Statistical analysis of engraving traces on a 3D digital model of prehistoric stone stelae

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\textbf{A R T I C L E   I N F O}

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\textbf{A B S T R A C T}

Studying cultural heritage artefacts, using 3D digital models, is gaining interest. It not only allows applications in documentation and visualisation, but also permits further contact-less examination. In this paper, we are presenting a statistical analysis of stone engravings based on features that were semi-automatically extracted from 3D acquisition data. Our objects of study are two Neolithic stone stelae and a faithful replica that was created in the course of an archaeological study. We use common statistical methods and investigate the populations of depth and diameter of the engraving traces, as well as their correlation. We observe that the erosion of the two prehistoric stelae results in a larger dispersion of the diameter distribution, as well as in a similarity of a linear regression model. Furthermore, we note a similar median in the height and depth distribution between the replica and only one of the prehistoric stela. This finding supports an archaeological hypothesis regarding the presumed engraving tools.

\section{1. Research aim}

The prehistoric stone stelae from the archaeological site of Petit-Chasseur (Sion, Switzerland) are important records of Neolithic cultures in the Alpine region. This is the first technology-driven, interdisciplinary analysis of these artefacts. We aim to complement traditional investigation methods and compare prehistoric engravings to a modern replica. The analysis is based on digital 3D acquisition data and aims to verify and extend archaeological hypotheses regarding the engraving tools, as well as to investigate erosion of engraving traces.

Impact traces of stone engravings bear valuable information and are traditionally studied by close, manual observation. A computer-aided, statistical evaluation allows for a repetition of the measurements in arbitrary environments. We aim to derive a methodology that will allow for a comparison of different traces and can be extended to a categorisation of different surfaces and engraving tools.

\section{2. Introduction}

The research in cultural heritage (CH) benefits from novel, digital acquisition techniques that permit an accurate documentation of colour and space. It has multiple advantages in ease-of-use, time saving and precision compared to traditional methods [1–4]. Cassen et al. [4] use lasergrammetric and photographic recordings to complement the documentation of a Neolithic tomb. The contours of the engravings are highlighted using a 3D dataset. Scopigno [5] summarises applications of 3D acquisition beyond visualisation. The possibilities range from supporting the restoration of fragmented artwork to shape comparison of CH artefacts. Important targets for a shape comparison are engraving traces, as they give evidence of the creation of a work of art. Levoy et al. [6] document and characterise the chisel marks of Michelangelo statues for the Digital Michelangelo Project. Different chisels have clearly distinguishable patterns of residual traces, which remain visible in unfinished statues. The pioneer work involved a labour intensive manual analysis, using cut-through planes in a 3D model and a manual measurement of residual traces from the engravings. Pietroni et al. [7] extend this idea by applying a local flattening
operator that transforms a local 3D surface to a 2D image. This allows standard image processing to automate the visualisation and detection of the residual traces and facilitates a comparison between different artefacts.

In this paper, we use a 3D acquisition as a foundation for a detailed analysis of prehistoric engravings and investigate the stelae from the archaeological site of Petit-Chasseur (Sion, Switzerland) [8]. These excavations are considered as important records for the understanding of prehistoric cultures in the Alpine region, and the artefacts have been exposed to various traditional investigation methods. A petrographic determination [9] unveils the composition of the stone and the age of the artwork. The graphical documentation of the engravings consists of fottoage and scientific drawings, which are summarised in [10]. Different hypotheses for a suitable engraving tool have been tested in the course of an experimental archaeological study, conducted by Haller and Gentizon Haller [11]. Recreated tools were applied to a stone board of similar durability and quality. A scaled replica of an entire stela was created using a replica silex engraving tool.

An open question remains; how can the knowledge of the archaeological study be transferred to different types of Neolithic stone stelae and how are the engraving traces affected by erosion? Building on the prior work, we go beyond a visual comparison and aim for a statistical analysis of the engraving traces. We acquire 3D models of selected artefacts under the same conditions. We then analyse two prehistoric stelae, created on different stone boards, to examine the different properties of the surfaces. A comparison to the archaeological study allows a closer look at different erosion states.

In contrast to Renaissance statues [6,7], the residual marks of prehistoric stone stelae do not show a characteristic 2D image pattern. Instead, the pointed stone and copper chisels cause an irregular pattern of punctual impact holes. The analysis of prehistoric stone engravings needs novel data processing approaches. Instead of analysing patterns, we focus on individual impact holes and process a large number of such traces in order to conduct a statistical evaluation. For a repeatable analysis, we employ a semi-automatic feature extraction that only requires manual selection and a verification of the feature extraction. The main idea is to reduce the complexity of a 3D digital model. First, we extract a 2D representation and a linel from which we derive simple descriptive features, namely depth and diameter. The proposed approach allows for a rapid selection of a large number of traces, which is the foundation of a statistical analysis. The remaining paper is structured as follows: in Section 3, we introduce the objects of study and the methods for the data processing and analysis. Section 4 presents the results of a statistical analysis and discusses the characteristics of the statistical populations, as well as the correlation between depth and diameter. We conclude and describe further work in Section 5.

3. Material and method

The proposed statistical data analysis is based on digital 3D models. For the data acquisition, we used a structural light scanner. The device is easily operated, highly mobile and allows adaptive, in situ acquisitions. The data analysis is performed semi-automatically requiring a manual selection of isolated engraving traces. We apply the proposed approach to two prehistoric stone stelae and an accurate replica that was created in the course of an archaeological study.

3.1. Objects of study

The objects of study are Neolithic stone stelae from Petit-Chasseur. They were discovered in 1961 by Bocksbarger [8]. In total, there are 30 engraved stelae that are explained in detail by Corboud and Curdy [10]. Depending on the period of creation, the artefacts can be classified as type A and type B. Type A is dated between 3000 to 2500 BC, type B between 2500 and 2200 BC. The second type shows more complex decoration and also exhibits different clothing and weaponry e.g. bow and arrow.

For this investigation, we use two Neolithic stelae: Stela 8 (Fig. 1a) and Stela 20 (Fig. 1b). Stela 8 and Stela 20 are both of type B and show large areas of engravings. Stela 8 is made of slate quartzite and exhibits a male human. Stela 20 is of grey marble and the engravings are largely carved out with a chisel tip. The impact holes are clearly visible, but shallower.

Both prehistoric stelae are compared to a faithful replica created recently in the course of an archaeological study (see Fig. 1c). Haller and Gentizon Haller [11] analysed different materials for the hammer and chisel tip. Several materials, such as copper or quartz, were ruled out, and silex remained the sole candidate for an engraving tool that fulfilled the requirements of durability allowing fluidity in the work process. Together with a hammer of a weight between 500 g and 700 g, this yielded the most convincing results.

The replica has been engraved and stored under well-documented circumstances. Therefore, we assume that this model has not suffered from erosion. The prehistoric stelae were stored in the same location for the same period of time.

3.2. 3D data acquisition

We acquire all objects with the same structured light scanner (Breuckmann, smartSCAN3D). The device contains a projector and two RGB cameras with a resolution of 1624 × 1234 pixel. It operates at a distance of 1 m, is highly mobile and allows adaptive, in situ acquisitions. We average every measurement four times to reduce noise. The resulting 3D model is automatically meshed, and has a pixel-size of 0.274 mm. The mesh data is free of unreferenced, isolated or duplicated faces and vertices, and has a regular structure, which facilitates further processing.

To cover the large surface of a stela, we used multiple scans from different positions and angles. These views are assembled by a contour-matching algorithm [12], which optimises the alignment as an iterative procedure in the overlapping area between the different scan views. As the surface of the rock has a textured and unique structure, contour-matching is an elegant way to achieve good merging results, without the need of external auxiliary reference bodies. The final result of a textured 3D mesh can be seen on Fig. 1. The RGB cameras are an integral part of the scanner and a registration of the texture as an additional step is not necessary. These merged 3D models are used for documentation and visualisation applications, and are the foundation for further evaluation.

3.3. Topological relief

Due to the pointed engraving tool, the stelae show an irregular engraving pattern that cannot be compared to each other directly. We focus on individual impact holes that are clearly identifiable, undisturbed by overlapping engravings, and show an almost flat local neighbourhood. Such regions of interest (ROI) are best selected manually, because it is important to include the entire impact hole and to avoid additional structures. Examples of selections are visualised on Fig. 2. The task is performed directly on the 3D model and it is therefore independent of the viewing angle and orientation of the engraving trace. ROIs can be selected rapidly and
inappropriate selections are to be discarded later. The selections are extracted as 3D mesh data, with an arbitrary coordinate system.

The ROIs are then transformed to a more coherent, 2D topological relief. We assume the local neighbourhood around the trace to be flat, and set the viewing z-axis orthogonal to it. We then relocated the origin of the coordinate system to the local minimum. These operations are conducted automatically, however the process requires a manual validation, and some ROIs could be discarded due to a concave local rock structure, or multiple minima. The topological relief is a 2D depth image, based on a local coordinate system (see Fig. 3). The z values of the vertex values are interpolated to a regular grid-data.

3.4. Feature extraction

Due to the heterogeneously shaped traces within each model (Fig. 3), it is infeasible to use image processing to classify the engraving traces. Instead, we apply a further abstraction, and automatically extract simple descriptive features from the topological relief. We chose the diameter and the depth along two orthogonal linecuts. Other descriptive features could be the volume, or the curvature along a certain axis. However, advanced features might require a higher resolution acquisition.

The feature extraction is illustrated on Fig. 4. Each topological relief is transferred to two orthogonal linecuts along the x- and y-axis. For each line, we start searching at the origin, which coincides with a local minimum. In both directions, the first value that is not increasing is estimated, and the smaller one determines the depth of the hole. Based on the depth, we calculate the diameter by intercepting the height with the linecut, starting from the origin in left and right directions. The results for the two linecuts can differ. For a visualisation of the topological relief (Fig. 3), we set the zero contour line based on the less profound of the two linecuts.

3.5. Datasets

The dataset is manually validated, the contour lines displaying an orthogonal view to the engraving trace are checked, and imprecise selections are discarded. This process yielded a total of 88 linecuts (see Fig. 5). Acquisitions from different views allowed us to assign the linecuts to different regions within the three artefacts.

3.5.1. Stela 8

Is a prehistoric stela of slate quartzite with its engravings mainly in the upper part? From the upper left part (see Fig. 2a), we extract 7 traces, and from the upper right part, we use 4 traces. The 22 linecuts based of these 11 engraving traces are shown on Fig. 5.

3.5.2. Stela 20

Is a prehistoric stela out of marble and the only stela from Petit-Chasseur engraved on both sides? We extract a total of 40 linecuts from various locations of the southern side. All traces are shown on Fig. 5.

3.5.3. Replica

Was engraved in the course of an archaeological study on a marble stone board. The traces are clearly visible due to a change of colour (see Fig. 2b). We select 26 linecuts from 13 traces (Fig. 5) from different locations of the stela.

3.6. Statistical tools

A coherent description by simple features is the foundation of a statistical evaluation. We use common statistical tools that are available for different software packages, such as Matlab or Excel. A Tukey boxplot [13] describes numerical data through their quartiles (three points that divide the data set into four equal groups). It is a descriptive statistical method visualising the
population of numerical data, without making assumptions of the statistical distribution of the data. A Wilcoxon rank-sum test\(^\text{[14]}\) is a nonparametric test that is used to check if the populations are the same. We apply the Tukey boxplot and the Wilcoxon rank-sum for to the diameter, as well as the depth population.

A regression analysis (e.g.\(^\text{[15]}\)) evaluates the correlation between two features. In this paper, we are analysing the linear relationship between the diameter and depth by an ordinary least square (OLS) regression. The error \(e\) is assumed to be independent and normally distributed. The analysis allows us to calculate a standard error, which is the variance normalised by the number of samples, an interval of confidence that denotes an area of 95\% certainty, and a \(P\)-value that indicates the likelihood of a linear relationship against a null hypothesis.

4. Results and discussion

Based on the extracted features, several statistical tests are applied. We examine the statistical population of depth and diameter individually, as well as their correlation. The results are discussed and connected to previous archaeological investigations.

4.1. Depth and diameter population

The two Tukey boxplots (Fig. 6) give an overview of the depth and diameter population. The datasets overlap, yet there are some notable trends for a discussion. The archaeological study has the smallest dispersion in the diameter distribution (Fig. 6a), while it covers the largest range of depth (Fig. 6b). We observe that the

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Fig. 3. Topological relief of isolated chisel marks. The depth image is based on a locally corrected coordinate system, and the centre is set to the local minimum. The relief with the dashed frame (first image, second row) is shown as a linecut on Fig. 5. All units are in mm: a: Stela 8; b: Stela 20; c: Replica.

Fig. 4. Linecut along x and y of an impact hole of Stela 8. Red line shows the depth, green line the diameter for the two cuts. This linecut corresponds with Fig. 3. First topologic relief from left in the second row.
depth distribution of the archaeological study is skewed (Fig. 6b), and the median value is similar to that of Stela 20. This similarity of the median also holds true for the diameter distribution (Fig. 6a). Both models are based on engraved marble, and the stone boards have the same durability and quality. A similar centre of random distribution of both features supports the hypothesis of a similar engraving tool. A notable higher median can be seen for Stela 8, which is based on quartzite.

The range of depth depends largely on the pressure and the number of hits that have been applied to the chisel tip. The narrow distribution of the diameter in the archaeological study depends on the engraving tool and the stone board. The larger diameter dispersion (Fig. 6a) of both prehistoric stelae is likely be caused by erosion. We assume that erosion affects the diameter and widens deep impact traces more. Evidence is a wider range of diameters that is independent of the type of stone. On Fig. 6a, the upper whisker of Stela 20 is lower than for the archaeological study. The boxplot shows few outliers of depth for Stela 20 where these values are within the dispersion of the archaeological study. This loss of depth of the traces might also be a result of erosion. Outliers in the upper range indicate that the processes did not affect all areas of the board equally.

Due to the large overlapping areas in the boxplots, we evaluate if the distributions of the data are the same using a Wilcoxon rank-sum test. We compare two populations consecutively. The null hypothesis (H0) assumes that the values of two populations are equal, and H1 assumes that the populations are not the same. The low $P$-value rejects H0 and the corresponding values are denoted in Table 1. We observe a statistically significant difference between the values of Stela 8 and Stela 20 and also between Stela 8 and the replica. However, we did not find a statistically significant difference between Stela 20 and the study, given a 95% confidence. This result coincides with the observations of the Tukey boxplots.

Fig. 6. Tukey boxplot [13], with the red line being the median of the distribution: a: boxplot of the diameter for the three models: The median value of the Replica and Stela 20 (both engraved marble) have a similar value, while the diameter of Stela 8 is significantly larger. The spreading is smaller for the study; b: boxplot of the depth for the different models: similar to the diameter, the median of the Replica and Stela 20 (both engraved marble) is similar, while Stela 8 tend to be deeper. The spreading of the Replica covers the largest scale, yet it does not have outliers as Stela 20.

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Although we lack information about the manufacturing process of the prehistoric stelae and a formulation for the erosion processes, the similarity between the archaeological study and Stela 20 is most noteworthy. It supports archaeological hypothesis that the prehistoric stelae had been engraved using a pointed silex chisel.

### 4.2. Regression analysis

In the following step, we want to evaluate the correlation between depth and diameter. We test for a linear relationship, by applying an OLS regression. The results of the regression analysis are given in Table 2 and the OLS regression with the 95% confidence interval is visualised on Fig. 7. The archaeological study has a lower slope ($b_1 = 1.2$), compared to the two prehistoric stelae that have almost a similar slope ($b_1 = 6.17$, respectively $b_1 = 6.81$). A higher slope means deeper traces are wider. Again, this is evidence that the prehistoric stelae are affected by the same erosion process.

We test the linearity by applying a t-test to the intercepts and slopes of all three models. Assuming an independent and normally distributed residual error, the null hypothesis ($H_0$: $\beta_0/\beta_1 = 0$) is rejected by a small $P$-value, which asserts a linear relationship. We see that the slopes of both prehistoric stelae are clearly statistical significant (with $P < 0.001$). The $P$-value for the slope of the archaeological study ($P = 0.013$) is still lower than 5%. Therefore, we have a statistical indication for a linear relationship between depth and diameter right after the engraving. This relationship is explained by the pointed chisel tip. A deeper impact hole automatically causes a wider diameter. It is notable that both prehistoric stelae show a strong linear relationship and almost the same slope, although they consist of different stone boards, and the traces have different depths and diameters. This is an indication that the slopes of the first two figures on Fig. 7 are caused mostly by erosion and not caused by an unknown engraving procedure. The only $P$-value over 5% is the intercept of Stela 8 ($P > |t|$ in Table 2). This means we cannot reject $H_0$: $\beta_0 = 0$, with our number of samples. We cannot include more samples closer to the origin, because all engravings of Stela 8 have a certain depth.

The archaeological study has a lower squared residual error ($R^2$ in Table 2) than both of the prehistoric stelae. The Skew in Table 2 indicates the asymmetry of the distribution along the regression. All values are positive, which means more samples can be found on the left side. Values between +3 and −3 indicate a normal skew. The Kurtosis in Table 2 measures the heaviness of the tails of a distribution. All three values confirm a similarity between the two prehistoric stelae. Although the individual distribution of depth and diameter between Stela 20 and Stela 8 are different, the linear relationship between both is rather similar.

Both engraving and erosion contribute to the linearity of the depth-diameter correlation. This analysis suggests that the

### Table 1

<table>
<thead>
<tr>
<th></th>
<th>Stela 8 - Stela 20</th>
<th>Stela 8 - Replica</th>
<th>Stela 20 - Replica</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>$1.4714 \times 10^{-5}$</td>
<td>$5.9101 \times 10^{-5}$</td>
<td>$0.5075$</td>
</tr>
<tr>
<td>Depth</td>
<td>$2.9405 \times 10^{-7}$</td>
<td>$0.0119$</td>
<td>$0.0943$</td>
</tr>
</tbody>
</table>

### Table 2

Results of a regression analysis, putting the depth and the diameter of engraving traces into y linear relationship. The t-test is applied to the intercept and the slope. The regression analysis includes squared residuals ($R^2$), Skew and Kurtosis.

<table>
<thead>
<tr>
<th>Intercept</th>
<th>Slope</th>
<th>Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_0$</td>
<td>$\beta_1$</td>
<td>$R^2$</td>
</tr>
<tr>
<td></td>
<td>$t$</td>
<td>$P &gt;</td>
</tr>
<tr>
<td></td>
<td>$t$</td>
<td>$P &gt;</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>Skew</td>
</tr>
<tr>
<td>Stela 8</td>
<td>1.5972</td>
<td>0.898</td>
</tr>
<tr>
<td>Replica</td>
<td>2.7938</td>
<td>0.231</td>
</tr>
</tbody>
</table>

Std. err.: standard error.

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Fig. 7. Distribution of depth and diameter, for the three acquisition models. The red line is a linear regression, estimated by an ordinary least square (OLS) model, with the 95% confidence interval.
stronger contribution is caused by the erosion. Two prehistoric engravings on different stone boards have a very similar linear correlation.

5. Conclusions and further work

Based on a digital 3D dataset, we analysed two prehistoric stone stelae and compared them to a replica that was created in the course of an archaeological study [11]. In order to investigate the engraving traces, we reduced the complexity of a 3D structure to descriptive depth and diameter values. A subsequent statistical analysis was built upon previous traditional investigations. The replica was engraved using a pointed silex chisel. In the presented data analysis, we noted a strong similarity between the archaeological study and only one of the prehistoric stela. These two objects are engraved marble, and this provided statistical evidence that the engraving tool and manufacturing process are also similar.

A correlation between depth and diameter is partly caused by the engraving itself. Evidently, a deeper impact hole yields a wider diameter. Yet, a stronger contribution for the correlation can be assigned to an erosion process. Two prehistoric stelae, engraved in different stone boards, have a similar correlation between depth and diameter.

This paper focused mainly on the data processing and analysis. Future work should investigate more objects of study. The approach can be applied to different artefacts that were created with stone or copper points, and show isolated engraving traces. A chronology of different engravings could be established and might complement manual observations, such as [16]. An extended comparison should be conducted on impact holes produced by different experimental instruments, such as rock crystal or copper points. Additional prehistoric artefacts that are created with unknown tools should be investigated and compared. This includes different time periods and location of the artefacts.

The approach could be extended by additional and more advanced features, such as higher order curvature or roughness. This requires a higher 3D resolution, and could be a foundation for a model of different erosion processes.

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