RESEARCH ARTICLE – VÝZKUMNÝ ČLÁNEK

# Rhyolite grinding-milling tools in focus: Assessing kinematics with the help of use-wear analysis

## Ryolitová mlecí zařízení pod drobnohledem: studium kinematiky nástrojů na základě stop opotřebení

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*Past societies have used various raw materials for making grinding-milling tools (GMT). These included rhyolite, a hard volcanic rock with a porphyritic texture and pores, which is suitable for grinding. Thus far, no experiments have been carried out involving use-wear analysis on rhyolite grinding stones, and more specifically on Neolithic GMTs made of this raw material. Therefore, in this paper, we present an experimental program designed to investigate the development of wear from the grinding of einkorn wheat (Triticum monococcum) on rhyolite GMT replicas. To test the resulting observations, four GMTs found at the Neolithic site of Vchynice were used as a case study. However, the results of the experiments can be used to study these important artefacts in other geographic and cultural areas. The experiment has yielded several important findings relating to the kinematics of the tools and throws new light on their users. The orientation of the tool relative to the user can be distinguished based on the distribution of the use-wear traces. The study of the archaeological assemblage revealed that substances other than einkorn wheat, which was used for our experimental grinding, were processed on the Neolithic GMTs.*

grinding-milling tools – raw material – replica – experimental use – use-wear – kinematics

*V minulosti byly mlecí zařízení (drtidla, zrnotěrky) vyráběny z mnoha druhů hornin, mezi něž patřila i porézní vulkanická hornina ryolit obsahující vyrostlice křemene a živce. Dosud nebyly provedeny žádné experimenty zahrnující traseologickou analýzu mlecích zařízení z této horniny, ani těch pocházejících z neolitických nálezových kontextů. V tomto článku proto představujeme experimentální program, jehož cílem bylo sledovat vývoj opotřebení ryolitových replik mlecích zařízení při mletí pšenice jednozrnky (Triticum monococcum). Pro ověření experimentů byly jako případová studie použity čtyři ryolitové mlecí kameny nalezené na neolitické lokalitě Vchynice, výsledky experimentů lze však využít pro studium těchto důležitých artefaktů i v jiných geograficko-kulturních oblastech. Experiment přinesl několik důležitých zjištění týkajících se kinematiky nástrojů a jejich vztahu k uživateli – například, že z vývoje stop opotřebení lze rozlišit orientaci nástroje vzhledem k jeho uživateli. Studium archeologického souboru ukázalo, že v neolitu byly pomocí mlecích zařízení zpracovávány i jiné plodiny než pšenice jednozrnka, která byla použita pro uvedený experiment.*

mlecí nástroje – surovina – replika – experimentální používání – stopy opotřebení – kinematika

## Introduction

This study deals with traces of use (use-wear traces) that are caused by the interaction of the two compatible parts of a replica grinding-milling stone tool set (lower stone and upper stone), made of rhyolite with the processed substance. In general, grinding-milling tools (GMT) are simple devices that have been widely used for at least fourteen thousand years for grinding inorganic as well as organic materials and substances (e.g. *Wright 1994*; *de Beaune 2004*; *Lidström Holmberg 2008*; *Adams et al. 2009*; *Peacock 2013*). There are

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several kinds of analyses that can be performed on GMTs. Besides contextual studies, bio-anthropological analysis, ethnographic analogies, analysis of micro-residues and analyses of morphometric characteristics also use-wear analysis combined with experimental program provide valuable reference data about the kinematics of the artefacts (e.g. *Leroi-Gourhan 1964*; *Dubreuil 2001*; *Sládek et al. 2016*; *Adams – Saed Mucheshi 2020*; *Santiago-Marrero et al. 2021*).

Rhyolite (also referred to as palaeorhyolite, or sometimes as rhyolite ignimbrite or quartz porphyry; see *Přichystal 2009*, 233–234; *Šreinová et al. 2013*) quarried in the Oparno valley originating from the northwestern part of the Czech Republic was used for different types of bipartite grinding sets since the Neolithic and was later used to make rotary mills up to the early Middle Ages (e.g. *Řídký et al. 2014*; *2020*). The basic composition of this volcanic rock is similar to that of other raw materials such as rhyolites and andesites found elsewhere (e.g. *Runnels 1981*; *Pavlů et al. 2007*; *Šreinová et al. 2013*). Since the Oparno rhyolite is a hard, cohesive, heterogeneous rock with pores that has a natural positive roughness, it does not wear as quickly, making it suitable for grinding. The fact that we know where rhyolite outcrops occur and how the material has been used over time and space are the main reasons why we started our controlled grinding experiments specifically on this raw material (e.g. *Řídký et al. 2014*).

Our experiment is focused on the grinding of dehusked einkorn wheat (*Triticum monococcum*), a typical domesticated cereal of the Near Eastern and European Neolithic, but sometimes still processed today (e.g. *Hajnalová – Dreslerová 2010*). We chose a common crop without husks to observe one use-wear pattern. The experimental set consists of a lower (passive) stone and an upper (active) stone. It was manipulated with the user mostly in a kneeling position and was held side by side with both hands being moved in a back-and-forth motion during use. Subsequently, four GMTs made of the same raw material (two lower and two upper stones) from the Neolithic site of Vchynice in the Czech Republic were chosen as a case study to verify and test the results of our experiment.

The primary aim of our newly established experimental use-wear program is to identify the diagnostic use-wear patterns produced by the grinding of einkorn wheat and to compare them with published data from tools made of different raw materials (e.g. *Dubreuil 2004*; *Hamon 2008*; *Fullagar et al. 2012*; *Hayes et al. 2018*, 104; *Bofill et al. 2020*; *Zupancich – Cristiani 2020*). Since rhyolite is a very heterogenic rock composed of different minerals, the focus is targeted on the individual types of mineral grains and the differences in the development of their use-wear. Furthermore, the spatial development of the use-wear on the entire active surface of the tool is also observed. This study, which is focused on the processing of crops used in Europe and the Near East since the Neolithic, thus complements the results of previous grinding experiments, regardless of the dating or origin of the comparative archaeological findings (e.g. *Fullagar et al. 2012*; *Bofill et al. 2020*; *Zupancich et al. 2019*; *Cristiani – Zupancich 2021*). We address several questions in our study:

What traces of wear are left by grinding einkorn wheat on rhyolite replica tools?

Are our results comparable to the results of other experiments using replicas made from other raw materials?

Do the work traces and their visibility change during use of the tools?

Do the findings provide any useful information about the kinematics (the way they move) of the tools and about the operating position adopted by the users?

Are the findings adaptable to the study of prehistoric tools?

## Grinding-milling tools and use-wear studies

Wear itself is not a material property, but a response to a process of use and therefore must be seen as a phenomenon that is dependent on many parameters (*Bhushan 2002*, 331; *Kato 2002*, 349). One of the main problems in the use-wear analysis of GMTs is the heterogeneity of the raw material. A rock is composed of many minerals with different properties. Its characteristics as cohesion, hardness and porosity also depend very much on how it was formed and whether it is classified as igneous, metamorphic, or sedimentary. The origin of the rock has a great influence on the effectiveness of the tool, and it also affects the formation of use-wear traces (*Procopiou 1998*; *Hamon – Plisson 2008*, 30; *Dubreuil et al. 2015*, 116; *Chondrou et al. 2021*).

The first studies dealing with the use-wear on GMTs only appeared in the 1980s predominantly in the USA (*Adams 1988*; *1989*; *Logan – Fratt 1993*). J. Adams was one of the first to conduct experiments and macroscopic examination of use-wear traces on sandstone GMTs (*Adams 2002*). At the same time, L. Dubreuil started to create another experimental reference collection developed for Natufian basaltic grinding tools (*Dubreuil 2001*). In the 1990s, *Risch* (*1995*) and *Procopiou* (*1998*) completed theses that included use-wear analyses. In the following years, many papers dealing with the analysis of use-wear traces on GMTs were published (*Menasanch et al. 2002*; *Risch et al. 2002*; *Zurro et al. 2005*; *Hamon 2006*; *Hamon – Plisson 2008*; *van Gijn – Verbaas 2009*; *Liu et al. 2010*; *2011*). C. Hamon created a reference collection for French Early Neolithic LBK sandstone grinding equipment (*Hamon 2008*), and R. Risch and S. Delgado-Raack carried out work on grinding tools in Spain (*Delgado-Raack – Risch 2009*; *Delgado-Raack et al. 2009*). In 2009, a collective article on use-wear analyses on grinding stones was published, summarising the state of research to date by the previously named experts (*Adams et al. 2009*). In the last ten years, the study of use-wear traces has seen the highest increase in articles and experts dealing with this topic (*Gilabert et al. 2012*; *de la Torre et al. 2013*; *Smith et al. 2015*; *Delgado-Raack – Risch 2016*; *Fullagar et al. 2017*; *Hayes et al. 2017*; *2018*; *Li et al. 2019*; *Kufel-Diakowska et al. 2020*; *Zupancich – Cristiani 2020*; *Chondrou et al. 2021*; *Cristiani – Zupancisch 2021*; *Santiago-Marrero et al. 2021*).

As they emerged, new technological tools such as confocal microscopy (*Bofill 2012*; *Bofill et al. 2013*; *Dubreuil – Savage 2014*; *Macdonald et al. 2019*; *Chondrou et al. 2021*; *Zupancich et al. 2023*), Scanning Electron Microscope (*Dubreuil 2004*; *Bofill et al. 2013*), and 3D modelling (*Caruana et al. 2014*; *Benito-Calvo et al. 2015*; *2018*; *Caricola et al. 2018*; *Zupancich et al. 2019*) were used. The recording and description of use-wear traces have been described in many articles, but the terminologies used are neither standardized nor universally accepted (*Zurro et al. 2005*; *Hamon 2008*; *Adams et al. 2009*; *Dubreuil – Savage 2014*; *Dubreuil et al. 2015*; *Hayes et al. 2018*). Because of this, we will first briefly summarize the recording approach and terminology used in this study.

As regards the raw materials, the experimental study collections have principally concentrated on the development of use-wear on sandstone (*Adams 1988*; *1989*; *Hamon 2008*; *Liu et al. 2010*; *2011*; *Gilabert et al. 2012*; *Zupancich – Cristiani 2020*; *Chondrou et al. 2021*), basalt (e.g. *Dubreuil 2004*), mica schist (*Risch 2002*; *Delgado-Raack 2009*), gabbro (*Risch 2002*; *Delgado Raack 2009*), granite (*Chondrou et al. 2021*), andesite (*Chondrou et al. 2021*), conglomerate (*Delgado-Raack 2009*), limestone (*Cristiani et al. 2012*; *Gilabert et al. 2012*), and quartzite (*Zurro et al. 2005*; *Gilabert et al. 2012*; *de la

*Torre et al. 2013*). These reference collections differ from each other mainly in terms of the heterogeneity of the raw material. Different variations have to be taken into account separately for each rock type (*Procopiou 1998*; *Hamon 2008*, 30; *Dubreuil et al. 2015*, 116).

## Materials and methods

### Use-wear analysis

The tools were first examined at a macroscopic level with the naked eye. Surface levelling and the distribution of irregularities were described. Using external low-angled light at a right angle to the objects helped us to identify the working surfaces, which bear linear traces, pits, homogeneous zones, and occasionally also potential shiny areas.

Microwear analysis was characterized using optical microscopes and involved two levels of observation. The first level of observation was at low magnification, i.e., less than 100x magnification. The low magnification approach commonly employs the stereomicroscope with an external light source at a right angle, which allowed us to comprehensively observe the relief in 3D, as well as the topography and use-wear traces (e.g. striations and mineral grain alteration) across the whole surface of the object. The reflected-light metallographic microscope for viewing opaque specimens was used in the high magnification approach, enabling a focus on the surface of up to 100x magnification (*Fullagar 2004*; *Dubreuil et al. 2015*, 124; *Hayes 2015*, 100; *Li 2020*, 14). For identification of distinctive and diagnostic use-wear patterns, especially polish, higher magnifications were needed.

The topography of the natural rock surface consists of protruding mineral grains dispersed within finer grains (matrix). The raised areas in the matrix are called asperities and between them there are spaces called interstices. In its natural state, each asperity has a different shape (*Adams 2013*, 32). When subjected to mechanical wear, the surface of the asperities can become abraded, levelled, rounded, or can develop cracks. During wear, not only the two surfaces and the crushed substance interact, but also the surrounding environment, causing tribochemical wear, which, unlike the previous destructive wear, is additive. It is formed after long exposure to different types of mechanical wear mechanisms such as adhesion and abrasion (*Varenberg 2013*, 336). A special environment is created on the surface where chemical reactions take place and the products form a smooth and shiny polymer film (*Czichos 1978*, 123–130; *Bhushan 2002*, 380). With tribochemical wear, deposits are formed on the surface and a conspicuous sheen develops (*Hamon 2008*, 1506).

Moving to the microscopic scale under low power magnification, the focus should be on the features that emerged from macroscopic observation and on the mineral grain alteration, mainly on the faces (levelled, fractured, unaltered) and edges (rounded, sharp). The use-wear development was described separately for each working surface area (WSA).

The analysis under high power magnification was focused on the polish, striations, and crystal alteration. Firstly, the development of the micropolish was described in terms of its density, distribution, dimension, brightness, and the appearance of the patches under 100x magnification. Then, attention was shifted to the texture (smooth, rough) and topography (flat, domed, reticular, pitted) of polished areas. If striations were present, their dimensions (length, width, depth), occurrence (frequent, occasional, scarce), polishing, appearance (polish, crystals) and orientation (parallel, oblique, chaotic) were noted. Finally, the appearance and modification of grains were also described for their faces (abraded, fractured, polished, striated) and edges (rounded, abraded, sharp, fractured; terminology used from *Adams et al. 2009*; *Dubreuil – Savage 2014*; *Hayes et al. 2018*; *Zupancich et al. 2019*).

## Experimental set

The raw material (Oparno rhyolite) used for the replicas has already been characterized in the scientific literature (*Šreinová et al. 2013*). The middle-grained, vesicular rhyolite has a porphyritic texture with large crystals of quartz and sometimes also feldspar (sanidine). Its color depends on the degree of weathering and the presence of manganese and iron in the matrix, thus variations between grey and reddish brown occur.

The experimental set (S1; *Fig. 1*) is composed of a "saddle-shaped" lower stone (L1) and an elliptical upper stone (U1) with only one active surface. The metrics are in given in table (*Tab. 1*). The replicas were manufactured by modern techniques using mechanized metal objects.

Use-wear analysis of GMTs is a challenge mainly due to the large size of the objects under investigation. In order to observe not only the patterns but also the spatial development of the use-wear, it was necessary to develop a recording strategy:

1. Before the experiments both of the tools were documented in detail, using photogrammetry, macro and micro photos, and 3D models.
2. The active surfaces of the L1 and U1 were divided into 5 areas (WSA) – one at each end, two on the margins and one at the centre (*Fig. 1: C, D*). Three locations were subsequently selected within each WSA, where the development of use-wear was to be observed microscopically.

   These observations should allow us to interpret the kinematics of the grinding set and the gestures involved in its use and to identify the substance being ground. According to the classification developed by *Leroi-Gourhan* (*1964*), and further elaborated by other scholars (e.g. *Nierle 1982*; *de Beaune 1989*; *Dubreuil 2001*), perpendicular, chaotic or longitudinal (back-and-forth, circular movement) gestures can be distinguished (*Dubreuil – Savage 2014*, 145). Determining the exact substance that was ground can sometimes be difficult, because of the complex history of the artefacts (*Adams 1988*, 312; *Hamon 2008*; *van Gijn – Verbaas 2009*). At the very least, it is possible to differentiate its hardness and to distinguish between plant, animal and inorganic matter.
3. The active surfaces were investigated under an Olympus SZX7 Stereomicroscope and an Olympus BXFM Optical Microscope. The microphotos were taken using a CANON EOS 1200D camera. Each tool was observed at low and high magnification: before the start of the experiments, then after 4 hours of use (phase one), and after 12 hours of use (phase two). In the case where the observed replica was too large for the manipulation space of the microscope used for high magnification (Olympus BXFM), silicon casts (3M™ Express™ Light Body Regular Set VPS Impression Material; i.e. *Fig. 3: F, G*) were taken of the tool's active surface.

| Designation | Feature | Type | Length (cm) | Width (cm) | Thickness (cm) | Weight (kg) |
|---|---|---|---|---|---|---|
| L1 | replica | lower stone – complete | 50 | 20 | 15 | 17.5 |
| U1 | replica | upper stone – complete | 30 | 15 | 11 | 5.3 |
| 712/08-432 | No. 59 | lower stone – fragment | 23* | 22 | 14 | 8.2* |
| 712/08-433 | No. 59 | lower stone – fragment | 22* | 21* | 16 | 6.5* |
| 190/08-199 | No. 28 | upper stone – fragment | 17* | 18 | 10 | 3.2* |
| 499/08-233 | No. 37 | upper stone – fragment | 22* | 18 | 7 | 2.6* |

Tab. 1. An overview of the main dimensions and weights of replica tools used in experiments (L1; U1) and fragmented artefacts from the Neolithic period (712/08-432; 712/08-433; 190/08-199; 499/08-233). Numbers with an asterisk refer to preserved dimension of the artefact.

## Test tools from the Vchynice site – macroscopic description

The four tools come from storage pits dated to the Stroke Pottery Culture (5000–4500/4400 BC; Late Neolithic in the Czech chronological system; see *Pavlů – Zápotocká 2013*), which were excavated at the Vchynice site. The site is located only 5 km away from the outcrops of rhyolite raw material. It was excavated during a rescue campaign carried out in 2008–2009. A total of 97 % of all GMT in the Vchynice assemblage were made of rhyolite. Following classification of the individual artefacts, the prevalence of used tools (18 upper stones, 9 lower stones) and particularly their fragments became evident. Incidence of flakes (21 cases) was confirmed, while complete semi-finished products and their fragments (9 cases) were the least represented group. A total of 14 hammerstones and at least 9 severely damaged or secondarily used polished stones were also recorded. According to the authors of the studies cited, they were used for processing of GMT (for details see *Řídký et al. 2014*; *2020*).

The size Neolithic artefacts seems comparable to experimental tools (*Tab. 1*). Selected grinding tools were documented using stereophotogrammetry with the Structure from Motion (SfM) method. This process generates a 3D model from multiple 2D images. (*Fig. 2*; *Online Supplementary Material 1*).

*Grinding tool 712/08-432*

This is approximately half of a lower stone which was found at a depth of 30 cm within the infill of a storage pit (feature No. 59). It is of rectangular shape, with one active surface, and has a straight longitudinal section and convex transverse section. The body was coarsely flaked. The dorsal part of the tool is straight in longitudinal section, but triangular in transverse section. It is possible that because of its poor stability it was originally embedded in the ground or in some kind of clay bench (?). This interpretation could not be verified in the experiment because the lower stone replica used had a flat bottom.

*Grinding tool 712/08-433*

This fragment of a lower stone (estimated preservation is 30 % of original size) comes from the same depth and the same storage pit (feature No. 59) as the previous artefact. It represents part of the edge of the tool and has only one active surface. This active surface is slightly concave in longitudinal section and straight in transverse section. The body was partly coarsely flaked during manufacture, but its side is finely flaked (suitable tools were found in the assemblage, see the introductory chapter). The dorsal face is flat, so it could have stood on the ground during use.

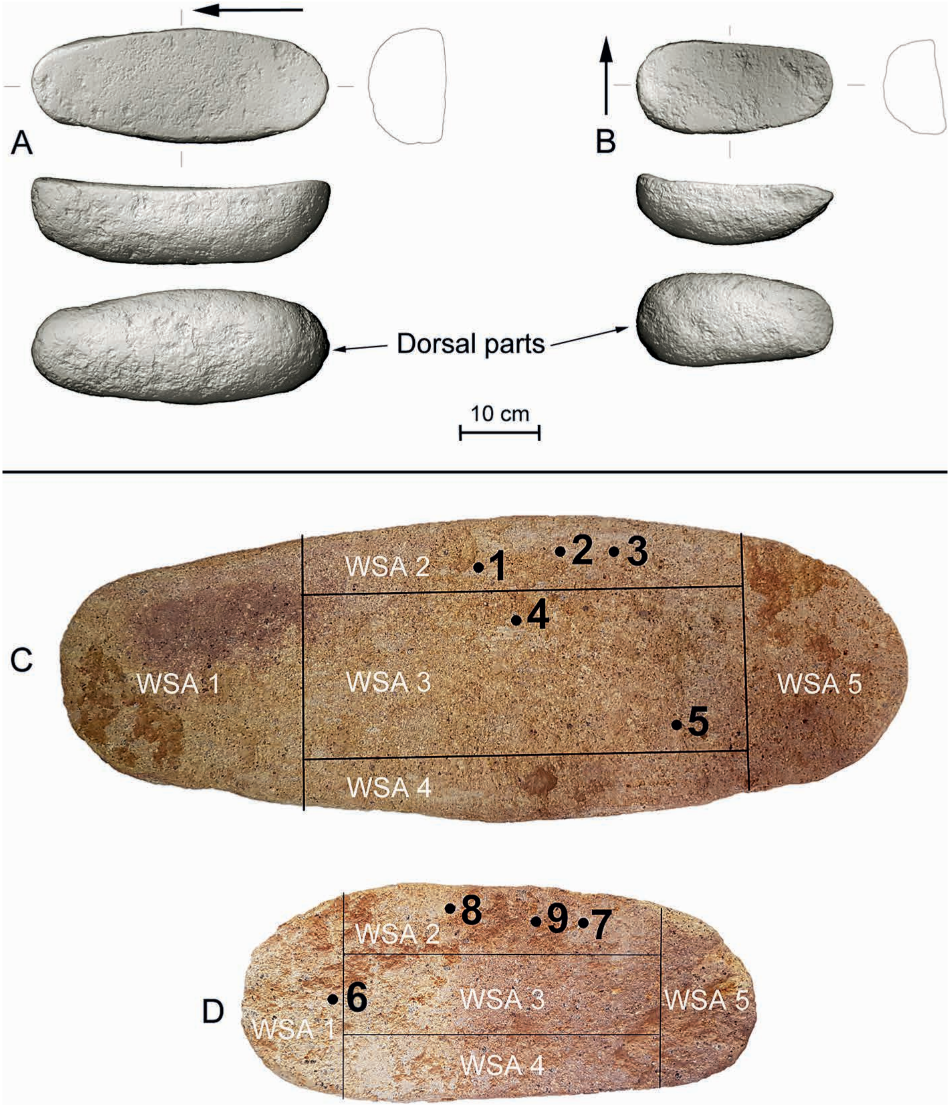

Fig. 1. Rhyolite replicas used in this study. A – 3D documentation of L1 (lower stone), the arrow indicates direction of grinding from the position of the user; B – 3D documentation of U1 (upper stone), the arrow indicates direction of grinding from the position of user; C – L1 with marked WSA and locations mentioned in the text; D – U1 with marked WSA and locations mentioned in the text.

*Grinding tool 190/08-199*

This fragment of an upper stone (estimated preservation is 30 %) comes from the infill of a storage pit (feature No. 28). It was found at a depth of 50 cm. Only the edge part of the original tool is preserved; the dorsal part is shaped for a better hand grip (probably for left hand) with a partly coarse-flaked, partly fine-flaked surface. The active surface is slightly concave in longitudinal section, and slightly convex in transverse section.

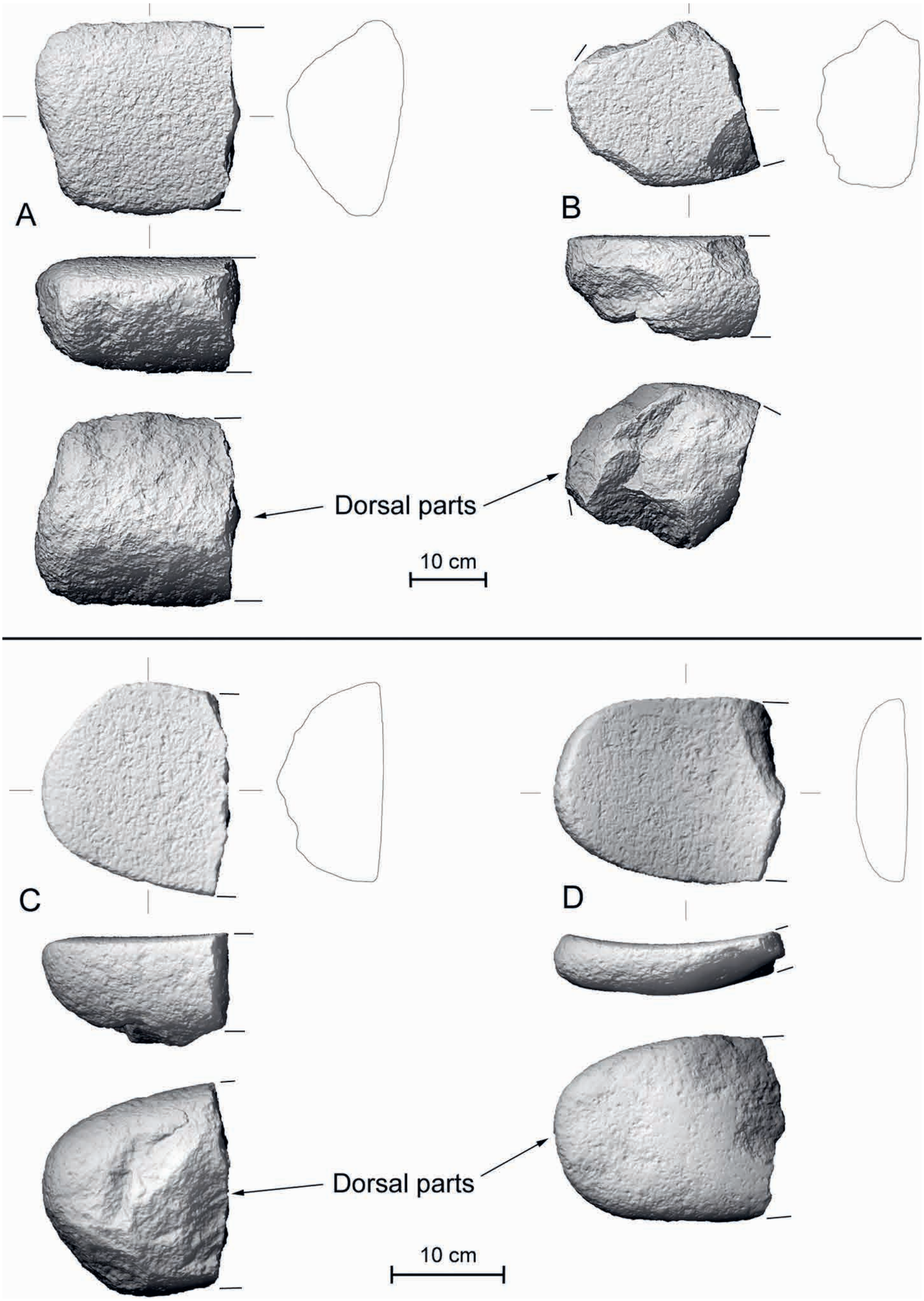

Fig. 2. 3D documentation of artefacts from the Neolithic site of Vchynice (NW Bohemia, Czech Republic). A – lower stone 712/08-432; B – lower stone 712/08-433; C – upper stone 190/08-199; D – upper stone 499/08-233.

*Grinding tool 499/08-233*

This edge fragment of an upper stone (estimated preservation is 50 %) comes from the 50 cm deep infill of another storage pit (feature No. 37). The tool is of oval shape with one active surface. This surface is concave in longitudinal section and convex in transverse section. The body is carefully fine-flaked and probably ground. Rejuvenation pits and striations perpendicular to the longer axis were observable by the naked eye on the active surface. It is believed that this tool was deliberately destroyed (*Řídký et al. 2014*).

## Results

### Experimental grinding

The experimental grinding of dehusked einkorn wheat was divided into two phases. In phase one lasting 4 hours, 1 kg of grain was ground into 977 g of flour which was then sieved using a 1 mm mesh. In the second phase, 4 kg were ground into 3869 g for approximately 12 hours. The wheat grains were ground in a back-and-forth motion and the U1 was held by two hands (see *Fig. 9: A*). Because it was difficult for the inexperienced user to remain in one position all the time, three positions were rotated: kneeling, squatting, and sitting (see *Fig. 9: B*). In general, the U1 moved mainly along the central part of the L1, closer to the person who was using it. However, an important observation from the experiment is that each change in position slightly shifted the point of contact between the upper and lower stone.

*The first phase*

After four hours of use, no major changes were observed macroscopically, but the active surface of L1 seemed to be a little more roughened and the production grooves started to appear. The edges of the central part seemed to be more levelled and larger homogeneous zones were concentrated there. The most striking changes took place in the middle section. The surface was more abraded and the protruding mineral grains (mainly feldspar) were slightly levelled, striated, and polished (*Fig. 3: A*). The edges of the mineral grains did not seem to be greatly affected. The grains of quartz minerals appeared to be more fractured and not so levelled (*Fig. 3: B, C*). The abrasion of the material was most significant in the part closer to the person operating the GMT, so even in this first phase taking only several hours of work, it was possible to identify the orientation of the tool relative to the user and the way in which the tool was manipulated (motion). However, the left side of the tool (WSA 4) was significantly abraded, which is probably because the user was right-handed. This in itself is another important finding.

On the active surface of U1, the changes were more apparent than on the lower stone, even macroscopically. The active surface was irregularly smooth and the margins were highly levelled into homogeneous zones. The left side of the tool (WSA 1) was mainly affected by abrasion of the material (*Fig. 5: A*). There were clear pits on the surface from extracted mineral grains and the faces of the grains were sometimes significantly fractured. This abrasion was probably due to direct stone-on-stone contact that was not inhibited by the presence of a layer of ground substance. There was also much more pressure on this side (WSA 1) because the user was right-handed. However, the most considerable changes occurred on WSA 2, where enough ground substance had probably accumulated

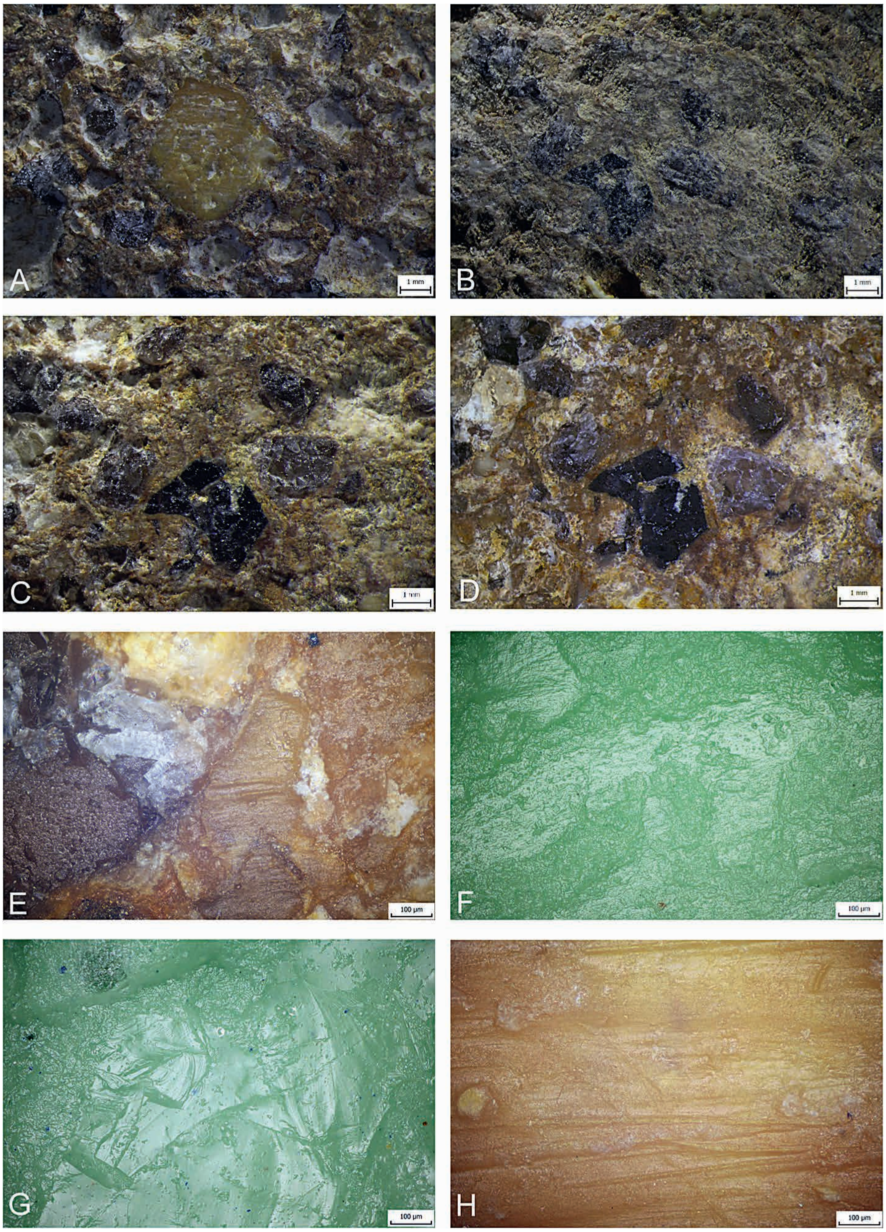

Fig. 3. Experimental lower stone L1, locations marked in *Fig. 1*. A – location 1 after the first phase, levelled surface with striated feldspar grains (OLYMPUS SZX7 Stereomicroscope, 16x magnification); B – location 2 before the first phase, uneven surface with quartz grains (OLYMPUS SZX7 Stereomicroscope, 16x magnification); C – location 2 after the first phase, levelled surface with fractured quartz grains (OLYMPUS SZX7 Stereomicroscope, 20x magnification); D – location 2 after the second phase, levelled quartz grains (OLYMPUS SZX7 Stereomicroscope, 20x magnification); E – location 3 after second phase, micropolish on quartz grains (OLYMPUS BXFM Optical Microscope, 200x magnification); F – imprint of the active surface on silicon casts, location 1 after the second phase, micropolish on the high topography (OLYMPUS BXFM Optical Microscope, 200x magnification); G – imprint of the active surface on silicon casts, location 4 after the second phase, polished crystal with abraded faces and rounded edges (OLYMPUS BXFM Optical Microscope, 200x magnification); H – location 1 after the second phase, deep long striations on the feldspar grain (OLYMPUS BXFM Optical Microscope, 200x magnification).

to form a protective layer on the working surface. Large homogeneous zones were created at the edge of this area. The grain minerals had levelled faces with fine striations and polished areas (*Fig. 5: B, C, D*). Towards the middle part of the tool, the surface had become uneven and irregular. There was some minor abrasion, which gave the impression of pits from dropped mineral grains. However, the quartz grains had levelled faces with fine polish. The area more distant to the user (WSA 4) was also highly abraded and levelled. The quartz grains remained fractured.

*The second phase*

After twelve hours of use, the active areas were much more defined on both parts of the experimental set. The active surfaces were still partially roughened, but grooves from production were no longer observable.

On the L1 type, large homogeneous zones formed in the parts where the stone-on-stone contact was most intensive, mainly at the edges. The central part was partially levelled, but still sufficiently rough. Moving to the microscopic level, the development of the wear intensified and became more pronounced. The surface became increasingly levelled. Spreading amalgamation of mineral grains occurred on homogeneous zones; the asperities started to merge with the matrix and their edges could not be distinguished. Although there were still dark fractured quartz crystals present, even these mineral grains gradually became homogeneous with a smooth surface (*Fig. 3: C, D*). The polish began to intensify and densely covered the active surface in large patches. It had a smooth texture and domed to flat topography (*Fig. 3: E, F*). The edges of large crystals were abraded and rounded (*Fig. 3: G*). Long, deep, polished, parallel striations appeared in the polished areas from the stone-on-stone contact (*Fig. 3: H*). the abrasion of the material was even more significant in the part located closer to the user (*Fig. 4: A, B*).

The U1 type was much more affected by abrasion of the raw material. WSA 2, located closer to the user, was highly abraded primarily at the edges. Many pits from dropped mineral grains occurred in this part and some crystals were still fractured (*Fig. 5: E*). On the homogeneous zones the mineral grains were levelled and the asperities merged with the matrix. The large mineral grains had rounded edges and polished and striated faces (*Fig. 5: F*). In the middle part, the active surface was more uneven and irregular with a lot of pits and fractured crystals. Homogeneous zones with levelled and polished mineral grains, but without striations, also occurred. The area of WSA 4 located more distant to the user was affected in the same way as the middle part. The grip areas of the upper stone were smoothed.

## Summary of the experiment

Both phases of the above-presented experiment yielded several important findings, usable in our planned test. Traces of use-wear appear relatively soon, after only a few hours of use, so it is possible to distinguish between rhyolite tools that have been used at least briefly and those that have never been used. After grinding of dehusked einkorn wheat, the same traces of use-wear can be observed on the rhyolite raw material as on other, softer (sandstone) or harder (basalt) types of raw materials. The use-wear traces after the first phase of grinding were difficult to distinguish macroscopically, probably due to the hardness and cohesion of the raw material. On closer observation, patterns that were not apparent on previous inspection began to emerge. On the one hand, the area close to the user

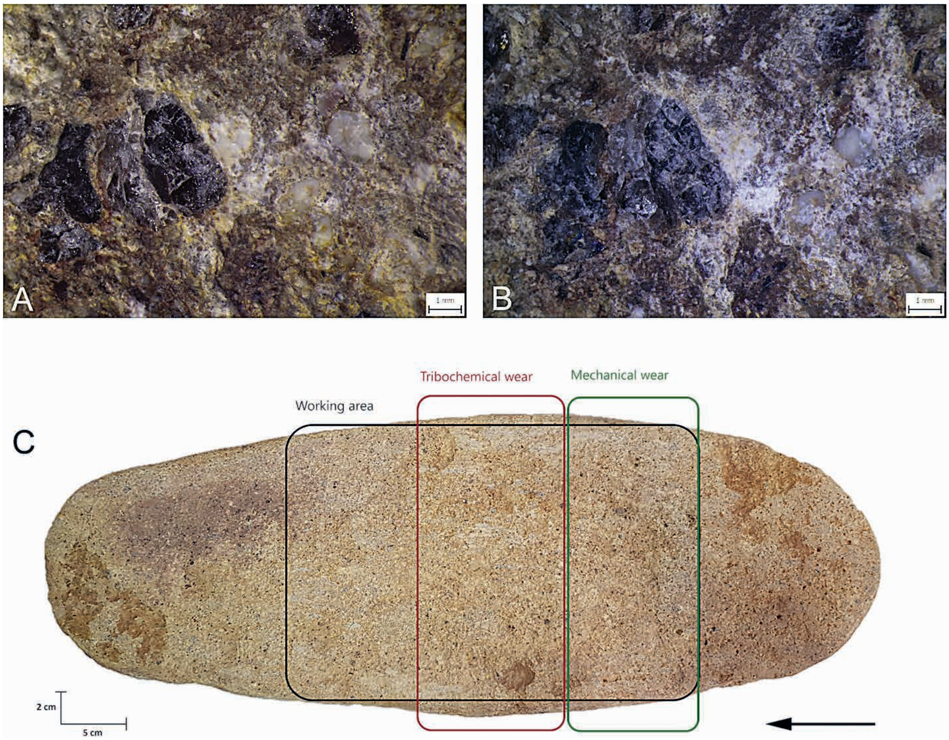

Fig. 4. Experimental lower stone L1, locations marked in *Fig. 1*. A – location 5 after the first phase, abraded surface with fractured grains (OLYMPUS SZX7 Stereomicroscope, 16x magnification); B – location 5 after the second phase, abraded surface with fractured grains (OLYMPUS SZX7 Stereomicroscope, 16x magnification); C – active surface of lower stone L1 with distribution of prevailing mechanisms of wear, the arrow indicates direction of grinding from the position of user, the right side on the picture is corresponding to the side closer to the user, the left side on the picture is corresponding to the side more distant from the user.

was greatly affected by mechanical wear (see *Fig. 4: C*). On the other hand, the middle part, where the accumulation of ground substance occurred, was much more affected by tribochemical wear (levelled surface with amalgamated grain minerals and well-developed polish). Therefore, we can determine the orientation of the lower grinding stone relative to the user (*Fig. 4: C*).

Each change of the position of the user shifted the point of contact between the upper and lower stones. Due to the application of different levels of pressure, reflected in differential mechanical wear, it was possible to determine whether the operator was left-handed or right-handed (*Fig. 5: G*). The dominant (right) hand just maintained the correct direction of the grinding motion and therefore applied little pressure. Wider homogeneous zones, caused by stone-on-stone contact, gradually appeared on the longitudinal edges of the lower stone. It is therefore possible to determine that the compatible upper stone extended beyond the edges of the lower stone. After the second phase of the experiment, the wear sequence started to intensify and traces overlap. However, it became more complicated to reconstruct the use-wear patterns, especially on the U1 on which the greatest abrasion of material occurs.

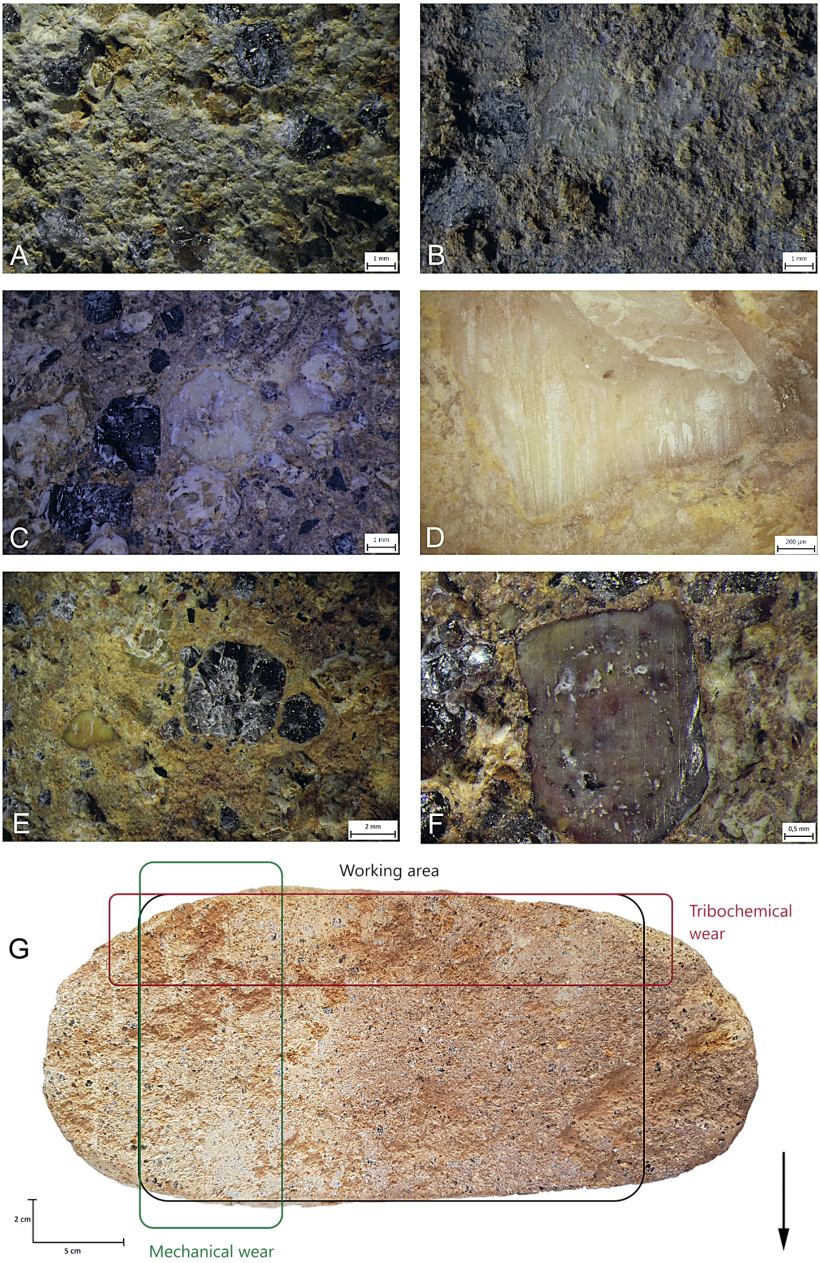

Fig. 5. Upper stone U1, locations marked in *Fig. 1*. A – location 6 after the first phase, surface with lot of pits and fractured grains (OLYMPUS SZX7 Stereomicroscope, 16x magnification); B – location 7 before the first phase, uneven surface (OLYMPUS SZX7 Stereomicroscope, 16x magnification); C – location 7 after the first phase, surface with levelled feldspar and quartz grains (OLYMPUS SZX7 Stereomicroscope, 16x magnification); D – location 7 after the first phase, micropolish with striations (OLYMPUS BXFM Optical Microscope, 100x magnification); E – location 8 after the second phase, levelled surface with fractured quartz grain, (OLYMPUS SZX7 Stereomicroscope, 12,5x magnification); F – location 9 after second phase, striated feldspar grain with rounded and polished edges (OLYMPUS SZX7 Stereomicroscope, 32x magnification); G – Active surface of lower stone U1 with distribution of prevailing mechanisms of wear, the arrow indicates direction of grinding from the position of user, the right side on the picture is corresponding to the side held by right hand, the left side on the picture is corresponding to the side held by left hand.

## Test of Neolithic tools from the Vchynice site

The purpose of this part is to use the findings from the experiment to inform analysis of microscopic use-wear on original archaeological tools and to test their applicability.

*Grinding tool 712/08-432*

Unfortunately, the active surface of this lower stone is not very visible due to the presence of a thin layer of sinter, but the tool was evidently used (*Fig. 2: A*). According to the shape of the active surface (convex in transverse-section) and based on the presence of light wear, it is likely that the active surface was already shaped this way during manufacture. Nevertheless, it is evident that the topography is very uneven, irregular, and considerably pitted. Only a small part of the surface shows clear traces of stone-on-stone contact. There is a concentration of mineral grains that have a levelled surface and a striated, flat micropolish has developed on the higher topography in separate small patches.

The lower stone was probably used only for a short period. Due to its fragmentary state and layer of sinter, it is not possible to determine the position of the user. The use-wear traces are unclear, so it is impossible to determine what substance was ground.

*Grinding tool 712/08-433*

Macroscopically, the active surface of this lower stone is covered by numerous pits (*Fig. 2: B*; *Fig. 6: A*). Therefore, the topography is uneven and the roughness is irregular. Some areas are slightly levelled. On detailed observation, these areas do not show a high degree of levelling or amalgamation of mineral grains, so they cannot be called homogeneous zones. The feldspar grains are sometimes levelled but the quartz grains are mostly fractured. The micropolish densely covers the high and low topography of the surface in large patches. It has a smooth texture with striated and domed topography (*Fig. 6: B*). The crystals are sometimes fractured, but they mostly have highly abraded and polished faces and rounded edges (*Fig. 6: C*).

This tool was used, but probably not for a back-and-forth movement. The user's position cannot be determined. The traces show some combined transverse and longitudinal movement. No clear traces of stone-on-stone contact are present. So, it is possible that the tool was used as a netherstone (grinding table) or with a wooden upper tool. The use-wear analysis and experimental tests have been already conducted with wooden upper tools (*Risch et al. 2002*, 111–129) and the use-wear patterns have certain common features. The ground substance was probably soft plant matter, but the traces found do not correspond to the experimental grinding of einkorn wheat.

*Grinding tool 190/08-199*

The active surface of this upper stone has a flat topography and irregular roughness caused by deep pits that densely cover the whole area (*Fig. 2: C*; *Fig. 7: A*). No clear homogeneous zones are macroscopically distinguishable. The surface was therefore divided into three WSAs. Microscopically, the topography is more uneven being covered by irregular pits and homogeneous zones with amalgamated mineral grains. The quartz crystals are sometimes levelled but also fractured (*Fig. 7: B*). The feldspar crystals mostly have levelled faces and rounded edges. The levelled mineral grains with rounded edges are principally concentrated in the middle part (WSA 2). WSA 3 seems to be more abraded and features lots of pits. The micropolish has a smooth texture with domed and striated topography and predominantly covers the high topography of the surface but also extends to the

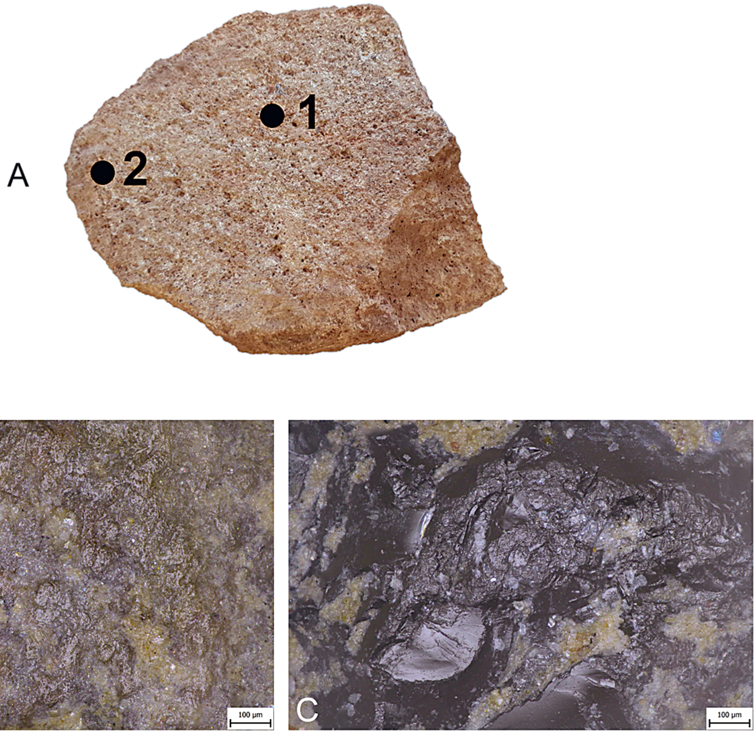

Fig. 6. Neolithic grinding stone 712/08-433 with marked locations mentioned in the text. A – location 1, distribution of micropolish (OLYMPUS BXFM Optical Microscope, 200x magnification); B – location 2, crystals with abraded and rounded edges (OLYMPUS BXFM Optical Microscope, 200x magnification).

lower parts (*Fig. 7: C*). The asperities are covered by short, fine, parallel striations with random orientations towards the grinding stone.

We assume that the tool was mainly used as an upper stone because of the predominant transverse direction of the striations. According to the use-wear traces, WSA 3 was probably closer to the user, which corresponds with the location of the handling spot. However, it is possible that the grinding stone may have been occasionally also used as a lower stone due to the longitudinally oriented striations. The stone was not used as an active tool for a very long time and it was probably slightly longer than the width of the compatible lower stone. It is unclear what caused the destruction of the tool.

The substance that was ground must have been quite hard but at the same time fleshy, as the traces of use-wear also affected the lower parts of the surface topography. It is probable that the artefact was used to process some kind of seeds (cereal or legume; *Dubreuil 2004*, 1618).

*Grinding tool 499/08-233*

Macroscopically, the surface of this upper stone fragment has a flat topography and irregular roughness. The entire surface is densely covered with long, deep, wide scratches oriented perpendicularly to the longer axis. In the middle part is a concentration of irregular deep pits. There is a large homogeneous zone with levelled mineral grains at the rim

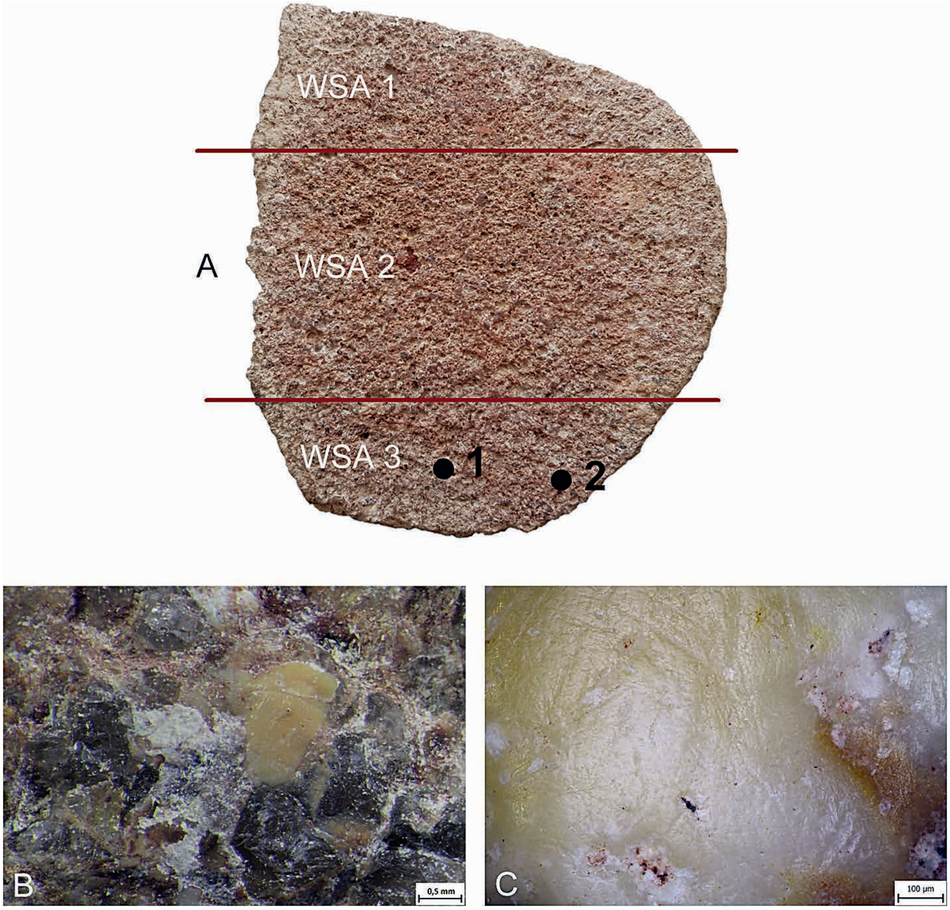

Fig. 7. Neolithic grinding stone 190/08-199 with marked WSA and locations mentioned in the text. A – location 1, levelled surface with fractured quartz grains (OLYMPUS SZX7 Stereomicroscope, 32x magnification); B – location 2, striated micropolish (OLYMPUS BXFM Optical Microscope, 200x magnification).

where a harder ferrous quartz vein passes through the stone. With closer observation, the tool surface was divided into four WSAs (*Fig. 2: D*; *Fig. 8: A*).

WSA 1 and 2 have a predominantly flat topography. They are covered with fine, short and parallel striations and the grains (predominantly the feldspar minerals), have levelled faces, and sometimes rounded edges. This use-wear pattern is most developed on the vein because the material is very cohesive and hard. For that reason, there was no visible abrasion of the material during grinding. When examined microscopically at a high magnification, it is evident that the micropolish is well developed on levelled mineral grains and on the homogeneous zone (vein); it covers the surface densely in large patches. It has a smooth texture and domed to flat topography with deep striations typical for stone-on-stone contact (*Fig. 8: B*). WSA 3 and 4 have a more uneven, irregular topography and are covered with irregular pits. The mineral grains are sometimes slightly levelled but more often fractured and covered with short deep striations (*Fig. 8: C*).

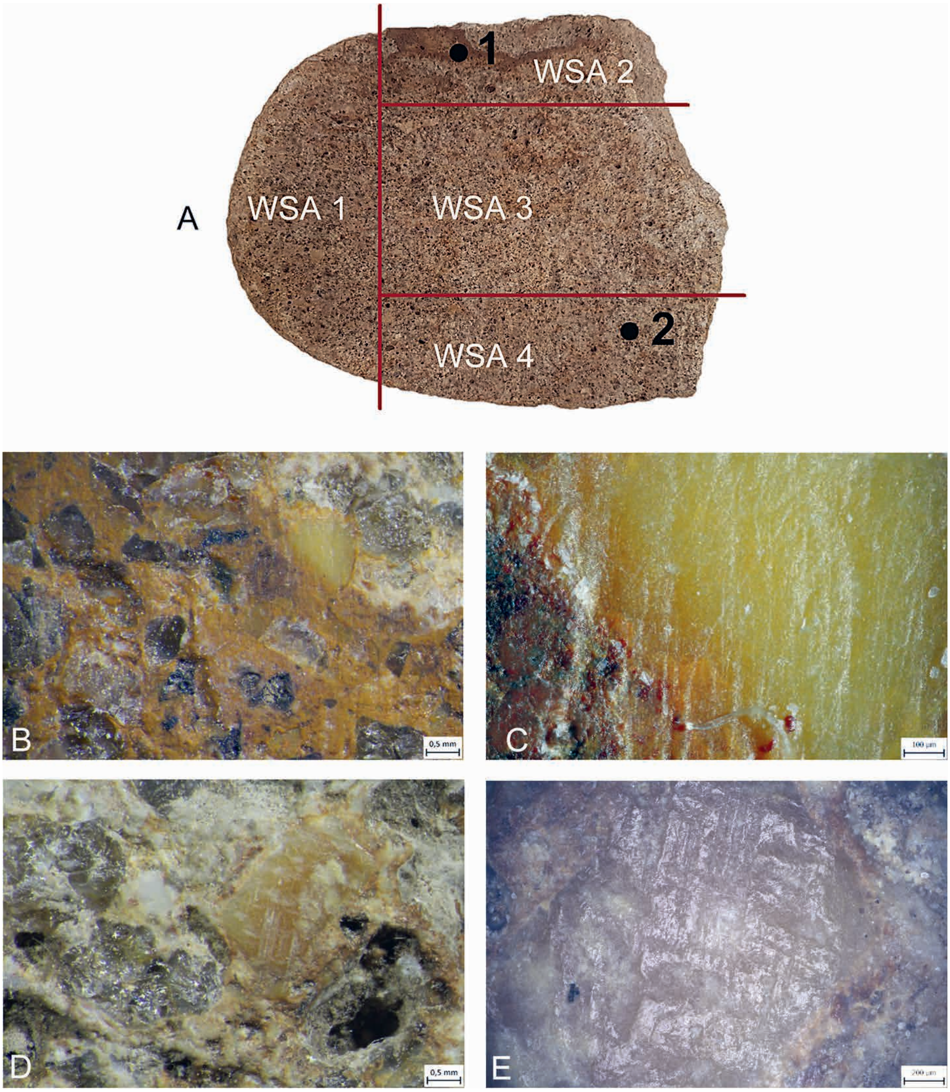

Fig. 8. Neolithic grinding stone 499/08-233 with marked WSA and locations mentioned in the text. A – location 1, levelled surface (OLYMPUS SZX7 Stereomicroscope, 32x magnification); B – location 1, striated micropolish on the feldspar grain (OLYMPUS BXFM Optical Microscope, 200x magnification); C – location 2, uneven surface with fractured grains (OLYMPUS SZX7 Stereomicroscope, 32x magnification); D – location 2, striated micropolish on the feldspar grain (OLYMPUS BXFM Optical Microscope, 200x magnification).

This upper grinding stone was probably used for a long time, which is evident from the well-developed wear in WSA 1 and 2, where the greatest stone-on-stone contact occurred. The use-wear pattern of WSA 3 and 4 indicate that the last activity related to the rejuvenation of the tool during which the breakage occurred. Therefore, it is not clear what substance was ground. As an active tool, it is likely that WSA 2 was located close to the user during grinding and the studied tool was longer than the width of the compatible lower stone.

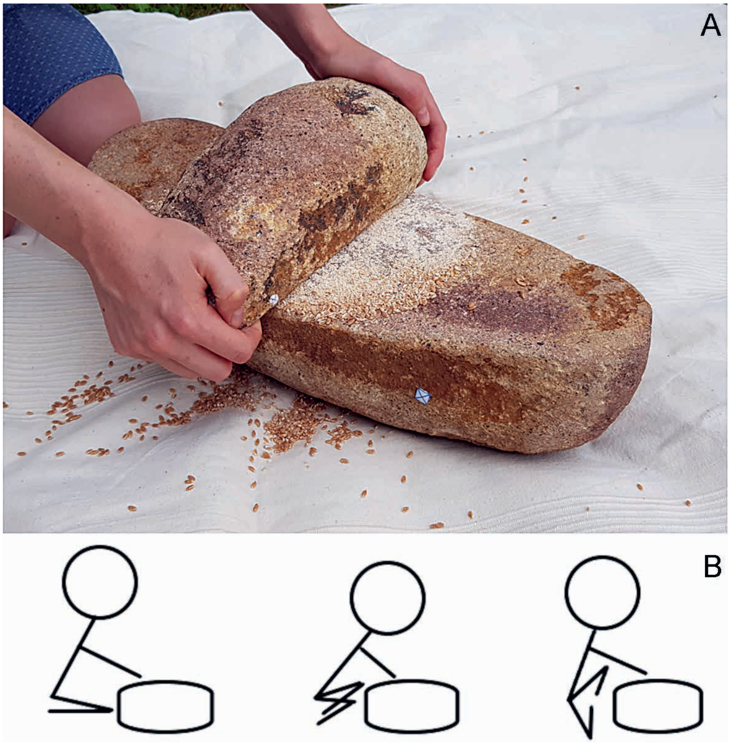

Fig. 9. A – handling of the tool during grinding; B – positions during grinding.

## Discussion

The results of the experimental program can be compared with data collected from previous analyses. According to them, the highest topography of the surface is flattened through stone-on-stone contact (*Dubreuil 2004*, 1618; *Bofill et al. 2013*, 228; *2020*, 18; *Zupancich – Cristiani 2020*). The processing of cereal creates residues covering the highest topography of the surface of homogeneous zones, which are then affected by levelling and smoothing of mineral grain faces and rounding of the grain edges (*Dubreuil 2004*, 1618; *Hamon 2008*, 1511; *Hayes et al. 2018*, 104; *Zupancich – Cristiani 2020*). The micropolish is characterized by a smooth texture and a domed to flat topography with the occurrence of parallel striations (*Dubreuil 2004*, 1618; *Bofill et al. 2013*; *Hayes et al. 2018*, 104; *Cristiani – Zupancich 2021*). Similar traces were documented in our study.

However, in contrast to previous studies, we focused on the development of wear on a material not yet included in the experimental programs. This volcanic rock appears to be very hard and cohesive with a porphyritic structure and the presence of large phenocrysts of quartz and feldspar. In the experiment, it was possible to observe the development of the use-wear on the individual minerals. The quartz grains had a much greater tendency to fracture; their faces became levelled only after a certain time and under certain conditions and the rounding of the edges was almost unnoticeable. Soft feldspar grains, on the other hand, did not fracture. Instead, the levelling of the faces and rounding of the edges occurred very rapidly.

The development of use-wear was observed and investigated on a set of GMTs that are specific in their shape. This confirmed the idea, already forwarded by many scholars (e.g. *Leroi-Gourhan 1964*; *Dubreuil 2001*; *Adams – Saed Mucheshi 2020*; *Dietrich 2021*; *Santiago-Marrero et al. 2021*), that the study of use-wear traces can throw light not only on the substance that was processed but also, and more importantly, on the kinematics – movement of the upper stone on the lower one – employed. Our experiment has also shown that it is possible to determine whether the user of a tool was right-handed or left-handed based on the degree of abrasion of the material on one particular side. At the same time, the orientation of the grinding stone relative to the user can be determined.

On the lower stone, the part closest to the user is more exposed to mechanical abrasion, while the opposite part witnessed greater accumulation of fine ground substance that protects and covers the surface. It is thus more exposed to the development of polish on the levelled surface (probably dominance of tribochemical wear). Such use-wear pattern is of course caused by the movement of the upper tool on the lower one, morphology of the tools and by the grinding strategy of the user as well. At the same time, it is clear that the longer time the grinding stones are used, the more illegible these traces become. The position of the user is much easier to determine on complete tools than on fragments.

The next part focused on use-wear traces on four archaeological artefacts, the test tools, on which the findings from the experimental phase were applied. The GMTs from the Neolithic storage pits on the Vchynice site had a very complex life history. Their fragmentary nature and conditions of deposition make interpretation difficult. Furthermore, the last activity also masked information regarding prior use, which is an issue many scholars pointed out (*Adams 1988*, 312; *Hamon 2008*; *van Gijn – Verbaas 2009*). Nevertheless, this method complemented and strengthened the evidence gleaned from macroscopic observation. At the same time, it provided a lot of information on the kinematics, grinding strategy, change of position within the set, secondary use, and characterisation of the substance that was ground.

## Conclusions

In this paper we have presented the first results of an experimental program that tests rhyolite replicas of grinding-milling tools for grinding of various substances, in this case dehusked einkorn wheat. The recorded use-wear patterns were used as a reference collection for the investigation of four GMTs, two lower stones and two upper stones, all made of rhyolite, from the Neolithic site of Vchynice.

It was confirmed that it is possible to prove the use of rhyolite GMTs for grinding of crops since their use produce traces similar to recorded on other materials. Moreover, it is possible to distinguish between tools in long-term and short-term use. Thanks to the study of use-wear we can also reconstruct the grinding methods and the positioning of GMTs during use (kinematics); we can also glean other details about the user. Using our test tools from the Vchynice site it was possible to trace changes in the function of individual stones, from lower stone to upper stone (GMT 190/08-199). We were able to determine, that both upper stones were slightly longer than the width of the compatible lower stone (GMT 499/08-233, 190/08-199). Last but not least, analysis of use-wear helped to determine the position of the user relative to the upper grinding stones (GMT 499/08-233, 190/08-199), according to the development of the use-wear traces, which corresponds also to position of handle (GMT 499/08-233). Although it is recommended to use complete tools for this type of investigation to reach more detailed conclusions, even these initial findings on Neolithic tools evident that wheat was not the only substance processed using such tools and the lower grinding stones were not always combined with stone upper tools. This study showed, among other things, the informative possibilities of the study of grinding-milling tools, which can enrich our knowledge about the activities and behavior of past societies and their dietary habits. For further comparative analyses and deepening the knowledge, it will be necessary to continue with controlled grinding experiments with differently shaped replicas and various substances.

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