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Traceological analyses of tool marks on western Iberian stelae and their replications: Stones and steel at the end of the Bronze Age

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ABSTRACT

For the study of carved rock art, particular tool materials can only be meaningfully hypothesized, identified, or excluded by combining traceological analyses with an accurate understanding of the physical-mechanical properties of the carved rock as well as knowledge of the available tool materials from an archaeological, material analytical, and experimental point of view. The aim of this study was to identify the tools that were used during the Final Bronze Age-Early Iron Age transition (c. 1200-550 BC) for the carving of western Iberian stelae by comparing the work traces on originals and replications with the same rock supports and the archaeologically identified tool-set. This was achieved by the traceological-technological study and categorisation of the carved lines and motifs, based on the profile sections of the engravings, on a sample of four western Iberian stelae made from granite-aplite, meta-arkoses, and silicate quartz-arenite. All components were replicated according to petrological and metallurgical analyses. This approach, which is based on 3D-scans in combination with GIS and a thorough evaluation of digital data, material analyses, and archaeological data, will be presented here for the first time. The application of GIS and DEM for the analysis of the profile sections of carved ornaments provided analytical and graphical results from 444 profiles, allowing the classification in six different profile typologies. The most striking result is that silicate quartz-arenites cannot be carved with bronze tools and that lithic tools only left superficial traces that are very different from the original stelae from this lithology. Therefore, this particular material, which represents over 20 % of all stelae, could only be carved with hardened steel chisels, while many granitoid and sedimentary rocks could also be carved with lithic tools.

1. Introduction

The western Iberian stelae are amongst the most iconic archaeological remains of the Final Bronze Age (FBA, c. 1200-800 BC) to Early Iron Age (EIA, c. 800-550 BC) transition in the Iberian Peninsula. These monuments are decorated stone slabs, ranging from c. 0.50 m–2.70 m in height, and a majority of them show depictions of swords, shields, and spears. Other frequently represented objects are mirrors, headdresses, helmets, musical instruments, chariots, animals, and anthropomorphic figures, which are sometimes displayed in scenes. These stelae are widespread in the inland areas and river valleys adjacent to the Atlantic facade of the Iberian Peninsula, from southern Galicia to the Algarve in the West and into the province of Ciudad Real in the East, with four isolated outliers near the Ebro and in the Gulf of Lion. The highest concentration was found along the Zújar river, while they appear to be absent in most of Alentejo and between the river mouths of the Guadiana

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and the Guadalquivir (Fig. 1).

Up until now, mainly the iconography, typology, socio-cultural interpretations and, to some degree, the landscape settings of the Iberian stelae have been studied (Araque Gonzalez et al., 2025a; Brandherm, 2013; Celestino, 2001; Díaz-Guardamino, 2010; Galán, 1993; Harrison, 2004; Rodriguez-Corral, 2017; Vilaça, 2011). However, the original purpose of these monuments remains unknown and debated, because almost no stelae have been found within archaeological contexts, or only within secondary depositions as a consequence of their reuse in ancient, historical, or recent times. Therefore, a conclusive chronology beyond the typological assignment of motifs can still not be established, although there is a broad consensus that the monuments date to the FBA-EIA transition period. Unfortunately, recent discoveries of stelae within a possible primary context in the necropolis of Cañaveral de León did not clarify the persisting problems, because no dates with satisfactory accuracy could be obtained (García Sanjuán et al., 2025; Rivera Jiménez et al., 2021).

On the other hand, due to their weight and dimensions it remains probable that most of the stelae were found close to their original position and cases where stelae are located more than 10 km from the next possible rock outcrop are rare (cf. Baptista et al., 2025). There is only limited evidence that slabs for stelae might have been transported over significant distances (see Merino Martínez et al., 2019). A study of 82 stelae carried out by the Institute of Applied Geology (IGeA) of the University of Castilla-La Mancha for the Institute of Archaeology-Mérida and the Spanish National Research Council (CSIC) concluded that the average distance between the nearest possible extraction site and the find spot is 1.85 km (Celestino Pérez and Paniego Díaz, 2025).

So far, only few studies focussed on possible carving techniques, sometimes including experimental approaches (Enríquez Navascués and Fernández Algaba, 2010; Díaz-Guardamino, 2023; Gutiérrez Sáez et al., 2020). On the other hand, the possibilities for the analysis of rock art have been revolutionized through the availability of new digital techniques (Celestino Pérez and Paniego Díaz, 2021, p. 78–79), most importantly photogrammetry and 3D modelling (García-Bustos et al. ,2024), structured light 3D scanning (García-Arilla et al., 2021), and Reflectance Transformation Imaging (RTI), which is a computational photographic method that can visualize hidden anomalies in the analysed surfaces (Díaz-Guardamino and Wheatley, 2013).

Within this trajectory, photogrammetric models and 3D-scans as well as RTI have been used on numerous Iberian stelae by a Spanish-British-Swedish research group (Díaz-Guardamino, 2023; Díaz-Guardamino et al., 2015, 2019, 2020, 2022; Rivera Jiménez et al., 2021), mainly with the objective to re-draw motifs with more accuracy than former interpretative drawings, to detect new motifs and palimpsests, and to a lesser extent, to detect work traces. García-Arilla et al. (2021) evaluated the stela from La Luna-Valpalmas (Zaragoza) based on a structured light 3D-scan in order to assess the use of different tools, however without specifying their type, shape or material. They provided depth measurements of the carvings (García-Arilla et al., 2021, p. 54–58), however no profile sections.

The traceological analysis of rock art engravings is still at an early stage, however there have been important developments and innovative approaches based on digital recording techniques. Two studies stand out for their comprehensiveness. Firstly, Russian researchers investigated petroglyphs in Siberia and developed a method based on photogrammetry, 3D-scanning, and archaeological experimentation to identify and distinguish the traces of metallic and lithic tools when used for pecking (Devlet, 2012; Zotkina and Kovalev, 2019; Zotkina and Davydov, 2022). The attribution is mainly based on the shape on plan of individually pecked traces within digital models from a top view. Most interestingly, they could challenge the chronology of Chukotka/Pegtymel petroglyphs, which had formerly been attributed to the Neolithic, since with their comprehensive approach it could be proven that the majority of them was made with iron tools (Devlet, 2012).

Secondly, work traces from surface levelling, high reliefs, and line incisions on the Glauberg statue in Hesse (Germany) from the La Tène period (5th-4th century BC) have been extensively analysed by Trefný et al. (2022). For the traceological part of their study, the researchers created a digital model with photogrammetry and applied a method they referred to as "mechanoscopy", aiming at the identification of contemporary La Tène tools and possible working techniques.

On the other hand, unlike many petroglyphs around the world that were made with direct percussion or indirect pecking, the western Iberian stelae were engraved with techniques that create continuous lines in the vast majority of cases, and bas-relief was not used on the western Iberian stelae except for the unparalleled example from Baraçal I (Curado, 1986). Eventually, the Glauberg statue as well as the Siberian petroglyphs were carved into rather soft sandstone and thus cannot be compared to the often very hard rocks that were used for more than 50 %

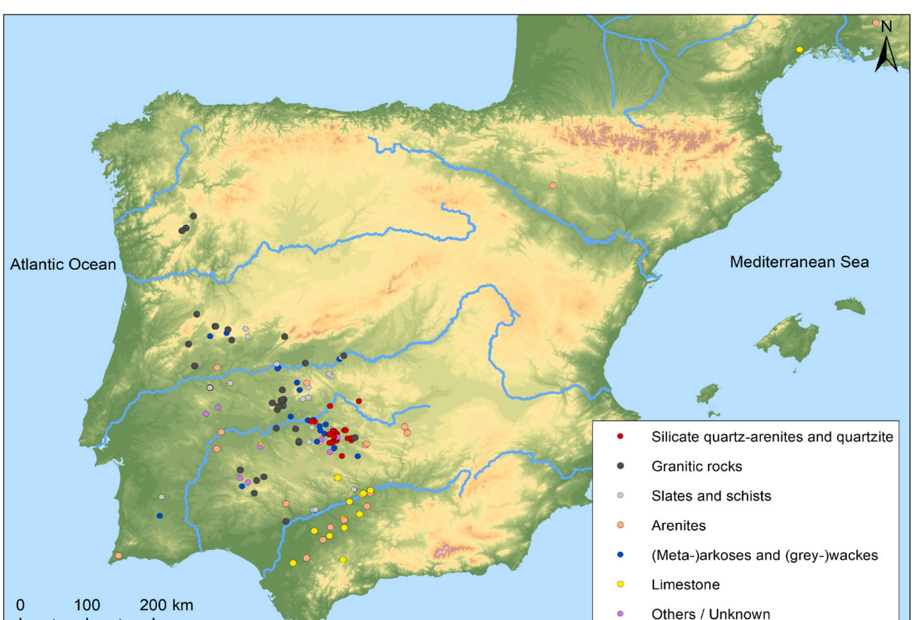

Fig. 1. Distribution map of western Iberian Stelae and their generalized lithology (Map: Pablo Paniego).

of the Iberian stelae.

In summary, the abovementioned approaches are comprehensive and useful for their subjects, but are difficult to apply to the Iberian stelae. This is because firstly, 54 % of all stelae are made from very hard rocks. Secondly, because the stelae are predominantly decorated with continuous line carvings, i.e. single, unbroken lines, that do not or rarely allow for the identification of individual tool marks from single impacts.

21 % of the stelae are made from silicate quartz-arenites/quartzite and those are concentrated in the Zújar and Guadiana river valleys. They always display a complex iconography centred around the human figure (or several anthropomorphic beings in groups or scenes). Recent research has shown that this material could experimentally only be carved with hardened steel chisels in a similarly accurate manner as the original stelae (Araque Gonzalez et al., 2023). Furthermore, another 21 % are made from very hard granitoid rocks and 12 % from hard (meta-) arkoses and wackes.

This contribution presents the traceological study of four original western Iberian stelae and their experimental replicas from three hard and frequently carved lithotypes that represent the materials used for 54 % of all stelae with a known lithology. Therefore, a combined approach comprising petrological and material analyses, experimental archaeology, and digital technologies, has been developed. Additionally, eligible tools were examined with optical and chemical analyses and science-based replications were manufactured (Araque et al., 2023, 2025b, 2025c). On this basis, a series of carving experiments were conducted with an expert stonemason. In a final step, the traces on the replicas were compared with the archaeological stelae. The results allowed to confirm as well as to reject several previous hypotheses.

The methodology that will be proposed here was especially developed to be applicable to rock art that consists of continuous line carvings. Therefore, this analysis is concentrated on the profile sections of the lines, which provide good evidence on the formal characteristics of the tools and the techniques that have been used. The traces of diverse tools on original and replicated stelae have been compared with GIS-based evaluations of line profiles on digitalised 3D-models. It must be emphasized that it is fundamental to take into account the rock types and the available materials for tools throughout the study of rock art.

2. Methodology

The approach towards the traceological analysis of the stelae is tripartite and comprised petrographic studies of the rocks and material analyses of FBA-EIA tools. The resulting data was used to acquire and replicate materials with corresponding qualities for the experimental carving of stelae. Finally, the digital analysis of the work traces was performed with 3D scanning and DEM evaluation of the resultant models. Traces on originals and replications were compared and checked for similarities and discrepancies of the line profiles in order to assess whether actually similar tools have been used. The objective was to test which tools that were available to FBA-EIA artisans could carve the three most commonly used lithotypes that were used for stelae (granitoid rocks, quartz-arenites, and arkoses). The main hypothesis to be tested was that silicate quartz-arenite (commonly referred to as "quartzite" in the bibliography) could only be carved with hardened steel chisels and not with bronze or lithic tools (first proposed by Araque Gonzalez, 2018: 187–189).

2.1. The analytical approach

The western Iberian stelae have been carved in areas with different geological situations, which resulted in localized selections and preferences for rocks by the artisans (see Fig. 1). The most frequent lithotypes from which the stelae were made (Celestino Pérez and Paniego Díaz, 2025; Ferreiro Mählmann et al., 2025; Merino Martínez et al., 2019) are silicate quartz-arenites and quartzite (21 %), granitoid rocks (21 %), slates and schists (15 %), (meta-)arkoses and (grey-)wackes (12 %), arenites (12 %), and limestones (10 %), while other rock types, including diabase, basalt, and tuff, were used to a much lesser extent (9 %). This shows a clear preference (over 54 %) for very hard (42 % silicate quartz-arenite/quartzite, granite and aplite) and hard (12 % meta-arkoses, wackes) rocks, whose carving must have constituted a challenge for artisans in the FBA-EIA.

The petrology of 53 western Iberian stelae has been studied within the project "The Iberian stelae of the Final Bronze Age: Iconography, Technology and the Transfer of Knowledge between the Atlantic and the Mediterranean[1]" (see Ferreiro Mählmann et al., 2025). For this research, the petrographic evaluation was carried out with mesoscopic analysis of stelae in the museums with a binocular on a tripod (50× magnification) to obtain a preliminary assessment of their lithology. Consecutively, minimal-invasive samples were collected from all stelae where an authorisation was given. The method of choice was core drilling (14 mm width, ca. 25 mm depth) to prepare thin sections for microscopy (16x to 2000× magnification) and obtain material for geochemical analyses with x-ray fluorescence (XRF) and inductively coupled mass spectrometry (ICP-MS). The drill-holes were subsequently restored with the capping from the core or epoxide and stone-powder by the stonemason. In a few cases, museums only permitted the acquisition of samples by chiselling, however this is a riskier method and must be conducted with thorough precautions to not cause fissures or uncontrolled breakage in stratified sedimentary and foliated metamorphic rocks.

It is important to state that only minimal-invasive sampling and microscopy can deliver definite results on the rock type, and together with geochemical analysis on its precise provenance. Once the lithotypes of the original stelae had been determined, the most probable outcrops were localized and sampled to clarify their provenance with the help of geological maps (IGME, 1995; Meireles, 2020) and advice from the colleagues working in the study area. This was followed by cross-referencing the results from the sampling of outcrops with the results of (according to data availability) mesoscopy, microscopy, and geochemistry from the original stelae in order to obtain a secure attribution (Araque Gonzalez et al., 2023; Ferreiro Mählmann et al., 2025).

Secondly, the possible stone-working tools that were available from the FBA into the EIA have been assessed from the archaeological records as well as in the local museums in Portugal and Spain. The rocks used for the most robust lithic tools were analysed with petrography, the archaeological bronze chisels and one steel chisel respectively with metallography; the bronze alloy compositions were analysed with pXRF (see Araque Gonzalez et al., 2023; Araque Gonzalez et al., 2025b, c; cf. Bottaini, 2012).

2.2. The experimental approach

To begin with the experimentation, the provenance of the original rocks was determined and slabs for the replications were acquired from the outcrops. The selection of lithotypes for the experiment was based on representing the 54 % of all stelae which are made from hard rocks. Amongst them, granitoid rocks and arkoses (together 33 % of all stelae) may vary in hardness due to a certain variability of compositions. However, regarding all petrographically analysed granitoid stelae, the majority has been identified as granite-aplite or fine grained leucogranites, which are generally the same rock type used for the Baraçal II replica. An absolute comparability of the original and replicated materials is given for 21 % of all stelae that are made from silicate quartz-arenite, which is a mono-mineral rock composed of >95 % quartz (Mohs hardness 7).

Subsequently, chisels from bronze and steel as well as lithic choppers and adzes were replicated according to scientific standards, based on the abovementioned analyses of originals. All replicated tools have direct

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parallels in the archaeological record, and they were handled by expert stonemason Giuseppe Vintrici, who has experience in traditional and medieval techniques, restauration, and experimental archaeology. All types of tools were tried on the rocks in a test phase, and the functional tools for each lithotype were then used to carve the ornaments in order to allow for a direct comparison of the work-traces with the originals. When a chisel is used with a hammer(-stone) or mallet, the weight of this implement is of major importance for the outcome. The stonemason found hammers with 500–800g to be ideal and 300–1000g feasible, however heavier tools cause outbreaks and imprecisions while lighter ones do not create enough impact to carve deep lines.

Surface preparation had been applied on the original granitoid stelae and was consequently applied on the replication partly with the time-consuming traditional method of grinding with sand, water, and a grinding stone, to record and calculate the effort, and partly with modern tools due to time restrictions (detailed discussion of results in Araque Gonzalez et al., 2025b). The motifs on the silicate quartz-arenite and arkoses stelae were carved into a red-bedded hard ground (lithification under oxidizing conditions) surface, which did not require surface treatment. This surface provides a contrast with the underlying, much lighter fresh rock, which highlights the ornaments.

In summary, the experimental protocol included the following work-steps.

1. Petrographic analyses of the stelae (mesoscopic and microscopic)
2. Determination of possible outcrops, sampling
3. Microscopic as well as geochemical analyses (XRF, ICP-MS) to assure the provenance.
4. Acquisition of corresponding rocks from identified outcrops
5. Preparation of the slab (if necessary)
6. Preparation of the surface (if necessary and applied on the originals)
7. Testing of tools to determine those which effectively carve the lithotype
8. Carving of the motives with corresponding techniques (chiselling, pecking, incision)
9. Documentation (photography, photogrammetry, 3D-scanning)

The approach was first applied in the village of Baraçal (Portugal), where the stelae of Baraçal 2 and Fóios were replicated within ten working days. In a second experimentation, the protocol was applied to stelae made with extremely hard silicate quartz-arenites from the Sierra de la Moraleja (Spain), namely the stelae of La Moraleja (Capilla I) and La Pimienta (Capilla VIII). The experimental replication is described in detail in Araque Gonzalez et al., (2023); Araque Gonzalez et al., (2025b), 2025c.

2.3. The digital approach

After the replication, the resulting work traces and line profile sections were evaluated in comparison to the original stelae with a newly established digital traceological approach. Modelling techniques for archaeological artefacts are now highly developed and many applications in the field of cultural heritage are based on the use of 3D models (Adamopoulos et al., 2020; Rahaman, 2019). The aim of this approach is to create a digital reproduction as identical as possible to the reality it represents. A common way to create 3D models is from the information provided by both 3D scanners or digital photogrammetry, which digitise an artefact or monument to obtain data on its shape, geometry and colour. Numerous studies have compared the advantages and limitations of 3D modelling by means of photogrammetry and structured-light scanning for the digitalization of cultural heritage and archaeological objects as well in engineering design, with similar objectives (Bianconi et al., 2017; Freeman Gebler et al., 2021; García-Bustos et al., 2024; Remondino, 2011).

For this study, structured-light scanning was chosen due to its well-established metric accuracy, and particularly the advantage of producing already-scaled models, thus avoiding the need for external references and with consistent accuracy across the entire surface, even in areas with low visual texture or repetitive patterns. Moreover, since high-resolution texture data was not required for the objectives of this research, the data acquisition and processing workflow was significantly faster than it would have been using a photogrammetric approach. This method was applied to the stelae and their replications, which have been digitised and modelled for this research.

Furthermore, for the development of this approach, the concept of a Digital Elevation Model (DEM), which is a digital representation of the bare ground surface, excluding other kinds of surface features, for example trees in geographical applications (Guth et al., 2021; Mesa-Mingorance et al., 2020), will be included. DEMs are usually generated from remotely sensed or LiDAR data, producing grid structures that define the planimetric position in which the altimetric data are stored (Polidori and El Hage, 2020). In the case of cultural heritage, DEMs can be used to monitor changes in cultural environments (Risbøl et al., 2015) or to detect historical sites (Snitker et al., 2022), and serve as a basis for different analyses in Geographic Information Systems (GIS) (Lü et al., 2019), which are applications designed to work with data referenced by spatial or geographic coordinates. GIS is a well-known tool in the fields of archaeology and cultural heritage management that can be applied, for example, to understand the spatial variations of prehistoric settlements (Li et al., 2021) or to analyse a spatial pattern in land use (Trapero Fernández, 2016), amongst many other diverse and widespread uses in archaeology (Conolly and Lake, 2006; Menéndez-Marsh et al., 2023).

For this research, the first step will be the creation of 3D models, using high-resolution scanners to generate point clouds and meshes. These 3D models will then be processed in GIS, just as a DEM, in order to analyse their surface, create transversal profiles, and study the depth and section of the carvings and incisions on the stelae, both on the originals and the replications. Once the profiles of the carved lines have been exported, they are compared and checked for correspondences and divergences and statistics on their width and depth are obtained. The shapes of the profile sections from carved lines are categorized, with the aim of being able to infer from this with which type of tool they have been made. The results from original and replicated stelae will then be compared and their similarities and possible differences will be evaluated. This aims at the identification of marks from particular tools on rock art monuments, the shape and condition of the working edge, and, in combination with other available data from materials analysis and experiments, to distinguish between work traces from lithic and metallic tools.

Eventually, the presented approach uses an exemplary selection of analysed work traces, similar to the abovementioned recent contributions (García-Arilla et al., 2021; Trefný et al., 2022; Zotkina and Kovalev, 2019). The methodology resembles the one that was employed by Jalandoni and Kottermair (2018) to detect rock art by combining photogrammetric and GIS models in some aspects, albeit with a different purpose and objective. Since this is a pioneering study in applying GIS-based surveys on 3D-models of rock art, we chose a limitation to exemplary sections for this moment, with the perspective of conducting larger scale analyses in a follow-up study.

Several sections through each motif that is present on the original and replicated stelae have been applied, wherever possible at correlating points on corresponding lines, in order to obtain a solid comparability of the profiles (datasets available at https://doi.org/10.5281/zenodo.15830491). Consequently, 42-66 section measurements per stela, depending on complexity, or 444 sections in total, were analysed to provide statistical relevance. This resulted in a representative overall picture which, in combination with findings from material analyses and archaeological experiments, provided substantial information on both the tools used and the working techniques for the engraved lines.

2.4. Data acquisition and processing

2.4.1. Digital recording equipment: 3D scanners

The scanning process was carried out with four different structured light 3D scanners, depending on the size of the stelae. For most of the scans, the Creaform Go!Scan 20 scanner was used. This is a portable structured light scanner with a nominal resolution between 0.1 and 0.5 mm and an accuracy of 0.1 mm. This scanner, which is mainly designed for small objects, measuring between 5 and 50 cm, gave good results for modelling the surfaces of most stelae except for the larger specimen named Baraçal II. For the latter (original and replica), the Peel3D scanner from the same manufacturer was used, which allows for a larger scanning area with an accuracy of 0.1 mm and a resolution of 0.5–0.7 mm. For the scanning of the replica of the Capilla VIII stela, which has been carried out by Vinzenz Rosenkranz at the Digital Humanities Center, University of Tübingen, the Artec Eva and Space Spider scanners were used, the former with an accuracy of 0.1–0.5 mm and a resolution of 0.2 mm, the latter with an accuracy of 0.05 mm and a resolution of 0.1 mm. All of the used scanners offer the possibility of applying texture, thanks to an integrated camera, but this option was deactivated as only metric information and no photographic information was needed for this study. Scanning without texture results in lighter models and faster processing.

Each scanner has specific software that controls the characteristics of the data acquisition and allows basic scan merging and cleaning operations (elimination of noise from the point cloud). The mesh generations and subsequent processing of all the 3D models to obtain the final products were carried out with the VXElements software (Creaform®). For the Capilla VIII replica, mesh generation and processing were carried out with the Artec Studio 18 Professional software. The resulting OBJ-files were then processed in an identical way.

2.4.2. Software

The Geographic Information System used is QGIS, a free and open source software application (QGIS, 2023). This GIS enables the creation, visualisation, analysis, editing, and evaluation of geospatial information. The MeshLab application was also used to change the 3D mesh format to XYZ format for integration into QGIS (Cignoni et al., 2008), which is needed to create a digital elevation model. Finally, the comparison of the carved line profiles was performed by programming a script developed in Matlab (MathWorks, 2024).

2.4.3. 3D scanning

Structured light scanners project a calibrated light pattern onto the scanned object, which is captured by the cameras integrated in the device and does not do any damage to the surface or the monument (Graciano et al., 2017). Based on the principle of optical triangulation, the cameras capture the deformation of this pattern on the scanned object and a point cloud is generated. For all scans, except for the Capilla VIII replica, adhesive reflective targets were stuck onto the surface (Fig. 2) as supporting points, which the scanner recognises and uses for self-orientation. It should be noted that these scanners work best in low light, as ambient light weakens the emitted pattern by reducing the signal-to-noise ratio. For this reason, the Baraçal II replica, which is located outside the Sabugal Museum, could not be scanned until late in the afternoon, when the light was dimmer (Fig. 2, right). The processing of the point cloud and subsequent generation of the 3D model in the VXElements software was done by cleaning the mesh, eliminating noise, correcting topological errors, and closing small holes. The 3D model of those parts from the stelae where the engravings are located was cut to size to export the point cloud, in order to align the scanned surface perpendicularly to the Z-axis, and treat it as if it were a digital elevation model.

2.4.4. Obtaining the profiles

First, the 3D model of each clipped decorated surface is being converted into a XYZ format using the Meshlab software, thereafter it is imported into QGIS as a vector layer. At this point, it must be made sure that the reference coordinate system (SCR) is a projected system. This vector layer of points (now in GeoPackage format) is then rasterised using the triangulated irregular network (TIN) interpolation method, which generates a raster layer, i.e. the DEM. The output X and Y pixel size is set to 0.1 mm.

For each 3D model, a raster layer was generated in TIFF format, on which QGIS provides tools to mark areas with a series of line profile sections to be studied, indicated with red lines in Fig. 3. In addition to the study of the sections on each stela (original and replica), the analysis included the carvings that were explicitly made for experimental tool comparisons on the back of the Capilla VIII replica (Fig. 3 h). On the latter example, the most representative zones and the best areas to apply sections had to be considered, since the traces of lithic tools were so superficial that the 3D scanners had problems in capturing them, even with 0.1 mm resolution.

Thereafter, the QGIS add-on “Profile Tools” allows the creation of profiles of raster layers or vector layers of points with an elevation field (Z coordinate). This add-on was used to graphically and numerically calculate the profiles of each line profile section, exporting the data that are stored in a spreadsheet and thereafter, to be processed process in the Matlab script.

2.4.5. Comparison of the profiles

The QGIS add-on called Profile Tools exports the numerical values of each profile into a spreadsheet, i.e. the distance X from the origin of the profile section and the height Z corresponding to each point of the profile. In order to compare the profiles between the homologous sections of the original stelae and the replicas, a script was programmed in the Matlab application. Previously, the profiles were denominated as “original” (for the archaeological stela) and “replica” and a reference was made to each analysed element of the engravings on the stelae, i.e. shield, diadem, anthropomorphic, etc. This script imports the data of each profile from the spreadsheet, which should be prepared with the data from both stelae (original and replica) and separated into several different sheets, one for each element of the engraving of the stelae.

Depending on how the ‘mode’ parameter is selected, the script can work in 3 different ways.

- Mode 1: It looks for the translation and rotation on the replica cut that minimises the distance to the original curve. If necessary, the two profiles are translated so that they have positive measurements.
- Mode 2: The profile of the replica is translated using the minimum of the two curves as the translation point.
- Mode 3: Manually select the translation point on each profile, choosing the lowest one. In addition, the points to calculate the width and height on the two profiles must be selected.

It was decided to work in mode 3, which offers the most information and versatility. In all cases, two figures are generated in PNG format, the first has been called ‘highlight’ and shows the two profiles after the operations described for mode 3, and highlighting the scale of the Z-axis for a better representation. The second figure was called ‘normal’ and shows the same figure, but with the same scale for the X- and Z-axes.

It was decided to program another script to work only with the sections on one stela, either original or replica, instead of with the comparative of both. In this case, the width and height of each of the profile sections and their corresponding highlighted and normal images are obtained for each individual stela or replica. These calculations make it possible to quantify the representativeness and to include more elements that allow for a better analysis. This set of variables, which is designed to obtain graphical and numerical results, facilitates an in-depth analysis of the stelae’s carvings, starting from their profiles.

The isolated sections without comparative superposition of the counterpart can then be used for object-based statistical analyses of line

Fig. 2. Scanning of the Fóios and Baraçal II stelae under indoor and outdoor light conditions.

depths and widths, profile shapes, and the combination of both in order to assess possible tools and carving techniques. The superimposed sections from original and replica show similarities and discrepancies between the originals and replications.

3. Materials

3.1. The rocks

The particular selection of stelae for the following analyses has a focus on the hardest and at the same time the most frequently used rock types for the monuments, which resulted to be granite-aplite (Baraçal II, Fig. 4), silicate quartz-arenite (Capilla I, Fig. 5 and Capilla VIII, Fig. 6), and meta-arkoses, which had formerly been incorrectly referred to as "greywacke" or "schist" (Fóios, Fig. 7).

Silicate quartz-arenites/quartzite (cf. Howard, 2005) are amongst the hardest rocks that can be used for sculpture, granitoid rocks are mostly very hard, and meta-arkoses is also considered a hard rock.[2] With respect to granitoids, all results from the experiment apply to granite-aplite and fine-grained granitoids with similar quartz (around 30–35 %) and feldspar (around 50 %) contents.

Concerning the problem of possible physical and/or chemical weathering, it can be stated that the chosen sample of stelae are exceptionally well preserved. Baraçal II shows a nanometric oxidation patina from humic solutions. A fine cover of isolated black to grey lichen is found mainly on the uncarved face, while the polished and decorated part is without vegetal cover. A very fine limonite dust can be observed between iron minerals and silicate minerals in the thin section, and plagioclase (the mineral most susceptible to weathering in this rock) is unaltered (see Ferreiro Mählmann et al., 2025). On the surface, grains are not abrasive, contrary to the lower part of the stela that was probably buried. The damage inflicted on the right half of the stela does not affect the original line depth or widths.

On the carved surface of the quartz-arenite from Capilla I, the syn-sedimentary to diagenetic intensive silicate cemented hard ground preserves its typical surface microstructures of upside flattened rounded grains and appears unweathered. Only at the right side of the hip from the anthropomorphic figure, and more prominent to the right and below its feet, a lenticular and leaved millimetric splintering of the top of the hard ground has damaged the surface. The same state can be observed on the upper face of the silicate quartz-arenite from Capilla VII. The original syn-sedimentary structure of fine ripple marks is well preserved. On the right side of the stela and below the spearhead, the most intensively silicate-cemented top is splintered.

The same situation as found on the Capilla I surface can be ascertained for the Fóios stela. The top, right side and bottom of the stelae are delimitated by natural vein cuts and borders. The left top and bottom salient angle are broken along a stratification joint. In summary, all stelae that were selected for this study can be determined as not affected by meteoric, eolian, or physical degradation. The stelae of Fóios and Baraçal II both have acquired a slight patina over the centuries, including sprinkles of modern paint.

3.2. The stelae and their replications

3.2.1. Baraçal II (Fig. 4)

The stela from Baraçal II is comparatively tall, measuring 190 x 64 × 24 cm (height x width x depth each value is the maximum due to irregular shapes), and has been found in the village of Baraçal in the Portuguese Beira Interior (Santos et al., 2011), where it was used as a bench in a courtyard. The design shows a so-called basic motif composition of a central v-notched shield, a sword and a spear pointing in opposite directions, with a mirror and a helmet (only partly preserved). In a later phase of its existence, the upper right part of the design has been heavily damaged with a pickaxe or steel chisel. The surfaces of the original, and accordingly of the replica, have been polished. This kind of preparation had been applied to all 28 granitoid stelae that have so far been examined within this project, without any exception (Araque Gonzalez et al., 2025; Ferreiro Mählmann et al., 2025).

The monument was made from a light coloured (leucocratic) muscovite-syenogranite aplite. The mineral composition of this monument is 32 % quartz, 43–58 % feldspar, 10–22 % muscovite. Its technical properties made it ideal for engraving because the fine-grained, isotropic structure with non-porphyry feldspar as well as the high mica content favoured the carving of straight lines. The rock used for the experimental stela is from the identical lithotype and the same outcrop. The dimensions of the experimental stela were 190 x 58 × 37 cm (max.), as comparable to the original.

3.2.2. Capilla I "La Moraleja" (Fig. 5)

The irregularly shaped stela measures 83 x 54 × 18 cm (max.), and it was found during agricultural works, being the first of a large and growing number of monuments to be discovered in the municipality of Capilla, Prov. Badajoz (Enríquez and Celestino, 1982). The precise, well-defined carvings show an anthropomorphic figure with a broad-brimmed hat and jewellery, including a necklace, earrings and a prominent semi-circular object above the figure (often referred to as "diadem"). Under the left hand of the figure, there is a plain rectangular motif that might as well be a modified (or erased) comb or instrument. This stela is made from extremely hard silicate quartz-arenite with a mono-mineral composition (>95 % quartz) and diagenetic transformation (Araque Gonzalez et al., 2023). The outcrops in the name-giving Sierra de la Moraleja, rising above the Zújar river near Capilla, provided a slab with a corresponding lithology for the replication. However, the motives had to be downscaled to 75 % due to a smaller slab size.

[2] https://geologyscience.com/rocks/sedimentary-rocks/non-clastic-sedimentary-rock/arkose/.

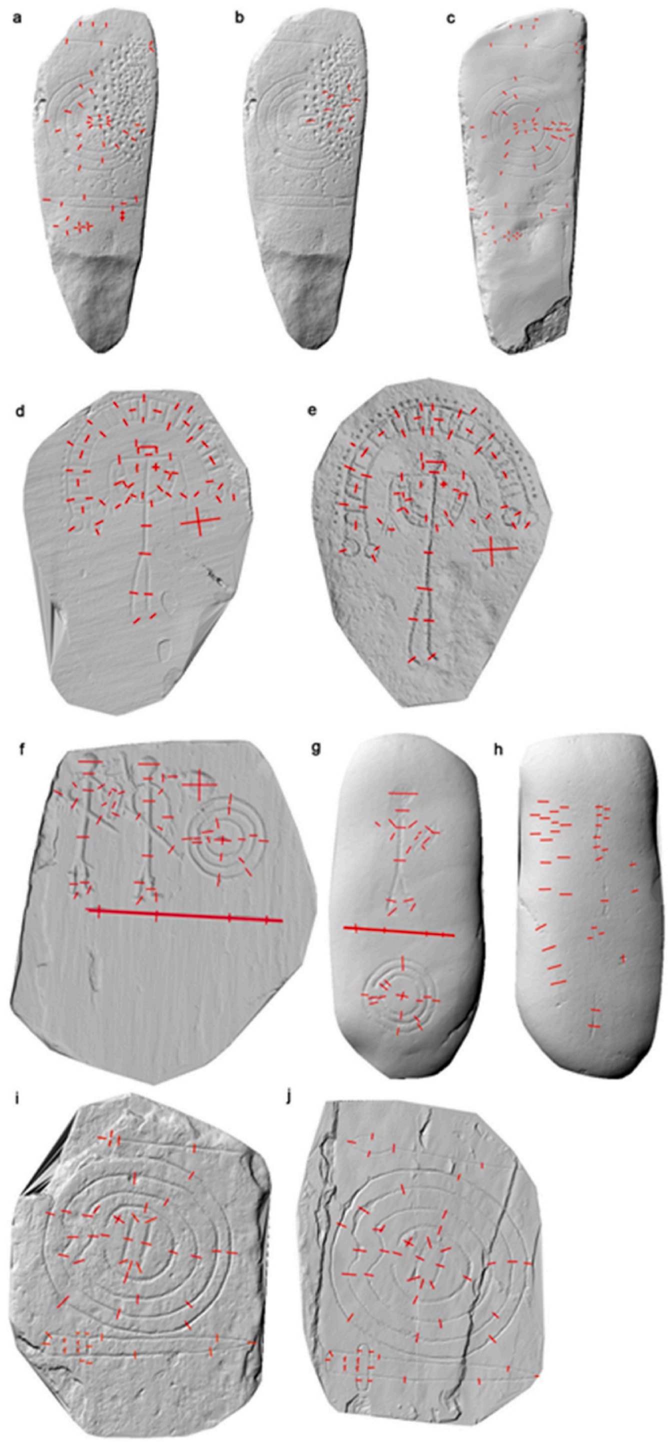

Fig. 3. Raster layer obtained from the 3D models of the original stelae and their replicas, with the applied profile sections on the carvings indicated in red. a) Baraçal original b) Baraçal original pecks c) Baraçal replica d) Capilla I original e) Capilla I replica f) Capilla VIII original g) Capilla VIII replica h) Capilla VIII replica back i) Fóios original j) Fóios replica (María-Eugenia Polo and Pablo Paniego). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.). All models are accessible at https://sketchfab.com/secad/collections/iberian-stelae-5224127c1c7141cda3c56ee6eadf7a33

Fig. 4. Baraçal II, left: original (Photo: Ángel M. Felicísimo, KRAKEN research group); right: replica (Photo: David Ferro).

3.2.3. Capilla VIII "La Pimienta" (Fig. 6)

This almost pentagonal stela with irregular sides, measuring 75 x 64 × 15 cm (max.), was an accidental find near the discovery spot of Capilla I. It shows two anthropomorphic figures with belted swords and possibly wearing boots or greaves. In addition, a bow and arrow as well as an unidentified triangular object, possibly a quiver, are engraved beside one of them, while next to the other there is a rectangular object with three attached dots, which might represent a mirror (see Baraçal II; Harrison, 2004, p. 152–154). The scene is completed by a prominent v-notched shield and spear. It was made from the same lithotype as Capilla I, so everything that has been said there applies. However, the lines are significantly wider and deeper than on Capilla I. The replication was only partial and limited to a few motifs (spear, shield, and one anthropomorphic figure) that were carved free-handed and unscaled into a river-rounded slab of silicate quartz-arenite with the same lithology. On the back of the replica, several tools have been tried to create comparative carvings.

3.2.4. Fóios (Fig. 7)

This stela shows a so-called basic motif composition of sword, spear and v-notched shield and measures 93 x 66 × 9 cm (max.). It has been found by a farmer in the Fóios village (Curado, 1986; Osório, 2005), and the rock could be traced to the outcrops of the nearby Côa river ford at Cabeço do Pisão, which is characterized by a formation of (meta-)sedimentary rocks along a stretch of 4 km (Ferreiro Mählmann et al., 2025). The slab of the stela is a meta-(sub-)arkoses with a hard ground surface that provides ideal conditions for the carving of motives without any need for surface preparation. The carvings are deep and well defined. For the experimental replication, a slab of corresponding lithology, measuring 83 x 73 × 8 cm (max.), was obtained from Cabeço do Pisão. The hardness of this rock is based on its 48 % quartz and 21 % feldspar

Fig. 5. Capilla I “La Moraleja”, left: original (Photo: Ángel M. Felicísimo, KRAKEN research group); right: replica (Photo: Ralph Araque Gonzalez). The square in the replica has been interpreted as a comb or instrument, in the picture before erasure by over-pecking.

Fig. 6. Capilla VIII “La Pimienta”, left: original (Photo: Ángel M. Felicísimo, KRAKEN research group); right: replica a) front, free-hand design (Photo: Ralph Araque Gonzalez) and b) back, trials of tools (Photo: Paula Rahmelow/Jasmin Rolke).

composition, embedded within a low-cohesive sheet silicate matrix (32 %). Technically, this composition facilitates the regrinding of lines into the matrix, once the hard and compact surface is broken.

3.3. Tools and their handling

The three fundamental groups of available materials for tools, based on archaeological finds from the FBA-EIA in Iberia, were copper-tin alloys (bronze), diverse stones (lithics), and iron-carbon alloys (steel). Amongst the lithic tools that can be used for rock carving are choppers, chisels, and axes or adzes. The selected lithotypes had to be available in areas with stelae and must not be too brittle, which would cause them to break under strain. Actinolite skarn (Fig. 8.1), which was frequently used for polished axes since the Neolithic and has a good shear strength, turned out to be a useful material. Quartzite (Fig. 8.2) was amongst the best lithic tools tried in this study and has already been used successfully in other rock art experiments on generically determined soft rocks such as sandstone, schist and greywacke (Breunig and Fels, 2023; Santos da Rosa et al., 2014; Vourc’h 2011).

Chisels were already made from metal since the Chalcolithic and can

Fig. 7. Fóios, left: original (Photo: Ángel M. Felicísimo, KRAKEN research group); right: replica (Photo: Pepe Vintrici).

be described as elongated, wedge-shaped, sharp-edged or pointed cutting tools that usually consist of a shaft, which is left in a soft state in order to absorb the shock of blows, and a sharp blade (defined as flat part with a very thin edge for cutting[3]) that is resistant and retains its cutting edge. Binary bronzes with high tin alloys were a hallmark of Iberian FBA metallurgy and chisels have been replicated after the massive model from the Freixianda hoard (Portugal) with copper and 10, 12, 14, and 16 % tin alloys. Analyses of Iberian FBA-EIA bronze chisels (see Bottaini, 2012) revealed that they had been hardened with heat treatments and cold-hammering, hence the corresponding procedures were performed on the replications by archaeometallurgist Bastian Asmus (Fig. 8.3); their hardness was measured with HV0.5 at 225, 316, 324 and 285.

Finally, recent analyses of an iron-carbon alloy chisel from Rocha do Vigio (Alentejo, Portugal) in the Guadiana valley, from a stratigraphic context that was C14-dated to 900-770 cal. BC, has revealed that hardenable steel was locally available from this period onwards. Chisels with a similar mechanical performance were made from modern C60 steel (0.57–0.62 wt% C), and hardened with quenching and tempering by professional blacksmith Alexander Richter (Figs. 8.4–5; Araque Gonzalez et al., 2023); their hardness was measured with HV0.5 between 736 and 831. All metallic tools were cold-ground for sharpening to avoid affecting the hardness of the metals.

It must be mentioned that up until now, no metallic chisels with pointed edges have been found from FBA-EIA Iberia. The latter would have been used for pecking with indirect blows, as opposed to continuous line carving, and create characteristic traces, which have been well-documented in plan within the study of petroglyphs in Siberian rock art (Devlet, 2012; Zotkina and Davydov, 2022).

Tool utilization can primarily be subdivided into indirect and direct percussion. Indirect blows are given with a chisel and hammer (-stone) or mallet. Direct percussion refers to hitting the rock surface with a handheld tool and this is usually less precise, has lower force, and is strenuous for the wrist of the artisan. Direct blows can also be applied with a shafted tool, such as a hammer or axe, which is even less precise but has more force, and is comparatively gentle on the joints.

The artisanal methods of carving ornamentation in stone are, firstly, chiselling with sharp or pointed tools and indirect blows, secondly, direct percussion with pointed or sharp tools, thirdly, hammering with shafted tools, fourthly, incisions with sharp objects and fifthly, grinding or regrinding lines. All analysed lines on the original stelae are consistent with these techniques as they have been applied and compared to the replicas. Two out of four stelae (Capilla I and VIII) show clear traces of indirect blows with a chisel, Baraçal II has a polished surface and traces from either direct or indirect blows with a sharp tool, and Fóios shows traces of possibly all abovementioned techniques.

The greatest problem for artisans who work with hard rocks, including modern stonemasons, is the blunting of tools and the constant need to re-sharpen them if the depth and visual qualities of the engravings shall be maintained. Therefore, the most important requirements for a tool are first, the durability and resistance of the material to maintain its sharpness as long as possible, even under heavy stress when working from different angles and with different intensities. Second, it must be possible to re-sharpen the tool without disproportional effort. As a matter of fact, metal chisels are easily re-sharpened, while it is often strenuous and time-consuming to get lithic tools back in shape.

Diverse tool materials react differently upon various rock types. For the purpose of this study and based on experiments, we have categorized the tools according to their blunting rate in combination with the rocks from our sample (Table 1). The blunting rate determines not only whether a rock can actually be carved, but will also be reflected in the tool-mark profiles (see below).

4. Observations and analysis: work traces and carving techniques

4.1. Typology of the profile sections from sharp tool use

In the following, the typology of the observed profile sections from carved lines on the sample of four Iberian stelae and their replicas will be presented (Fig. 9). These profile sections allow for a good understanding of the applied techniques and provide evidence on the shape of the blade as well as its degree of sharpness, and sometimes on blunting processes, however not directly on the material of the tool. This makes it all the more important to combine the analysis of the profile sections with the petrology of the rock and the eligible tool materials in order to draw

[3] https://dictionary.cambridge.org/de/worterbuch/englisch/blade.

Table 1
Tool materials and their blunting rates. Immediate blunting = blunts without breaking the rock surface. Rapid blunting <5 min until re-sharpening; slow blunting <10 min until re-sharpening; resilient: >10 min until re-sharpening. Immediate breakage: blade or tool breaks or splinters without breaking the rock surface. Frequent breakage = blade or tool breaks after <10–15 min working time. * = Not used in the original experiment, estimates based on preliminary trials in workshop.

Blunting rates used on:	Granite-aplite	Meta-Arkose	Silicate-quartz arenite/quartzite
Actinolite skarn	Rapid blunting, frequent breakage	Slow blunting	Immediate breakage*
Quartzite (metamorphic)	Rapid blunting	Resistant	Rapid blunting
Bronze (binary, 14–16 % tin)	Immediate blunting	Immediate blunting	Immediate blunting and breakage
Steel C60 (hardened)	Slow blunting*	Resistant*	Rapid blunting

reliable conclusions on the actual tools that might have been used.

The profile sections of all analysed original and replica stelae are provided graphically and numerically in the datasets (available at https://doi.org/10.5281/zenodo.15830491) to scrutinize the categorizations, which are naturally based on *su visu* evaluation. This was performed independently by four of the authors for all stelae and sections without having known about each other. Subsequently, the definitions were further refined and elaborated in a second and third round until there was an unanimity of >90 % in the third evaluation.

It is important to address some fundamental issues: firstly, the lines on most stelae often have depths below a millimetre, especially on those made from very hard rocks. Accordingly, the scale which is indicated on each profile must be carefully considered, because this shows how much penetration by a tool is sufficient to create a visual effect on each rock type, and hints on how much effort was spent to engrave the motifs. Secondly, in the vast majority of cases, it is not practicable to juxtapose the blades of tools (Fig. 8) with the traces in the rock surface, because the overall average depth of the lines is 1 mm, over which length the shapes of blades from the used tools do not vary significantly. Thirdly, the individual imprints of tools within continuously drawn lines can often not be singled out and identified from the top view because they are chiselled with numerous blows from different angles. Therefore, this approach is especially designed to evaluate continuous line carvings (Fig. 10). Exceptions to this are the peckings on Fóios and impressions from a modern tool on Baraçal II (Figs. 11 and 12), as well as some of the experimental lines on the back of the Capilla VIII replica.

Most importantly, in the distinctive context of the Iberian stelae, all carving methods aim at the visual effects that create a line and design by either simply revealing the colour differences between a darker, for example hard-ground surface and the often lighter fresh rock, or, in polished monochrome rocks (mostly granitoids), through cast-shadow and differences in surface structure. The different line profile shapes can aim at particular optical effects and accents, beyond simply being the result of the use of a particular tool and a degree of sharpness.

4.1.1. V (Type 1, Fig. 9 a, b, c)

Definition: A V-shape is defined as a "curve or a graph that shows a sharp fall followed by a correspondingly sharp rise.[4]" The bottom can be almost pointed or, more often, *narrow and convex*. The main defining feature is that the cut displays a sharp angle, however it does not have to be perfectly symmetric or homogeneous in shape. The aim of the stonemason is to create a narrow, precise line with well-defined edges. The V-shaped profile provides an optical cast-shadow-effect and is amongst the modern stonemason's "ideal line profiles" for inscriptions and ornaments.

Practical genesis: When using sharp tools, this line profile is created by vigorous and at the same time precise, hence usually indirect, blows from the side angles with the edges of a sharp chisel. Ideally, no ridge is left in the middle and straight sides are created. An experienced artisan could create such lines in softer rock types with direct blows from a robust, sharp tool, and with a caveat, in granites. Pronounced V-profiles in rocks with a low-cohesive matrix embedding can also be created by regrinding the line with a sharp tool to emphasize the V-furrow of a previously carved line.

Implications and interpretation: Primarily, V-shaped profiles in hard rocks indicate the use of sharp tools with blades and the consequent maintenance of their cutting edge. Pointed and blunt tools must be excluded. V-profiles in rocks with a low-cohesive matrix embedding can be indicative of re-grinding the line, especially when grinding marks, or streaks, are visible (see 5.3).

4.1.2. U (Type 2, Fig. 9 d, e, f)

Definition: The U-shape is defined as a curve with steep parallel edges, preferably almost vertical, and a convex bottom. Slight inclinations towards a sharp angle are acceptable and might constitute interpretative dilemmas with V-shaped profiles (cf. Fig. 9 f), however the *broad and convex* base is indicative for this profile definition. The ratio of the bottom to the sides is ideally below or around 1:3. The aim of the stonemason is to create a broad line with well-defined edges. The cast-shadow-effect applies increasingly with depth, which is best visible on the original Capilla VIII (Fig. 6).

Practical genesis: U-shaped profiles require multiple vigorous and precise blows from the side angles to define the outline and amplify the cut. The carving-out and deepening of the lines requires accuracy and meticulous working with a sharp chisel and indirect blows using the edges of the blade. The U-profile line is usually executed in a broad and deep manner, aiming at clarity and providing an eye-catching effect.

Implications and interpretation: U-shaped profiles in hard rocks indicate the use of sharp tools with blades and the consequent maintenance of their cutting edge. Pointed and blunt tools must be excluded.

4.1.3. Vv (Type 3, Fig. 9 g, h, i)

Definition: This type is a V-shaped profile that either displays a smaller v- or u-shaped gradation on one of the sides, or shows a sharp, V-shaped depression within a broader tool mark. The defining criterion is that the deeper and the lesser trace are both within the limiting edges of the line width, thereby excluding accidental blows that landed outside the intended line limits.

Practical genesis: This line profile is created by vigorous and precise, usually indirect blows from the side angles with the edges of a sharp chisel (see V-profile). The Vv-shaped profile can be the result of the blunting of the chisel during the workflow, causing a lesser penetration of the rock in one or more blows before re-sharpening. In granitoid rocks, which naturally incorporate coarser minerals of varying hardness, it can also be indicative for hitting a harder mineral on one side of the cut, while having a softer spot and deeper penetration on the other side. Therefore, the rock type has to be considered to evaluate the possible genesis of this profile. Finally, a combination of both causes (blunting and hitting a harder mineral) is possible.

Implications and interpretation: Vv-shaped lines indicate the use of sharp tools with blades and the consequent maintenance of their cutting edge. Pointed and blunt tools must be excluded. The Vv-profile can indicate that during the carving, one of the sides was not cut as deep as the other side. This is either due to a slight blunting of the tool, or to an irregularity in impact of the blows, both requiring the artisan to perform additional blows from the same angle. It can hence indicate a point in the work flow when the blade began to blunt and re-sharpening would need to be considered, or when the stonemason was concentrated on the precision in the line management and varied the intensity of blows. On granitoids or coarse grained rocks, it might represent the outbreak of a

[4] https://www.collinsdictionary.com/de/worterbuch/englisch/v-shaped.

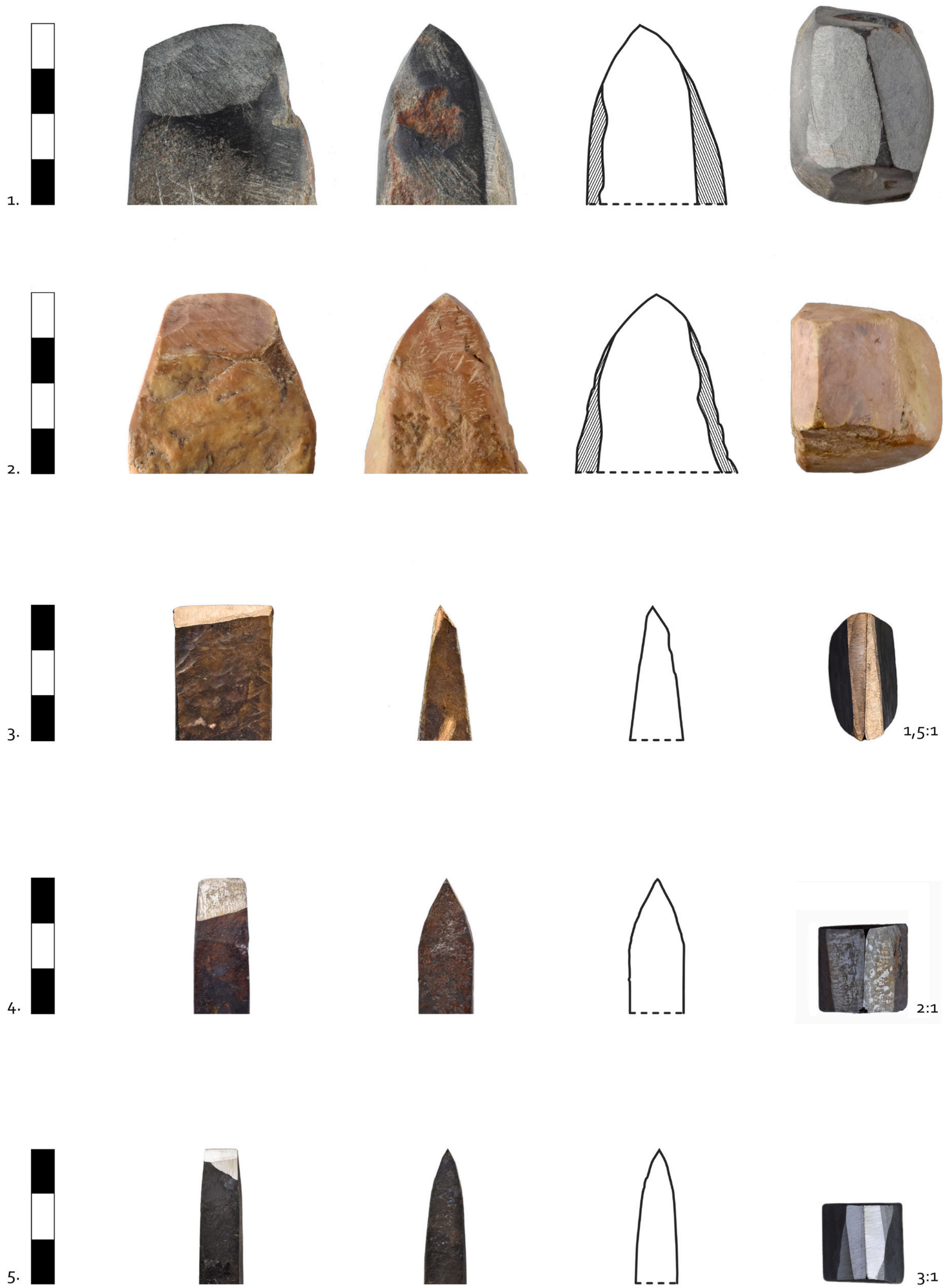

Fig. 8. Working edges and blades of the tools used in the experiment (front, side, profile drawing, top view), all sharpened before carving: 1. Actinolite skarn. 2. Quartzite. 3. Bronze (exemplary 14 %). 4–5. Steel (C60). Scale 1:1 unless otherwise indicated (photography and illustration: Vera Rammelkammer and Paula Rahmelow).

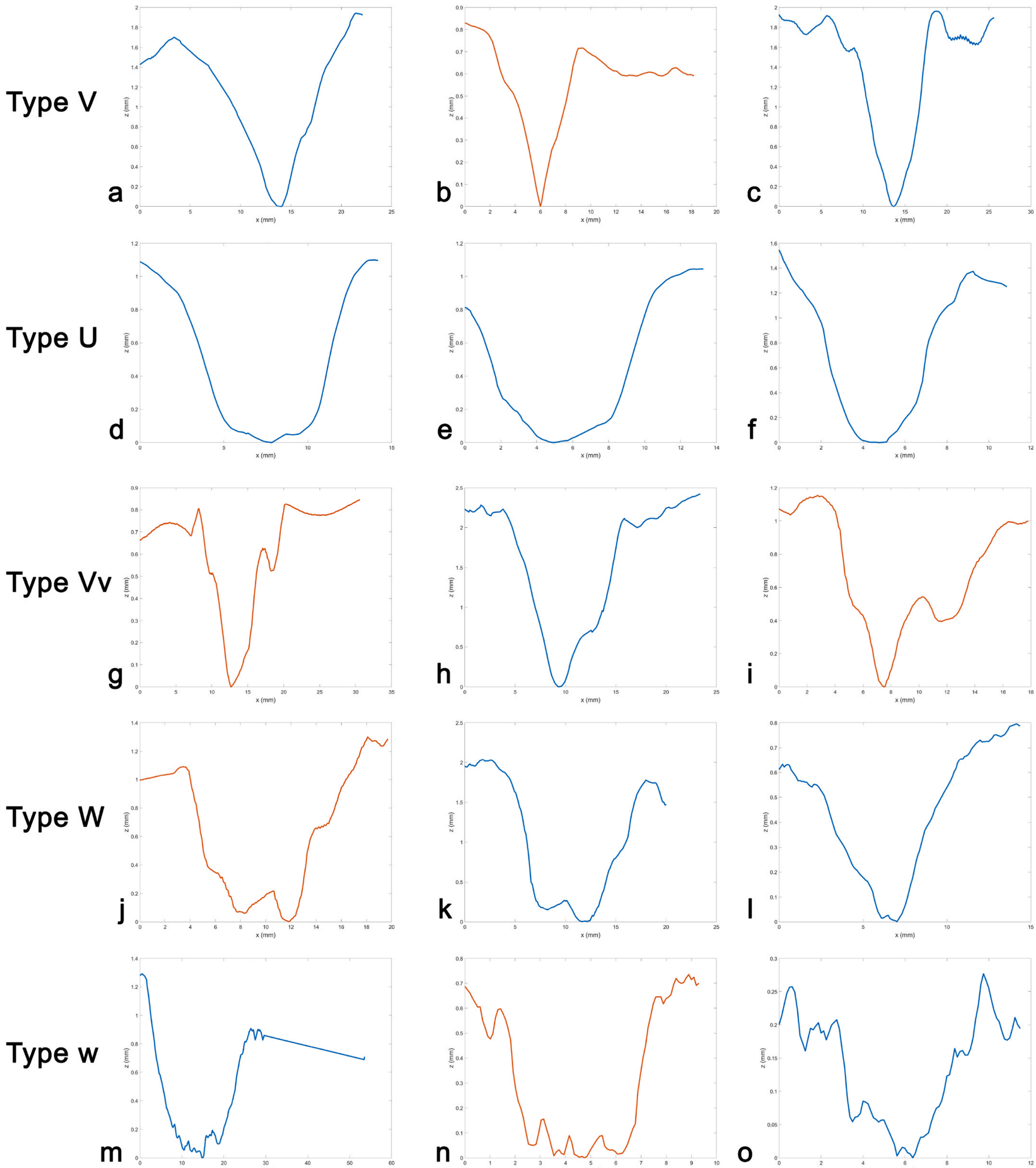

Fig. 9. Exemplary sections representing the determined types of line profiles created with sharp tools; blue lines refer to original stelae, orange lines to replicas and all images refer to highlighted profile sections. The numbering corresponds to the order of the cuts in each element of each stela in the datasets available at https://doi.org/10.5281/zenodo.15830491, e.g. name_original/replica_motif_1, etc. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.) **Type V**: a) Baraçal II, shield 2-3. b) Fóios replica, shield 3-6. c) Fóios, shield 4-4. **Type U**: d) Capilla VIII, shield 2-2. e) Capilla VIII, shield 3-1. f) Fóios, Sword-14. **Type Vv**: g) Baraçal II replica, shield 3-5. h) Fóios, shield 1-1. i) Fóios replica, shield 4-2. **Type W**: j) Baraçal II replica, shield 5-2. k) Fóios, dots 1. l) Capilla I diadem 20. **Type w**: m) Capilla I, anthropomorphic 14. n) Capilla I replica, diadem 20. o) Capilla I, necklace 3 (Illustration: María-Eugenia Polo and Pablo Paniego).

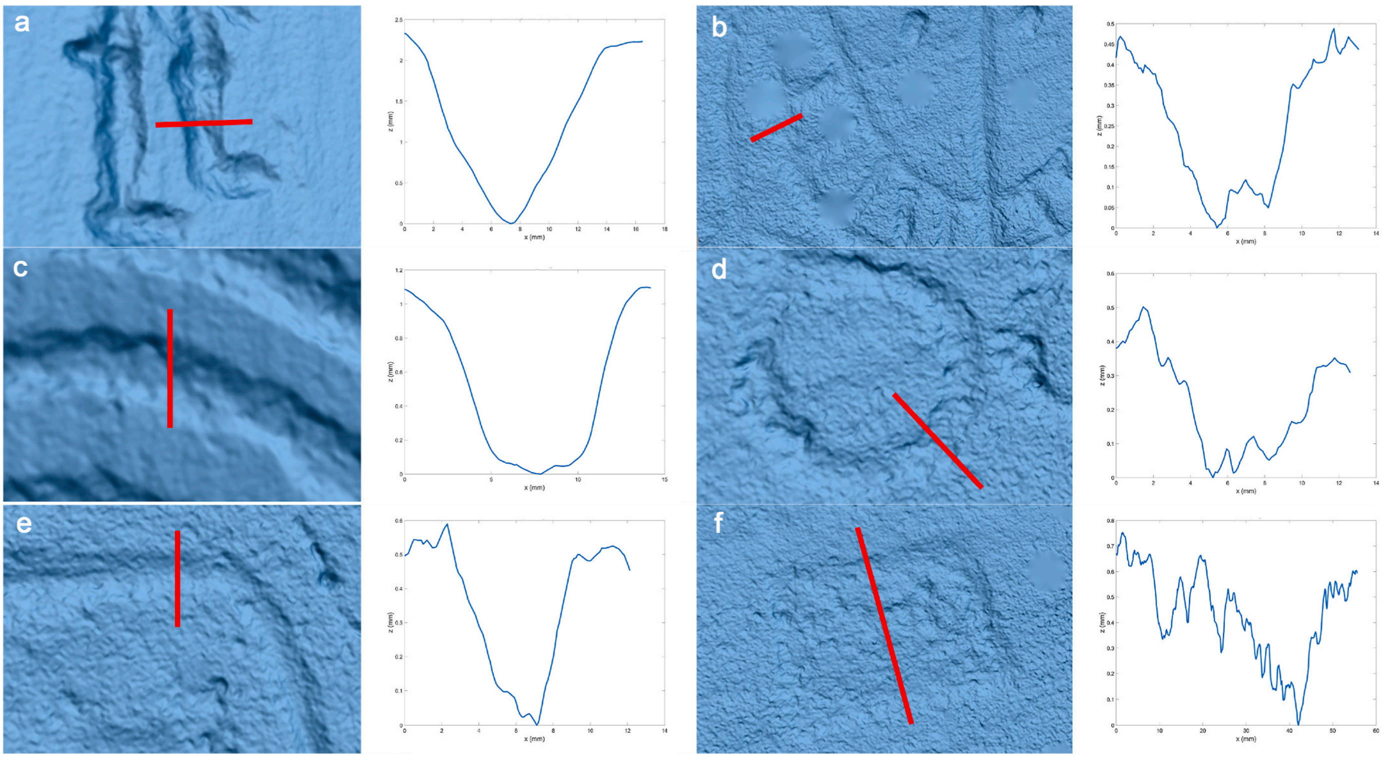

Fig. 10. Macro-images of line segments on original silicate quartz-arenite stelae Capilla I and VIII. a) V-Profile: Capilla VIII anthropomorphic 1–4. b) W-Profile: Capilla I necklace 1 c) U-Profile: Capilla VIII shield 2-2 d) w-Profile Capilla I Diadem 31. e) Vv- Profile: Capilla I anthropomorphic 13. f) areal pecking: Capilla I Square 1 (María-Eugenia Polo and Pablo Paniego).

larger grain (often rather u-than v-shaped) that results in a gradation and unequal depth of the section.

4.1.4. W (Type 4, Fig. 9 j, k, l)

Definition: This shape – a generous interpretation of the letter "W" – can include one or several ridges between steep sides, hence its bottom and the lower parts of the sides can be irregular. Nonetheless, this type of profile is defined by its significant depth, which shows the intention to create a deep and broad line with well-defined edges for visual effects that correspond to V- and U- shaped profiles alike. W-shaped profiles might be regarded as a hybrid between V-shape and U-shape, since they are mostly wider than ideal V-profile lines and can have almost parallel, vertical sides, although their bottom does not reflect the convexity of U-profile lines.

Practical genesis: W-profile lines require multiple vigorous and precise blows from the side angles to define the outline and amplify the cut. Everything said for V- and U-shape applies. However, the W-shape might be the result of minor imprecisions due to several strokes from the side-angles, resulting in one or more ridges on the bottom of the line. The blows could be indirect or direct, depending on the tools and techniques applied in the carving.

Implications and interpretation: W-shaped lines in hard rocks indicate the use of sharp tools with blades and the consequent maintenance of their cutting edge. Pointed and blunt tools must be excluded. The ridges and irregularities might represent moments of hitting again with a blunting edge before sharpening. In addition, the ridges show that no careful re-touching and particularly no re-grinding of the line has taken place. However, this is clearly about nuances that might not be easily detectable without magnifying technologies. Finally, several "W"s, possibly in combination with "Vv"s, indicate that no re-grinding has been applied to a line segment.

4.1.5. w (type 5, Fig. 9 m, n, o)

Definition: This type of section profile corresponds to often shallow lines with well-defined edges and pronounced sides, however they can be steep or shallow, and mostly the width of the cut exceeds its height. The bottom of these lines appears "wavy" or irregular and often reflects the impacts of numerous smaller blows. The aim is to break the surface and create a visual effect through a colour contrast or, in the case of polished-surface granitoid rocks, through the change in texture, with no intention to create greater depth or additional visual effects. On the replica stelae, this was the only profile from lines carved with a hardened steel chisels that is usually wider than deep.

Practical genesis: The w-profile corresponds to often slightly more than superficial indirect or direct blows with moderate to low impact from a sharp tool. Nevertheless, while the interior can be carved with a rather blunt edge, it initially still requires a good sharpness of tools to create well-defined edges of the lines, and thereby differs considerably from "flat" or pecked profiles (see below).

Implications and interpretation: w-shaped lines in hard rocks indicate the use of sharp tools with blades. This technique is mainly used for smaller details and features, it does not require hard blows, and can therefore be executed with already blunting chisel blades or in order to avoid rapid blunting. It could be considered a tool-conservative method and requires precision by the stonemason if it is applied to small details, where careful small blows deliver the desired result. Finally, w-shaped profiles contradict subsequent re-touching or grinding of the lines, not only for their very irregular bottoms but also because of their shallowness.

4.1.6. Areal carving: levelling of surfaces (type 6, Fig. 10 f)

Definition and practical genesis: In some occasions, a surface area has been carved to create a visual "filling effect" of a motive (for example, the rectangle on Capilla I, Figs. 5 and 10 f). In the case of the replicas and the studied originals, a number of indirect blows with a sharp or blunting chisel with varying intensity from various angles and with several overhauls were applied to this area, leaving a very irregular surface profile, usually with overall low depth including greater ranges

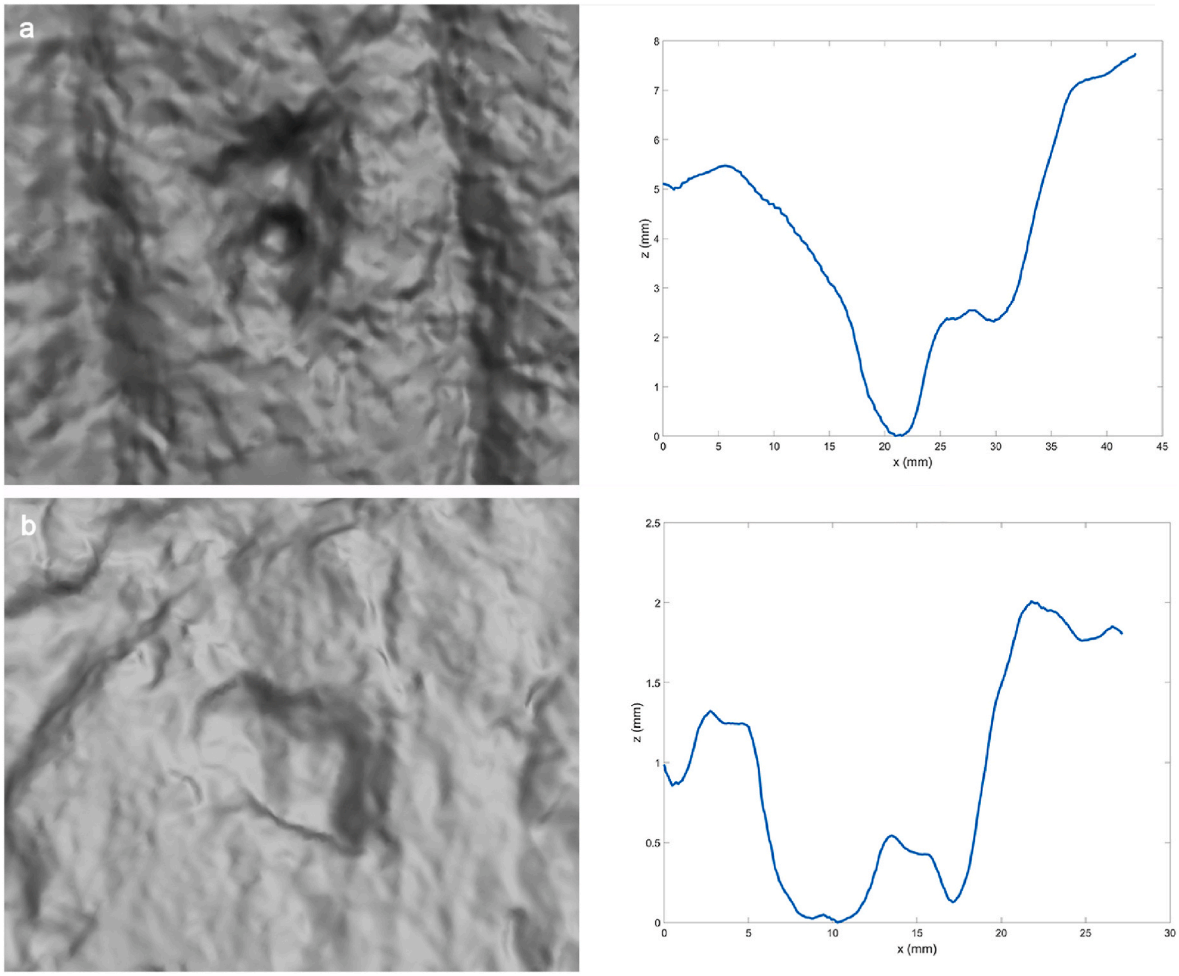

Fig. 11. Profile sections and view in plan of a) a single impact from a pointed steel tool ("piquetazo") on Baraçal II (Peck 7, in the datasets) and b) an isolated tool mark on Fóios (dot 3, in the datasets available at https://doi.org/10.5281/zenodo.15830491) (María-Eugenia Polo and Pablo Paniego).

from one strike to the next. Individual tool marks cannot be singled out due to the density of traces.

Implications and interpretation: This type of section profile is dissimilar from the well-defined line profiles; however, the edges are usually defined by precise outlines, which were created with indirect blows while the tool was sharp. A high degree of irregularity on the bottom of the section contradicts any attempt of regrinding. Importantly, the aspect of an areal carving with a chisel clearly differs in appearance from a pecked area with flat superficial strokes (see below, flat profile/Type 7).

4.2. Direct percussion and pecking

Pecking refers to the making of punctual marks in order to produce a figure or motif through their spatial proximity, without necessarily forming a coherent line. Pecking is often done with direct as well as indirect blows from pointed, sharp, or pointed-blunt tools that can be made from a variety of materials, depending on the rock that is carved, and occasionally, pecking might be done with shafted tools. The individual percussion dents from this technique are often easy to recognize, even when they form a line, and an analysis from the top view is particularly useful, as the contours of the tip of the tool can be captured and assigned to a particular shape (Fig. 12e; cf. Zotkina and Kovalev, 2019).

However, despite its prominence in other rock art traditions, the use of pecking can be regarded as an exception on those western Iberian stelae that are made from very hard rocks. Within the sample discussed in this study, only the original stela from Fóios has traces from classical pecking (Fig. 12 a).

Overall, only a small number of silicate quartz-arenite/quartzite stelae with a hardground surface display this technique as an intentional way to create motifs, for example the monuments from Zarza Capilla I and II (Fig. 12b and c; Celestino Pérez, 2001, p. 380–382). On the other hand, pecking was occasionally used to "erase" motifs by destroying the original lines, for example on Zarza Capilla I (Fig. 12 d) or for later additions, as in Esparagosa de Lares II "La Barca" (Fig. 12 e; Celestino Pérez, 2001, p. 381; Domínguez de la Concha et al., 2005, p. 41).

4.2.1. Flat profile (type 7, Fig. 12 a)

Definition and practical genesis: The "flat" profile is defined by an almost non-detectable (even with 3D-scanning resolutions of 0.1 mm), very shallow, very wavy-irregular section (Fig. 12 a; see datasets "Capilla VIII back replica, cuts 1-18, available at https://zenodo.org/records/15830492). It is mostly created with direct percussion from a sharp or blunt, often lithic tool on hard to very hard rocks to break the below-millimetre thin surface of in order to reveal a colour contrast between an often darker top layer and lighter fresh rock below it. The ornaments are usually ill-defined and have frayed edges in plan (see Fig. 12a–d). As a standard, the resulting profiles are considerably much wider than deep.

Implications and interpretation: The flat profile is the result of the least crafty way to carve a motif into a very hard rock that could be observed on the Iberian stelae. This highly characteristic profile is indicative for

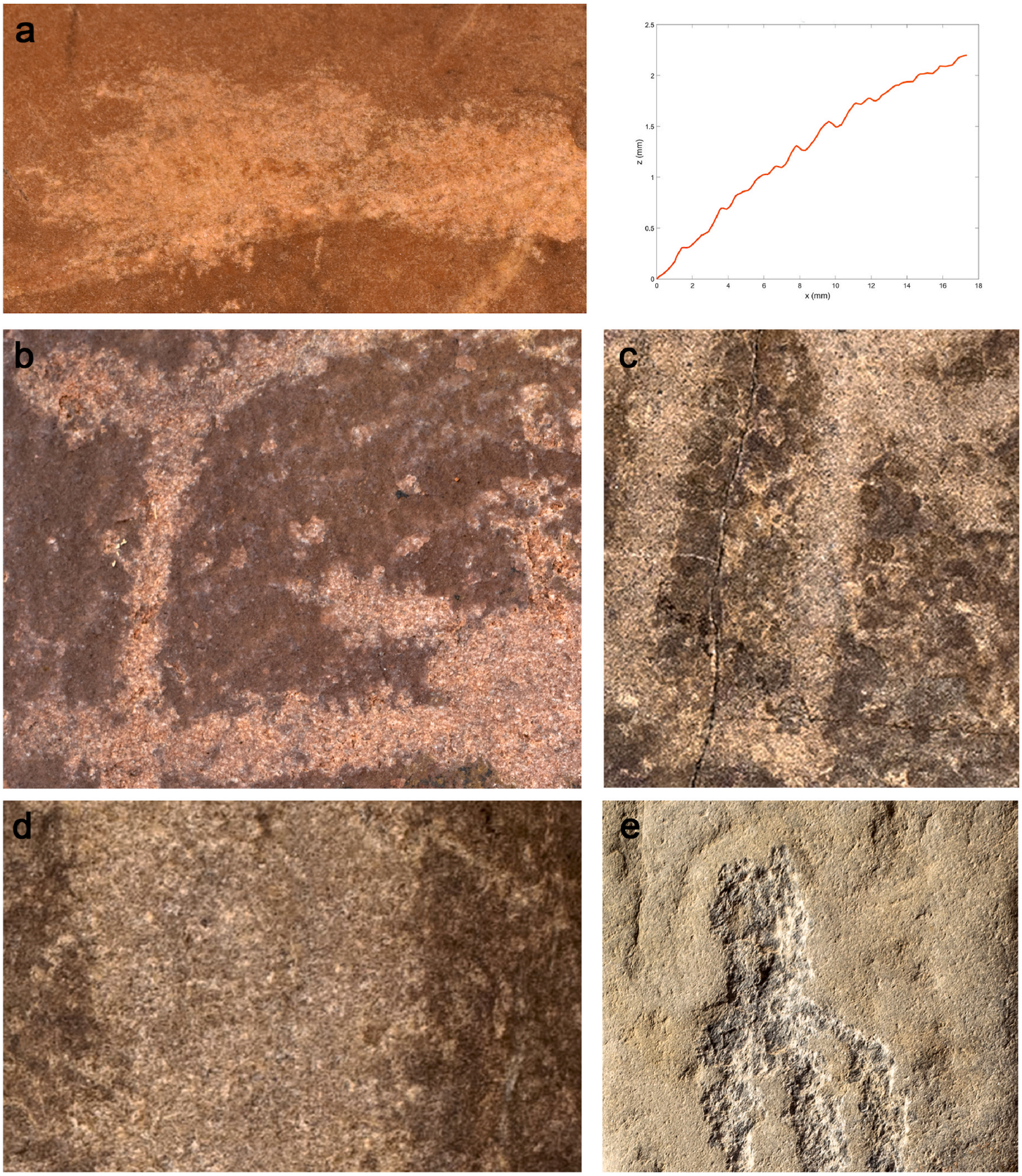

Fig. 12. a) Macro-photograph of the experimental replica Capilla VIII (silicate quartz-arenite) with superficial carving from a quartzite chopper (photo a: Paula Ramelow) and its corresponding flat profile b) Detail of the carving of the anthropomorphic and the diadem in Zarza-Capilla II c) Detail of the carving of the anthropomorphic in Zarza-Capilla I. d) Detail of the erased bow in Zarza-Capilla I. e) Detail of the pecked anthropomorphic in Esparragosa de Lares II (photos b, c, d, e: Ángel M. Felicísimo, KRAKEN group).

low tech pecking with lithic tools, imprecise because the strikes are direct, shallow and ill-defined because the tool is rapidly blunting and the rock surface resistance is great. It only rarely appears on the analysed original stelae or the replications, and in these few cases it is most likely – or, as known to the authors concerning the replication, definitely – indicative of a blow with a blunt steel chisel on silicate quartz-arenite/quartzite, or representing a carving failure by the artisan.

4.3. Working without blows: grinding, (re-)grinding of lines, and incisions

Grinding aims at the smoothing of a surface and can also be applied to previously worked areas or carvings, and incision refers to cutting the surface in order to create (incise) a line. Grinding, in the sense of polishing, can be applied to surfaces by using an abrasive agent (for example quartz sand or emery), a lubricant (water), and a grinding tool (grindstone). This technique is well-suited for granitoid and most fine-to-medium grained rocks and has been used worldwide at least as early as the Paleolithic, because it is a practical and simple, however time-consuming method of stone-working (Santos, 2019, p. 62). Polishing is, for example, essential for bas- or high-relief rock art. Surface polishing leaves characteristic streaks and various grinding marks that can be detected meso- or microscopically (down-polished crystals). On the other hand, while granitoid rocks are well-suited for surface polishing, only a granite (-aplite) with a very fine grain structure can be incised with an accordingly sharp tool (see for example González Bornay, 2021, p. 35). Coarser granites do not leave much opportunity to incise the surface because coarse brittle feldspars, especially when present as porphyritic crystals bedded in a finer matrix, prevent the creation of fine cuts.

Silicate quartz-arenites are principally suitable for polishing (grinding with a very fine abrasive) since their dense structure provides a smooth, eye-catching surface by enhancing the colours, structures, and gloss; however, a very time-consuming and labour-intensive process is necessary to obtain this effect. The best-known examples of polished silicate quartz-arenite sculpture stem from Egypt, where they emerged in the 14th century BC and remain unique expressions of circum-mediterranean stone-working during the Bronze- and Early Iron Age (Aston et al., 2000, p. 53–54).

Contrariwise, the re-grinding of pre-carved lines, whereby the embedded grains are shifted against each other and thereby dismantled, or pressed into micro-porosities in arenites, or into the plastic matrix (micas in the studies cases), is an entirely different process. It requires a sharp or pointed grinding tool that fits into the line grooves and is suitable to abrade the matrix of the rock without itself being abraded too quickly.

Both, the regrinding of carvings and incision of fine lines are based on the same technical-mechanical process, which is a scraping or cutting back-and-forth movement and thus differs completely from techniques that use direct or indirect blows. The lithotypes that are most suitable for regrinding carved lines or incising the surface are sedimentary and meta-sedimentary rocks with a low-cohesive matrix embedding, such as some arkoses, some arenites, and (grey-) wackes. The most resistant to incisions and grinding are the hard mono-mineral quartz rocks (Mohs hardness 7) with a cemented (silicate quartz-arenite) or interlocking (quartzite) microstructure, or interlocking granitoids. Consequently, the regrinding or incision of lines could not be observed on the studied sample of stelae except for the superb example of Fóios (Fig. 13), which is made from a lithotype that favours their application.

5. Results

The numerical values that form the base of all further interpretation are presented in Tables 2–4. Table 2 provides an overview of the overall distribution and percentage of the different types of line section profiles. Table 3 shows the average, maximum, and minimum measurements of the sections from linear carvings that have been applied in matching areas of the corresponding motifs (Fig. 3), eliminating those that represent superficially worked areas, peculiar techniques for creating dots, and odd measurements resulting from the natural rock shape or outbreaks. However, the results in Table 3 should be regarded with scrutiny because they have been obtained with a limited number of sections, thus if fewer or more sections would have been taken, the mean measurement values would change. Table 4 compares the depth-width ratios of lines on original stelae and replicas.

5.1. *Individual results from each stela and its replication*

5.1.1. *Baraçal II, granite-aplite*

On the granite-aplite original and replica stelae, 94 % of the profile sections coincidentally indicate the carving with very sharp tools (types V, U, Vv, W, and w) into the freshly polished rock surface (Table 2). The intention to create a V-Profile line is represented by V- and Vv profiles 51 % on the original and 57 % on the replication. U-shaped profiles are also frequent (35 % on the original, 26 % on the replica). The line depth is similar with 1.2 mm on average on the original and 1.0 mm on the replica. The overall narrowness of the original carvings, only around 10–12 mm wide (Table 3), points towards a tool that allowed for a precise handling, could hold its sharpness, and was probably easy to re-sharpen to maintain the workflow. The ratio depth-to-width is 1:9 in both, original and replica which further confirms the comparability of the applied carving techniques (Table 4). Regrinding of the lines was certainly not applied on the Baraçal II stela, and no incisions could be detected.

Within the experiment, the lines on the replica were carved partly with an actinolite skarn and predominantly with a quartzite chopper (Figs. 8.1 and 8.2), both of which had to be constantly re-sharpened (after 5 min on average), which was done with an angle grinder to save time and nerves. It must be noted that the re-sharpening of lithic tools by hand-polishing is time consuming and can be pain staking. Bronze chisels with any binary alloy from 10 to 16 % could be discarded, because they blunted, bent, or broke immediately on the polished granite-aplite (Araque Gonzalez et al., 2025b, 2025c). The analyses of the chisel from Rocha do Vigio had not yet been conducted at the moment of experimentation in 2021, hence a steel chisel was not used

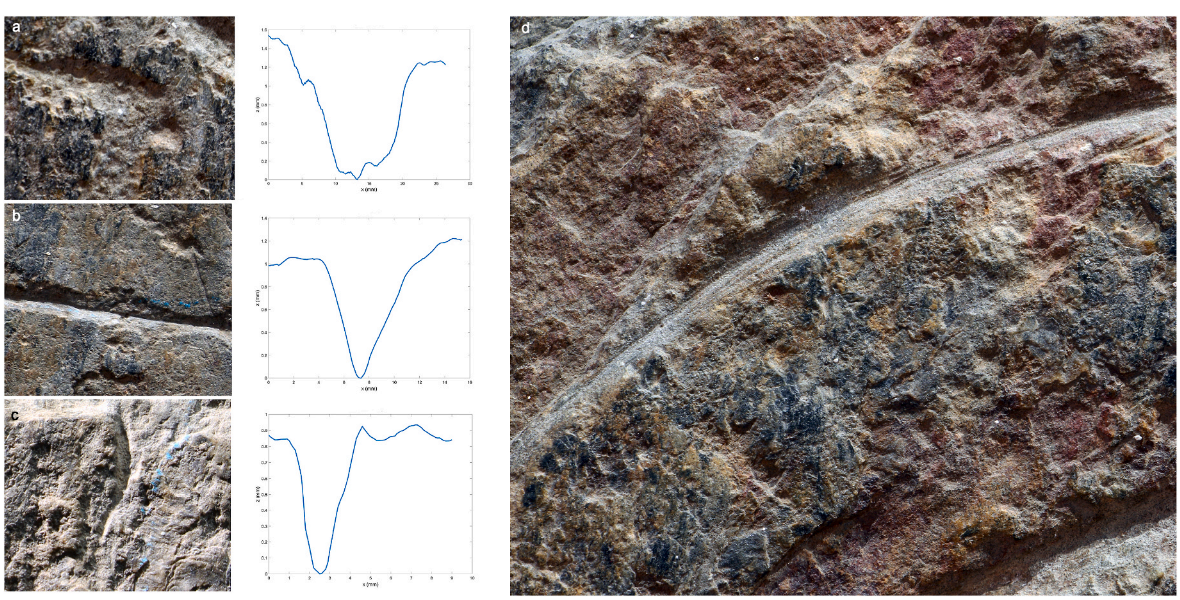

Fig. 13. Macro-photos and line profiles on Fóios original from a) pecking (Fóios Shield 5-2), b) re-grinding (Fóios Sword-2) and c) incision of the parry bar (Fóios Sword-12) and d) a photograph showing the typical streaks as grinding marks (photos: Michael J. Kaiser).

Table 2
Percentage of each line section profiles. For each typology of the line section profiles, the number of cuts and their percentage is indicated (María-Eugenia Polo).

Stelae	Type V	Type U	Type Vv	Type W	Type w	Type flat	Superficial and other	Total numbers of cuts
Baraçal I	13 (25.5 %)	18 (35.3 %)	13 (25.5 %)	4 (7.8 %)	0 (0 %)	1 (2.0 %)	2 (3.9 %)	51
Baraçal I Réplica	25 (46.3 %)	14 (25.9 %)	6 (11.1 %)	5 (9.3 %)	1 (1.9 %)	0 (0.0 %)	3 (5.6 %)	54
Capilla I	2 (3.0 %)	11 (16.7 %)	14 (21.2 %)	7 (10.6 %)	27 (40.9 %)	0 (0.0 %)	5 (7.6 %)	66
Capilla I Réplica	29 (43.9 %)	4 (6.1 %)	17 (25.8 %)	13 (19.7 %)	1 (1.5 %)	0 (0.0 %)	2 (3.0 %)	66
Capilla VIII	11 (18.6 %)	30 (50.8 %)	6 (10.2 %)	10 (16.9 %)	0 (0.0 %)	0 (0.0 %)	2 (3.4 %)	59
Capilla VIII Réplica	6 (14.3 %)	19 (45.2 %)	2 (4.8 %)	0 (0.0 %)	4 (9.5 %)	8 (19.0 %)	3 (7.1 %)	42
Fóios	20 (37.7 %)	6 (11.3 %)	11 (20.8 %)	9 (17.0 %)	2 (3.8 %)	0 (0.0 %)	5 (9.4 %)	53
Fóios Réplica	15 (28.3 %)	8 (15.1 %)	10 (18.9 %)	8 (15.1 %)	6 (11.3 %)	1 (1.9 %)	5 (9.4 %)	53
All stelae Total	121 (27.2 %)	110 (24.8 %)	79 (17.8 %)	56 (12.6 %)	41 (9.3 %)	10 (2.2 %)	27 (6.1 %)	444

and the experimental approach remains therefore yet incomplete in this aspect.

5.1.2. *Capilla I and VIII, La Moraleja and La Pimienta, silicate quartz-arenites*

The two original Capilla stelae and their replicas, made from very hard silicate quartz-arenite, were carved into the natural hardground surface. On the Capilla I original, 93 % of the lines, similarly to 97 % on the replica, indicate the carving with sharp tools (types V, U, Vv, W, and w). Coinciding 97 % of the lines on the original Capilla VIII stela indicate the carving with sharp tools (types V, U, Vv, W), while on the other hand, on its replica only 74 % of the corresponding sections have these profiles and 26 % remained superficial, despite the carving with modern steel (Table 3). Additionally, the lines on the original are almost three times as deep on average with 1.4 mm as on the replica with 0.5 mm. The originals have respectively narrow lines (respectively Capilla I: 7.3–9.1 mm and Capilla VIII: 10.9–18.3 mm) with well-defined edges and no frayed fringes that could be indicative for the use of lithic or generally blunt tools (Fig. 12). Unsurprisingly, there are no traces of regrinding the lines or incisions. Both replicas were made with hardened C60 steel chisels and the blades were mechanically reground, which allowed for a work flow that resulted in slightly narrower lines (Table 3).

On the Capilla VIII replica, where the experimental steel chisel was used for very closely spaced lines, for example the hands or bow and arrow, there was a tendency by the stonemason to handle it with low impact to increase precision and resulting in w-shaped (10 %) or even flat profiles (19 %), however the lines always had well-defined edges due to the steel blade. In this respect, the prevalence of w-shaped profiles on the Capilla I original, where however no flat profiles could be detected, appears interesting. Furthermore, the average line depth of Capilla I original and Capilla VIII replica is almost identical around 0.5 mm and the average width very similar (Table 3). Finally, the average depth-to-width ratio of Capilla I original is 1:16 and on the replica of Capilla VIII it is 1:15, while crosswise, the ratio on Capilla VIII original with 1:8 is similar to the Capilla I replica, where it is 1:6 (Table 4). This indicates comparable preconditions concerning the rocks and tools for the carvings. Nonetheless, the lines on Capilla VIII original are clearly the deepest carvings on all analysed specimens and exceed the depths of Capilla I replica (Table 3).

Knowing that the silicate quartz-arenite replicas were made with a hardened C60 steel chisel, the excellent elaboration of Capilla VIII original, with much deeper and broader lines than on the experimental specimens, clearly stands out. In this context, it seems astonishing that the latter have been carved with more effort, which must have included consequent tool maintenance such as re-sharpening and re-hardening, than on the replications with the modern steel. The consequent line management suggests that the used chisel could be handled with precision, corresponding to indirect blows, and allowed for uncomplicated frequent re-sharpening to ensure a constant workflow, pointing to a metallic material. In the experiment, lithic tools and bronze were absolutely incapable of creating any of these effects on the silicate quartz-arenite. The resulting hypothesis is that the originals from this lithotype must have been carved with hardened steel chisels which must have had material qualities similar or comparable to hardened C60 steel.

5.1.3. *Fóios, meta-arkoses*

The stela of Fóios displays the widest array of diverse techniques that were used for its creation in our sample, which is mostly due to the technical possibilities provided by the meta-arkoses with its low-cohesive matrix. Fóios shows a combination of closely pecked lines and carvings, which were partially reground and revealed several processing stages. Initially, the outlines must have been pecked or carved with a sharp tool, which was subsequently used for tracing the lines of the spear, the sword and the outer rings of the shield. The results were the pronouncedly V-shaped lines of the spear and sword, while some of the partially still visibly pecked lines of the shield were emphasized with a continuous furrow on the bottom (Fig. 13 b). In the experiment, all of these techniques could be performed with an actinolite skarn or a quartzite chopper. On the other hand, bronze chisels with hard binary alloys (14 and 16 % tin) were problematic to carve lines, since they blunted rapidly (see Table 1), but they were well-suited to create the four dots that depict the studs of the sword hilt, with a powerful vertical strike and subsequent turning the tool with a drilling effect. The profile sections of the dots on the replica in this area correspond to the original (Fóios Dots 1-3 at https://zenodo.org/records/158304929).

Subsequently, at an unknown stage of its existence, a more extensive revision and re-tracing of lines took place on the left side of the decorated part. This was done with a scraping and grinding tool which left sometimes very obvious streaks and grind marks (Fig. 13 d). It is not clear why only the left and lower parts of the stela were affected. This might be due to maintenance works, for example the removal of overgrowth or repair of minor damage. However, there was seemingly no interest in harmonising the appearance of the design with the lines on the right side, which was left un-retouched. Most probably, a wedge-shaped, probably lithic tool with a medium-fine granulation was used for the purpose of regrinding the affected lines where streaks are prominent. The tool used for regrinding on the original Fóios stela was certainly different from the tools that were used for regrinding on the replica, and no corresponding traces that would parallel prominent grinding streaks visible along the affected lines on the left-hand side of the original's decorated face could be created (Fig. 13 d).

Moreover, incision with a thin, sharp or pointed tool has also been used for minor details, for example the small fibula on the left fringe. Within another step of revision, the sword hilt was extended with a parry bar, also using incision with a thin, sharp tool. It cannot be excluded that this was a later addition because the expected shape of a sword would have changed with time and the formerly absent parrying bar would have been perceived as missing in its image. This was done with a sharpened bronze chisel (14 % tin) in the experiment. The incisions correspond to very narrow V-shaped profiles (Fig. 13 c).

Contrary to the previously described stelae from very hard rocks, the V-shaped line profiles, which make up 38 % on the original and 28 % on the replication (Table 2), were created mainly if not exclusively by first working with a sharp tool to break the surface and then regrinding the lines. Traces from sharp tools (in this case, U, Vv, W and w) are represented by 53 % of profile sections on the original and 60 % on the

Table 3
Average, maximum and minimum depths and widths of lines at the measured profiles for each stelae and replica. Values marked with an asterisk (*) have been considered statistically non-significant due to having fewer than four data points. Units in mm (María-Eugenia Polo).

Stelae	units in mm	Type V	Type U	Type Vv	Type W	Type w
Baraçal I original	Average width	11.6	10.4	10.2	11.7	
	Average depth	1.2	1.2	1.3	0.3	
	Maximum width	15.2	20.4	14.4	13.0	
	Minimum width	7.5	5.8	5.2	9.0	
	Maximum depth	1.8	2.0	2.1	1.9	
	Minimum depth	0.6	0.6	0.6	0.4	
Baraçal I replica	Average width	8.3	7.7	9.2	11.3	9.7 (*)
	Average depth	1.0	0.8	0.7	0.9	0.8 (*)
	Maximum width	11.9	12.1	12.0	14.3	
	Minimum width	5.5	4.7	6.3	7.8	
	Maximum depth	1.6	1.3	0.9	1.3	
	Minimum depth	0.2	0.4	0.4	0.6	
Capilla I original	Average width	7.3 (*)	6.9	7.6	9.1	8.8
	Average depth	0.7 (*)	0.5	0.6	0.5	0.5
	Maximum width	11.3 (*)	9.7	12.0	13.0	25.0
	Minimum width	3.2 (*)	2.1	3.6	6.8	4.9
	Maximum depth	1.1 (*)	0.7	0.9	1.0	1.1
	Minimum depth	0.4 (*)	0.3	0.3	0.3	0.2
Capilla I replica	Average width	5.4	5.6	6.2	7.0	5.4 (*)
	Average depth	1.0	1.0	0.9	1.0	0.5 (*)
	Maximum width	7.0	5.8	19.5	12.9	
	Minimum width	1.3	5.1	3.1	4.1	
	Maximum depth	1.6	1.2	2.4	1.6	
	Minimum depth	0.3	0.8	0.4	0.4	
Capilla VIII original	Average width	10.9	12.3	14.9	18.3	
	Average depth	1.4	1.5	1.5	1.2	
	Maximum width	15.4	17.7	17.9	29.1	
	Minimum width	6.3	1.8	10.2	13.3	
	Maximum depth	2.6	2.8	2.2	1.5	
	Minimum depth	0.5	0.4	0.9	0.8	
Capilla VIII replica	Average width	8.9	7.9	7.4 (*)		11.0
	Average depth	0.6	0.5	0.6 (*)		0.4
	Maximum width	9.7	11.2	7.6 (*)		16.6
	Minimum width	7.8	3.5	7.1 (*)		7.4
	Maximum depth	1.0	1.0	0.7 (*)		0.6
	Minimum depth	0.3	0.1	0.5 (*)		0.1
Fóios original	Average width	9.1	10.0	13.9	13.3	14.9 (*)
	Average depth	1.6	1.7	1.7	1.5	1.2 (*)
	Maximum width	14.0	14.1	17.3	18.8	19.1 (*)
	Minimum width	3.3	7.0	10.8	3.7	10.6 (*)
	Maximum depth	3.0	2.2	2.2	2.7	1.5 (*)
	Minimum depth	0.9	1.1	1.2	0.7	1.0 (*)
Fóios replica	Average width	6.2	9.2	8.0	13.6	8.4
	Average depth	1.1	1.0	1.0	1.0	0.5
	Maximum width	8.5	15.9	11.7	20.8	12.4
	Minimum width	4.3	7.3	5.8	7.0	6.4
	Maximum depth	2.1	1.7	1.3	1.9	0.6
	Minimum depth	0.5	0.6	0.5	0.6	0.2

Table 4
Ratio of line depth to width at the measured profile sections on original stelae and replicas (María-Eugenia Polo).

Baraçal II	Ratio depth/width original	Ratio depth/width replica
Average width/Average depth	1:9	1:9
Capilla I		
Average width/Average depth	1:16	1:6
Capilla VIII		
Average width/Average depth	1:8	1:15
Fóios		
Average width/Average depth	1:7	1:10

replica, including the dense pecking that frequently corresponds to W-shaped (original 17 %, replica 15 %; Fig. 13 a) or w-shaped (original 4 %, replica 11 %) profiles (Table 2). The significant amount of "other" section profiles, 9 and 10 % on the meta-arkoses specimens, is mainly due to the heterogeneity, unruliness of this stratified lithotype that favours outbreaks on the fringes of lines wherever mineral concentrations or micro-layers which are parallel to the bedding are hit. Due to the characteristics of the rock type and possibly a greater effort spent on the carvings on the original, the Fóios replica has both shallower and narrower lines than the original (Table 3) and the ratio of depth-to width reflects the deeper carvings on the original with 1:7, compared to 1:10 on the replica (Table 4).

5.2. Compared results

The sample of four stelae and their replications from granite-aplite, silicate quartz-arenite and meta-(sub-) arkoses, are representative for ca. 54 % of the known Iberian stelae as well as for the hardest lithotypes used for these rock art monuments. The combined approach of digital images, GIS, material analyses, and carving experiments allows for a thorough evaluation of tool traces. The profile sections from carvings on stelae and replicas have been examined to detect similarities and differences in their shapes, width, and depth. From there, the probable shape of the working edge (blade, point, blunt) of tools and the degree of sharpness, as well as the handling with direct or indirect strikes, can be determined. Subsequently, the possible tool materials can be narrowed down by consulting data from petrology, metallurgy, and experiments. The comparative average depths and widths of the profiles in originals and replications from adjusted data are compiled in Table 2, and the percentages of identified profile sections on each stela in Table 3.

There are three principal aspects of the analyses that have been used to deliver the presented results. Firstly, the degree of sharpness of a tool is a determining factor for creating both width and depth of a line. A well-sharpened chisel will create more depth and less width with a tendency to leave a V-shaped profile, while an under-sharpened or blunt tool will tend to produce more width and less depth. As sharpening is required at regular intervals, there are minor, however detectable irregularities in the profile sections, which are expressed in Vv- and W-shaped profiles or, more obviously, in w-shaped profiles. It can be stated that V-, U-, W-, Vv-, and w-shaped profiles are representative for sharp tools, and except for the latter, they are indicative of a consequent maintenance of sharpness. In summary, it can be made clear that 94 % of all 444 examined profile sections on all stela and replications fall into this category, and this confirms that the carvings on the studied rock art monuments were predominantly made with sharp tools.

Secondly, indirect blows create lines that are often deeper than wide and allow for more precision in the line management, particularly if the carvings are complex in shape, while direct blows tend to create broader and shallower lines with irregular edges. This is another most important observable feature of the carvings and indicates the techniques that were made for the stelae creation. Particular recurring profiles, especially V-, U-, W,- and Vv-shapes indicate that a sharp tool was used with indirect strikes. Line depth and width (the deeper and the narrower) can be a supportive argument for the latter.

Third, the tool materials for all four stelae can be narrowed down to lithic, preferably quartzite implements (Baraçal II and Fóios), and hardened steel chisels (Capilla I and VIII). On the contrary, even hardened high-tin bronze was too soft for carving the three examined lithotypes. The failures of copper as well as tin bronzes for carving medium hard to hard rocks had been observed already in related studies, where they were experimentally tried on sandstone and had to be discarded, because they blunted instantly (Zotkina and Davydov, 2022, with cold hardened 8 % tin bronze). During the study of petroglyphs in southern Sweden, a team of researchers tried replicated bronze tools, however without specifying the alloy or any hardening applications, on an open-air granite panel by the sea. Logically, they failed as soon as the soft weathering layer was removed and the fresh, hard granite was hit (Liebl et al., 2023, p. 119–122). Contrariwise, the weathering crust had been removed by polishing on all of the granitoid western Iberian stelae, and the carvings were always done in the fresh granite.

The above mentioned Siberian findings have also shown that lithic tools (quartz and quartzite have been tried) are already problematic for creating accurate and continuous lines in the soft sandstone due to the quick change in shape of the rapidly blunting tool tip, and correspondingly the impact marks. Only a regrinding of the lines, as could be observed on the Fóios stela, could have brought some desired stringency to the aspect of pecked lines made with stone tools.

In conclusion, three of the studied western Iberian stelae have only typical traces from blows with sharp tools (Baraçal, Capilla I and VIII), of which at least two (Capilla I and VIII) display characteristics of indirect blows with a chisel due to the narrowness, clear line management, homogenous aspect and overall precision of the carved lines. Generally, it could be observed that steep sides of continuously carved lines point towards sharp tools with blades. The use of other techniques for creating rock art, for example grinding, pecking with a blunt or pointed object, cutting or incising, or – for the sake of completeness – sanding, could be excluded for these three stelae. On the other hand, Fóios was made from a softer rock than all other studied examples and the stela incorporates pecking, regrinding of lines, and incisions. Only for Fóios, it can be unambiguously stated that different types of chisels, axes, or choppers, could have been used, and the rock type facilitated the retracing of the designs as well as incisions.

Furthermore, it can be stated that none of the evaluated lines on the originals was made with a shafted tool, mainly because they are generally precise and at the same time narrow, which is difficult to achieve with the latter – as our experimentation has shown and stonemasons would confirm. This does by no means contradict the use of shafted tools, for example quartzite hammers, for the rough hewing and shaping of some stones and their surface.

With relevance for the comparability of profiles on original stelae and replicas, Fig. 14 shows several examples of the superposition of corresponding shapes in similarly situated sections on the original stela (blue) and the replica (orange), measured by the lowest point and with the scale of the ZX axis highlighted for a better visualisation of the similarities between both carvings. Finally, it stands out that in three out of four cases, the carvings on the originals are deeper than on the replicas, for example significantly deeper by a factor of 2.8 on Capilla VIII original than on the replica with modern steel, and 1.9 times deeper on Fóios original, which points towards a higher effort was spent on their making. However, there is the exception of Capilla I, where the replica has 1.8 times deeper lines than the original, which, on the other hand, corresponds very well to the replica of Capilla VIII with its average depth and width (Table 3).

6. Discussion

With the proposed method, it is possible to determine the nature of the chisel tip, which must have had a sharp blade in all studied cases, in agreement with the experimental tools, which left similar traces as on the original stelae. Sharp blades are best suited to carve continuous, solid lines. As a limiting factor, it is not possible to decide on first sight whether a line has been carved with lithic, bronze, or steel chisels, because sharp blades leave similar traces. Hence, the shape of the tip and the degree of sharpness can be determined with the analysis of the line profile sections, but not the tool material. As long as the blade of a tool is *hard and tough* enough and its sharpness can be maintained, the material does not appear to matter for the outcome.

As a consequence, petrographic analyses of the carved rock and a precise knowledge of the contemporarily available tools from the archaeological record are fundamental to obtain reliable information on the tool material (see Araque Gonzalez et al., 2023, 2025b, c). Moreover, to narrow down the range of realistic possibilities, it must be studied which of the eligible tool materials can at the same time penetrate the rock surface (hardness) and can hold the sharpness without blunting too rapidly or breaking due to brittleness (toughness).

Since no comparable traceological studies of rock art that are based on line section profiles exist thus far, it is important to compare the observations from other compatible approaches that distinguish between the tools used in rock art. The most related are the works on the traceology of Siberian petroglyphs, where researchers performed analysis of tool marks in the form of percussion dents seen from the top view in plan and used experimental archaeology to scrutinize the interpretations of archaeological rock art (Devlet, 2012; Zotkina and Kovalev, 2019; Zotkina and Davydov, 2022). This method can be regarded as complementary to the analysis of the line profiles, which has a clear advantage when no percussion dents can be singled out.

The archaeological traces on the predominantly soft lithotypes used for Siberian rock art, such as schist and Devonian sandstone (cf. Devlet, 2012; Zotkina and Kovalev, 2019), display "most typical signs of using iron tools" (chisels) with "even contours of indentations and stably repeating shape of traces" (Zotkina and Davydov, 2022, p. 66). In addition, traces from metal tools were found to have a depth that is larger or equal to their width, which can be confirmed by our analyses. On the other hand, traces from lithic tools were found to be characterized by "their form (being) never sustainable" and "(T)he width of traces

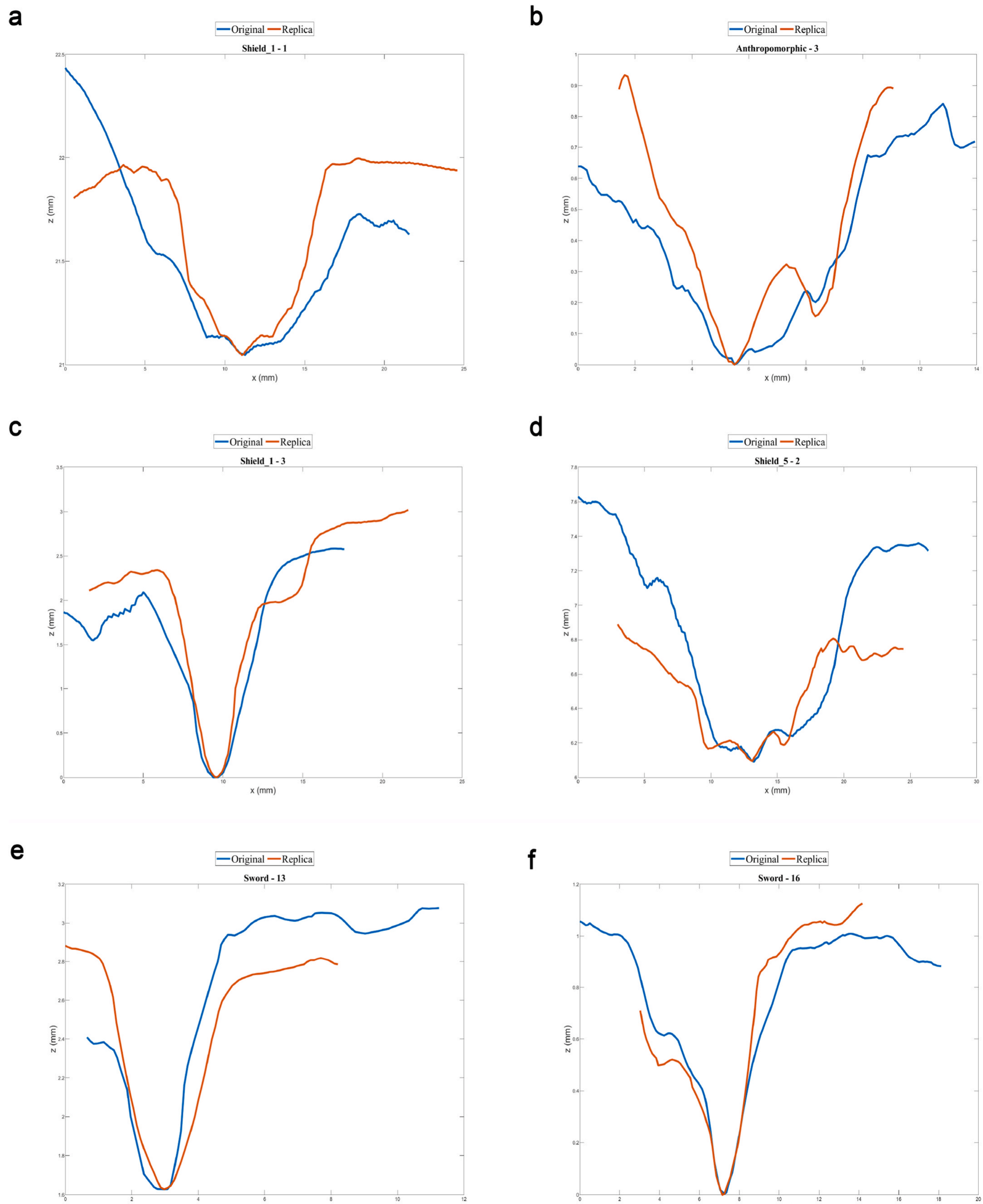

Fig. 14. Superimposition of similar profile sections at the same motifs on originals (blue) and replicas (orange). a) Baraçal II, Shield 1-1 b) Capilla I, Anthropomorphic 3. c) Fóios, Shield 1–3. d) Fóios, Shield 5-2. e) Fóios, Sword 13. f) Fóios, Sword 16 (María-Eugenia Polo and Pablo Paniego). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

is always more than their depth. And the edges of traces are irregular" (Zotkina and Kovalev, 2019, p. 3). To be more precise, Devlet (2012, p. 140) description of the differences between peckings from stone and iron tools seems to confirm our observations of the profile lines: "(…) the main diagnostic feature distinguishing pecking pits left by a stone punch tool from traces of an iron tool was the quick change [of shapes in plan] in the work area (…) traces showed a dynamic transformation from sub-rounded or sub-quadrangular pits to linear elongated ones. Another important feature of the use of stone tools was the wide entrance hole and the lack of sharp drops between the peaks and depressions." Moreover, Devlet (2012, p. 146) observed that lines created with iron tools "(…) are straight with smooth bends in some parts and vary in length. They are narrow and have an identical U-shaped profile." They did not provide a definition or illustration of a U-shape profile, but based on this analysis, it is reasonable to assume that they refer to a similar feature to what has been found on several Iberian stelae. Hence, there are obvious concurrences in the distinguishing of metallic and lithic tools in support of our hypotheses as well as supportive arguments for the metallic nature and mechanical properties of the chisels used on the examples from Capilla, where similar traces have been created in much harder rocks. Furthermore, the lines on these stelae have predominantly sharp drops (V-, U,- Vv-, W-profiles) and are rather fine, on average 8–12 mm. This combination indicates excellent tools and a precise handling of the latter, including their maintenance through constant re-sharpening and, if applicable, re-hardening. The stonemason who performed the experimental carvings on silicate quartz-arenites commented that he believes that the person who made Capilla VIII, with perfectly accurate and well-defined lines more than twice as deep as what he achieved with the C60 steel, must have used "better" chisels than him. This being a modern craftsperson's perception, it could still be assumed that the ancient chisels did not perform worse than the interpretative replication. This is evident in the clear-cut outlines and sharp profiles which are unthinkable to be made with a blunt or pointed tool and no eligible material other than steel would be capable of performing similarly on silicate quartz-arenite/quartzite.

Contrary to claims based on macroscopic or *su visu* assessments (Enríquez Navascués and Fernández Algaba, 2010, p. 160–164; see also Gutiérrez Sáez et al., 2020, p. 97–99 and 101), neither do the lines on Capilla I nor on Capilla VIII show any traces of regrinding, nor does any of the studied stelae from equivalent lithotypes in the Museum of Badajoz. It must be made clear once and for all that with the available means in the FBA-EIA, the grinding of lines, defined as the shifting and dismantling of grains or as their impression into micro-porosities of the matrix, is mechanically impossible on silicate quartz-arenite/quartzite. These rocks are so tightly cemented or interlocked that quartz grain and matrix have the same hardness and they rather break through the grains and not along grain boundaries (see also Howard, 2005). The same is true for interlocked granite rocks, where the grains are delaminated by hitting and exfoliating the sheet silicate material (micas) to loosen the harder parts (quartz and feldspar). These hard lithotypes can only be grinded with abrasive agents in combination with lubricants and grinding tools, which is a fundamentally different technique. Nowadays, diamond cutters or water-cooled milling cutters would be used for grinding ornaments in silicate quartz-arenites as well as granites. It is hard to imagine how to substitute this with the available means in the FBA-EIA, or which materials and devices would have been used to grind ornaments into isotropic fine-grained quartzite. The application of water and fine sand with a grinding tool would constitute a formidable challenge on this material, because abrasion works two ways. In any case, such a procedure would leave detectable grinding marks, even if a hypothetical combination of a super-fine abrasive and a manually operated high rotation process would have been used. Bronzes with any alloy and equally a hardened C60 steel chisel are immediately abraded by the quartz components without leaving traces if they are tried to regrind lines in silicate quartz-sandstone or granite. Finally, apart from a lack of grinding marks and the mechanical obstacles to grind lines into silicate quartz-arenite, the observable irregularities in the below-millimetre realm indicate that the lines have been left un-retouched.

While this is not the place to debate imaginary and esoteric technologies that could possibly not be grasped by our analyses neither by common sense, the hypotheses for a grinding/regrinding of lines should be discarded for silicate quartz-arenites and it remains very improbable for granitoid rocks. However, granitoid rocks can be scratched superficially with quartz or similarly hard implements, for example to sketch the lay-out of a design or to depict small details, such as fingers, as well as thin lines (see for example the Cañaveral de León stela 2, García Sanjuan et al., 2025, p. 11). In summary, the re-grinding hypothesis for the aforementioned hard rocks has become a frequently copied misinterpretation, which should now be corrected on the basis of material science and simple physics. On the other hand, the regrinding of lines was definitely possible on other stelae that were made from softer rock types, which share the characteristic that the grains are embedded in a matrix with low cohesion, for example some arkoses, sand- and siltstones, or (grey-)wackes, and it has been applied where suitable, for example on the stela from Fóios.

Lastly, the results show that the two original silicate quartz-arenite stelae from Capilla have indisputably been carved with a sharp chisel, which must have been used with indirect blows for precision and made from a material that allowed for a continuous workflow due to its toughness and relatively easy re-sharpening (Table 5). This implies that these examples (and all counterparts with precise lines carved into similar lithotypes) must have most probably been made with hardenable steel, i.e. having a carbon content of above 0.45 wt%, and the artisans must have known techniques for re-hardening them when worn-out. This strongly supports the hypothesis of an early and highly developed iron metallurgy in the Iberian FBA-EIA (Araque Gonzalez et al., 2023; Araque Gonzalez et al., 2025). In this context, the silicate quartz arenite/quartzite stelae can arguably be regarded as indirect indicators of this technological advance and their chronology can be connected to the moment when iron working was established in the surroundings of the Guadiana valley.

7. Summary and conclusions

The approach towards line section profiles allows for the identification of tool shapes and working techniques for continuous line carvings. There is a high potential for identifying sharp tools with a blade and the general aspects of their use (blows from different angles, areal peckings, reworking of lines by retouch or regrinding). The traces of this process can be recognized, documented, and evaluated with the 3D scanning and application of GIS, which has been introduced with this contribution. Furthermore, it permits conclusions on the tool guidance concerning precision, impact intensity, direct and indirect striking, adaptions due to the rock surface, etc. The blunting of the blade during the workflow, as well as mistakes such as unintentional strikes outside the line limits or breakouts on the line margins, can also be detected.

Table 5
Interpretative comparison of line section profile. Legend for depth assessments.

Type/	Accuracy	Edges	Depth	Width	Skill
V	High	Defined	Deep	Narrow	High
U	High	Defined	Deep	Medium	High
W	High	Defined	Deep	Medium	High
Vv	High	Defined	Deep	Narrow to medium	High
w	High	Defined	Shallow	Medium	Regular
Areal	Intermediate	Defined	Medium	Broad	Regular
Flat	Low	Blurry	superficial	broad	low

Superficial = < 0.4 mm; Shallow = 0.4–0.8 mm; Medium = 0.9–1.5 mm; Deep = >1.6 mm.
Legend for width assessments: Narrow = 2–7 mm; Medium = 8–12 mm; Broad = 13–20 mm.

Fine and precise lines such as on the stelae from Baraçal II, Capilla I and VIII, which served as examples for very hard rocks and as models for the experiments, were carved with a sharp tool that is hard and tough enough to break through (quartzite) or along (granite and granite-aplite) the grains to dismantle them. The softer meta-arkoses stela from Fóios was made with different techniques, including regrinding, direct percussion, and incision, which are facilitated by its different material properties.

We have shown that granite-aplite (as a representative for fine-grained granitoids) can be reasonably carved with lithic tools, especially with quartzite tools. However, there is a caveat due to the problem of permanent re-sharpening of the lithic tools (on average every 5 min) which appears to be a disproportionate ratio between carving and tool maintenance. On the other hand, it could be demonstrated that the lines on the studied silicate quartz-arenite stelae (Capilla I and VIII) must have been made with very hard, tough, and easily re-sharp enable tools, which were presumably used with indirect blows for precision. The most realistic option for their actual material remains certainly hardened steel, which was also used for their replication. Actually, the lines on Capilla VIII are wider, almost three times deeper, and more meticulously chiselled than on the replicas from the same rock that were made with a C60 steel chisel.

The particular advantage of this comprehensive traceological analysis is the good prospect for the identification of tools which were suitable for their use on the stelae. It becomes clear that the resulting combined method is a powerful analytical tool to reconstruct the making of rock art by combining digital technologies, material analyses of tools and rocks, and experimental archaeology. The results obtained for the Iberian stelae have chronological, technological-historical, and social implications.

There are future possibilities to apply the proposed method for the determination of working directions and possibly other technical aspects that might become evident with an evaluation of a higher number of profile sections per line, which will also enhance the overall statistical power of the results. The analyses of line profile sections can be perfectly combined with other methods, for example the top view analyses of tool marks in plan.

Most importantly, it can be concluded that the starting point for any technical analysis of rock art must be a precise knowledge of the lithotypes, physical rock structure, and material properties of rocks and possible tools from the archaeological record. From there, the relations between the lines and their profile sections can be explored for each type of stone, sharp and pointed edges can be distinguished, and the tool materials can be narrowed down based on their required technical properties. In the course of this research, it has been shown that bronze chisels are inadequate for the carving of any hard rocks, which is in accordance with the abovementioned archaeological experiments. In the case of the silicate quartz-arenite stelae, the hypothesis that they were made with hardened steel chisels could be further consolidated (Araque Gonzalez et al., 2023). The composition of the chisels could have been similar to the example that was found in the FBA hamlet of Rocha do Vigio besides the Guadiana river, C14-dated to the 9th century BC. The introduction or invention of iron technology, from smelting to forging and hardening, could thus be regarded as a *terminus post quem* for the stelae made from silicate quartz-arenite/quartzite. Within this trajectory, further research must show whether the knowledge of iron smelting was an Iberian development, possibly derived from copper smelting, or whether it has to be contextualized with external intercultural contacts, ostensibly with eastern Mediterranean craftspeople.

Eventually, a new problem arises: it remains unresolved how the FBA-EIA craftspeople would have hardened their contemporary refined steel from bloomery iron to an equivalent HV0.5 of 700–800, or which other material would have had similar technical properties to substitute this. Therefore, new experiments with refined steel chisels are planned and their performance will be scrutinized in comparison to modern, homogenous steel (cf. Mink, 2025). Additionally, since no steel chisels have been tried yet on granite-aplite or other granitoids, this omission requires an extension of the analyses and experiments, and a systematic comparison of the traces.

CRediT authorship contribution statement

Ralph Araque Gonzalez: Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **María-Eugenia Polo:** Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Pablo Paniego Díaz:** Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vera Rammelkammer:** Writing – review & editing, Visualization, Validation, Formal analysis. **Bastian Asmus:** Investigation. **Michael J. Kaiser:** Investigation. **Alexander Richter:** Investigation. **Giuseppe Vintrici:** Investigation. **Rafael Ferreiro Mählmann:** Investigation.

Data availability statement

All 3D models that were used in this research are publicly accessible in the collection called 'Iberian stelae' on Sketchfab. The models can be downloaded free of charge under the CC Attribution-NonCommercial-NoDerivs licence.

https://sketchfab.com/secad/collections/iberian-stelae-5224127c1c7141cda3c56ee6eadf7a33.

The raw data (3D models, all the profiles and the excel sheet with the calculations) is shared on Zenodo: https://doi.org/10.5281/zenodo.15830492.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ralph Araque Gonzalez reports financial support was provided by the German Research Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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