined as the relation between the multi-scale coefficients of two profiles measured in two different conditions or as the relation of two different surfaces on an hierarchical basis of scales. That allows a comparison of two surfaces at all scales (see more in detail Lee 1997; Mezghani 2005; Vargiolu 2008).

$$FT(a) = \frac{[S Ma(a) _ Surface _ x] - [S Ma(a) _ Reference _ surface]}{[S Ma(a) _ Reference _ surface]}$$

A case study: diasporite stone celts from late Neolithic and early Bronze Age Aegean

We applied this method for the study of diasporite celts from late Neolithic and Early Bronze Age Aegean contexts (5th-4th millennium BC). Recent thorough study of available material (Boleti 2009, 2013) showed that diasporite celts of generally small dimensions¹ are mainly known for these periods from sites in the Cyclades, in the islands of the eastern and southern Aegean, as well as in Anatolia (Fig. 3) and represent a characteristic element of the Aegean prehistoric material culture. They are found in settlements and some of them are surface finds (eastern Naxos, Karpathos, Latmos). Major sources of diasporite exist on the Aegean islands: Naxos, Ios, Sikinos and Herakleia in the Cyclades, Samos in the East Aegean, as well as on the Asia Minor coast, mainly in the Menderes Massif (Önay 1949; Jansen 1977; Feenstra 1985; Yalçın 1987; for extended bibliography see Boleti 2009). Diasporites are metabauxites and appear in contact with emery sources. Their main constitutive, diasporite (7 on Mohs' scale of hardness), under a higher degree of metamorphism turns into emery's main constituent, corundum (9 on Mohs scale of hardness). As diasporite celts and chisels were found away from source-bearing regions (Fig. 3), we can conclude that they made part of the exchange networks connecting Mainland Greece, the Aegean islands and the Anatolian coast (e.g. Broodbank 2000; Sotirakopoulou 2008; Şahoğlu 2011).

Morpho-technological analysis and experimental reproduction of diasporite celts, showed that these were produced by knapping (direct percussion), pecking and abrasion (Boleti 2009, 2013). Abrasion was applied for shaping as well as for final polishing. We firstly evaluated the efficiency of possible abrasives. We therefore polished simple flakes, as well as celts' preforms, produced experimentally out of diasporite coming from the Küçükcamlık Tepe mines in Turkey. Petrographic analyses (thin section, XRD: Laboratory of Petrology and Mineralogy of the Institute of Geology and Mining Exploration of Greece) confirmed that this is an homogeneous fine-grained rock mainly composed of diasporite (diasporite 82.8%; hematite 17.2%) with a microcrystalline texture. The average hardness of the rock was evaluated at 982 HV (equivalent to 6.5 on the Mohs scale). The morphology of preforms and the abrasives were selected in order to reproduce as closely as possible the forms and surfaces observed in the archaeological record.

Evaluating abrasives' efficiency and distinguishing manufacturing stages. A first reference series

We polished diasporite flakes with natural sand, ground emery and ground corundum from Naxos. The sand was

coming from the north-eastern coast of the island (Azalas) and samples analysed at IGME were found to contain mainly quartz and garnet and very low occurrences of corundum. Emery came from the mines of Stravolagada known to contain mainly corundum and iron oxides, as well as mica. Ground corundum was issued from a vein of pure corundum crystals (without any iron inclusions) of blue colour from Arhatos. So, abrasives of different average hardness on Mohs scale were used (quartzitic sand with garnet: 7, ground emery: 8, ground corundum: 9). They were all locally available, while emery and corundum were ground with experimental stone tools (granite and basalt querns - granite or emery pounders and handstones) similar to the archaeological ones.

Other parameters such as lubricants, movement and working tables remained at this stage undifferentiated in order to evaluate the abrasive's performance. Water was used as lubricant, a granite block was used as a working table and a stable back and forth movement was maintained (Fig. 4). The same quantity of abrasive was used for every operation (100g) and the grains' size was also controlled (\leq mm). Direct contact with the working table was avoided during polishing as sufficient abrasive material was used and granite was therefore not influencing the final result (Fig. 4).

The 3D measurements of polished surfaces (Figs. 5-6) have been analysed by ponderation function at T1= 30 min, T2= 60 min and T3=90 min. The geometrical aspect of the surface on the first two levels of wavelengths corresponds to shape and waviness respectively and allows the identification of shaping techniques. The last level corresponds to roughness and allows the identification of polishing (finishing) techniques (Fig. 2). Therefore, in order to evaluate the efficiency of the abrasive during shaping, we have studied the wavelengths above 500 μ m. This group of wavelengths reveals the alterations of the surface during the first stages of shaping. According to the mean value of the variation of F_T , (Fig. 7), from T1 to T2, we notice a diminution of F_T of the order of 13% for sample A polished with quartzitic sand and sample B polished with emery, while for sample C polished with corundum this decrease reaches 45%. The variation of F_T for sample A from T2 to T3 presents an increase by 23%, which means that the action of polishing produces a waviness of the surface of more important amplitude compared to the variation between T1 and T2. For samples B and C, variation increases by 3% and 0% respectively, which means that at this stage, polishing (abrasion) has almost no effect on surface topography at this level.

In conclusion, emery and corundum are the most efficient abrasives for taking-away material independently of the geometry of the original surface. In fact, during abrasion with these materials, waviness remains the same. The surface appears rough and uneven. The quartzitic sand, on the contrary, alters progressively the surface's waviness, after at least 50 minutes of abrasion and produces a smooth and homogeneous surface, required during the final stage of polish. The choice of the

¹ The dimensions of the smallest celt studied are 3.8 x 1.4 x 0.7 cm and those of the biggest one are 9.3 x 3.6 x 2.5 cm.

abrasives appears intimately related to the desired final surface (Procopiou *et al.* 2013) but also to the technical investment.

Identifying abrasives

We attempted to identify the abrasives used for polishing prehistoric diasporite celts with a second series of experiments. In this exploratory series, an average time of 30 minutes of polishing on a sandstone working table was necessary for reproducing polished surfaces similar to archaeological ones. Abrasives varied from natural quartzitic sand (from Naxos: Haghios Dimitrios and France: Drôme) to pure ground corundum from Naxos (Arhatos) with intermediary mixtures of quartzitic sand with different percentages of emery (Lyonas, Stravolagada) or pure corundum (Fig. 9). In the cases of mixtures, quartzitic sand mostly served as a vehicle for the more resistant emery and corundum grains without altering their performance. Likewise, in some cases olive-oil was used as a lubricant instead of water, in order to hold together and better convey the harder and more angular corundum grains. The use of such a greasy substance did not seem to generate different use-wear traces compared to water, but did produce a shinier surface.²

Comparison of experimental surfaces with three prehistoric diasporite celts from Naxos (Chora: Grotta(01) – Dimitrokalli (02); (A)malia) (03, fragmentary) using the method of CWT (Fig. 8) showed that pure corundum or abrasives containing a high percentage of corundum did not produce surface states similar to those known archaeologically. The experimental surfaces that came closer to the archaeological ones were produced with a mixture of quartzitic sand and corundum of an order of 10%.

Conclusions

These results show that the method of CWT is an efficient tool for evaluating different abrasives and determining their morphological signature. On this basis, we can assume that corundum could have been preferred for polishing diasporite celts in Late Neolithic and Early Bronze Age Aegean, either as a natural sand's component or as part of a preparation. In all cases, this study of abrasives' performances and morphological signatures suggests that, since Prehistory, Aegean craftsmen knew empirically the physical properties of available abrasives and were able to identify, select, transform and exploit them in the most efficacious way for polishing. In this way, they have obtained high-quality polish equivalent to modern ones industrially produced. Additional systematic experimentation and comparative analysis by the method of CWT are actually in progress. Results could further contribute at the study of prehistoric Aegean stone

handcraftsmanship including not only celts, but also vases, figurines and other stone artefacts.

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² For the role of lubricants more precisely, as well as that of visual perception in the process of polishing see Procopiou *et al.* 2011, where additional series of experimental polishing of diasporite and new analytical methods are presented.

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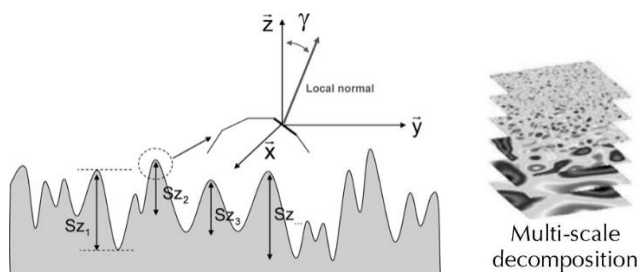


Fig. 1. Roughness parameters. Local Normal and S_z .

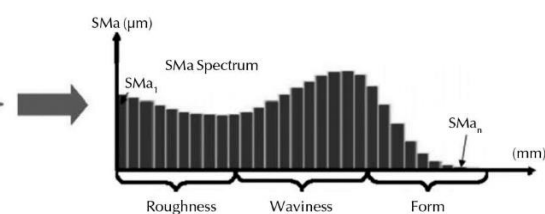


Fig. 2. The SMA coefficient.

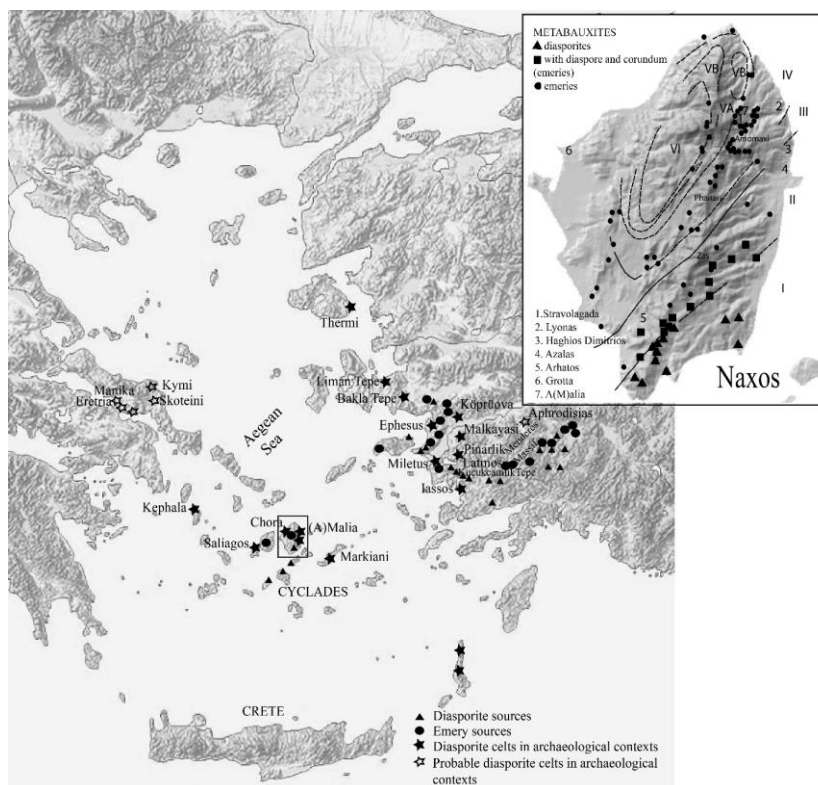


Fig. 3. Map showing metabauxites (diasporite and emery) sources in the Aegean (after Feenstra 1985) and distribution of diasporite celts in Late Neolithic and Early Bronze Age (Boleti 2009).



	Sample A	Sample B	Sample C
Abrasive	Quartzitic sable	Ground emery	Ground corundum
Lubricant	Water	Water	Water
Time	T1 = 30 min T2 = 60 min T3 = 90 min	T1 = 30 min T2 = 60 min T3 = 90 min	T1 = 30 min T2 = 60 min T3 = 90 min
Working surface	Granite	Granite	Granite

Fig. 4. Experimental protocol applied for polishing diasporite celts. Only abrasives vary.

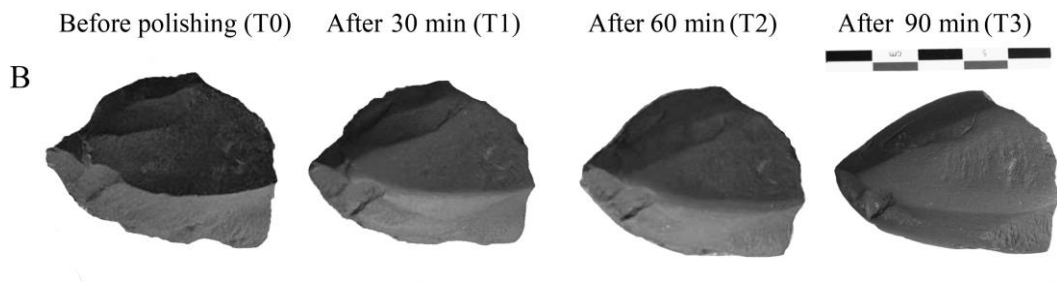


Fig. 5. Diasporite flake B polished after protocol Fig 4.

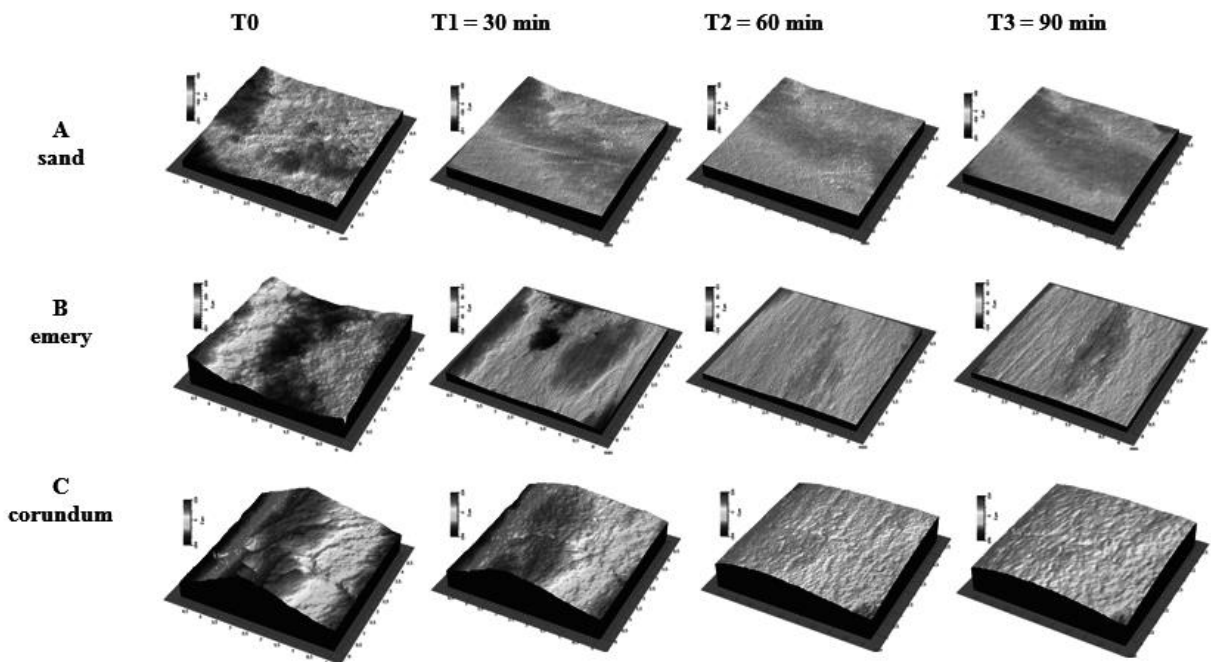


Fig. 6. Topography follow-up of a 2x2 mm surface.

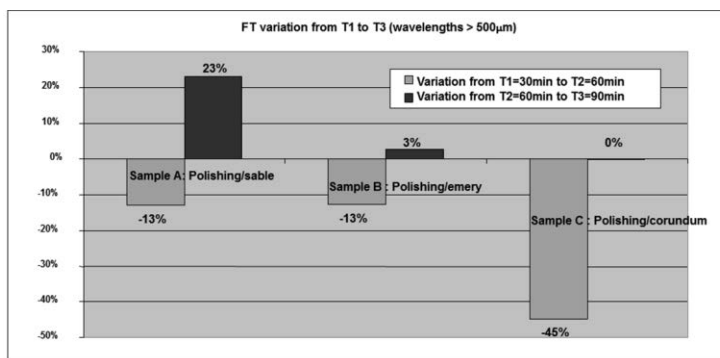


Fig. 7. Variations of wavelengths > 500µm during shaping.

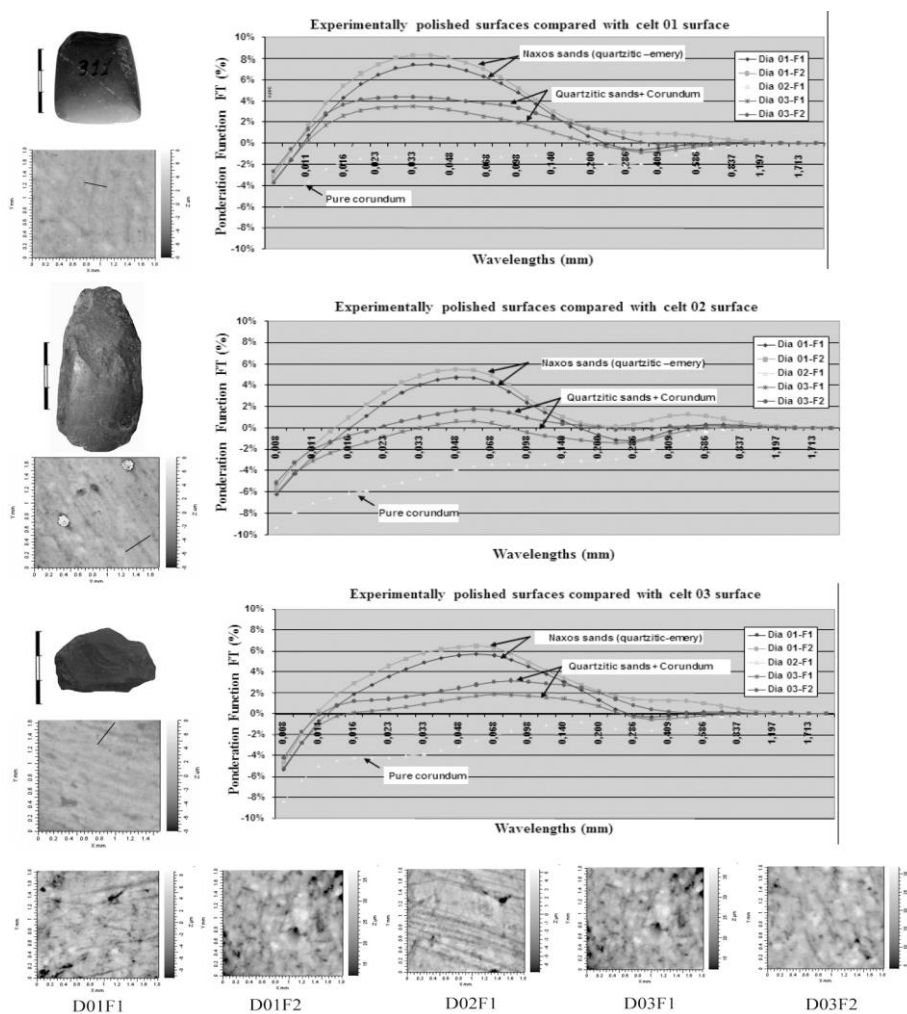


Fig. 8. Signature of polishing on diasporite surfaces and comparison of experimental pieces with archaeological celts from Naxos.

Sample	Time	Lubricant	Abrasive
Dia 01F1	30 min	Water	Naxos natural sand containing no corundum
Dia 01F2	25 min	Water	Naxos natural sand containing emery components + ground emery
Dia 02F1	>30 min	Olive-oil	Ground corundum
Dia 03F1	20 min	Olive-oil	Drôme sand + 10% ground corundum
Dia 03F2	25 min	Water	Drôme sand +50% ground corundum

Fig. 9. Experimental protocol for polishing diasporite celts.