The study of ancient technologies frequently involves a combination of experimental modeling and traceological analysis. The results depend on the physical properties of the materials. The results of the traceological analysis of archaeological artifacts and their experimental models are compared and in this way ancient technologies are reconstructed. Stone, bone, and metal possess certain combinations of characteristics that make it possible to process and use these materials (Girya, 1997). Experiments and traceological analysis reveal the ways in which the ancients manufactured and used their artifacts. The technological and functional aspects of these processes are critical (Semenov, 1957).
The traceological analysis of petroglyphs focuses on the morphology of tool marks and assesses the possibilities of processing a specific rock. Experimental data have been used in petroglyphic studies since the end of the 19th – beginning of the 20th century (Whittaker, Koeman, Taylor, 2000). The technological aspects of the execution of rock art images have been addressed by M.A. Devlet, S.V. Kiselev, T. Mirsatov, D. Kabirov, A.K. Filippov, and other researchers (Devlet, 1998; Kiselev, 1930; Mirsatov, Kabirov, 1974; Filippov, 1994, 2004). E.Y. Girya and E.G. Devlet applied a new approach to petroglyph studies based on methods elaborated by A.S. Semenov (Girya, Devlet, 2008; Devlet, Girya, 2011). Their technological and traceological analyses of well preserved, pecked petroglyphs revealed traceological features of percussion traces characterizing the material (stone/metal) of which the pecking tools were made (Ibid.). The data obtained made it possible to indirectly date certain images pecked using metal tools to later periods, yet the data does not provide information that would indicate the exact age of such images (Sher, 1980). Experiments show that this method has great potential. It is a method that makes it possible to distinguish the pecking technique used (direct percussion when the striker leaves traces on the rock surface; indirect percussion when a hammerstone strikes a chisel placed on the rock surface), as well as certain properties of the metals and stones used to create the instrument itself (e.g., the degree of wear resistance), etc. Traceological analysis of rock art discloses multiple technical options and devices whereby pecked representations are created. Combinations of specific technologies are informative as they attest to traditions in the choice of technique and tool. No doubt the principal criteria for the attribution of petroglyphs are image and style (Ibid.). However, technology is also an important constituent, which is inherently related to other criteria. Thus, analysis of technologies of percussion can provide new insight into the chronological and cultural attribution of petroglyphs (Zotkina, 2012).

Technological studies in archaeology include experiments at different levels with various objectives. Initially, they are helpful in understanding the technological properties of materials used. While these experiments cannot provide us with an understanding of an entire technology, they are helpful in correctly formulating lines of enquiry, gaining prospects for further experiments, constructing models replicating specific techniques and extrapolating these onto actual archaeological findings. The next step is to look for answers to questions that arise at the initial stages of analysis. By juxtaposing technological findings with those of the traceological analysis, we are able to specify our conclusions. At the final stage, the technological process is replicated, and the resulting replicas must match actual prototypes.

Within the framework of field studies conducted in 2012 focused on the technology of rock art in the Minusinsk Basin, a series of experiments was performed at various levels. Blocks of red-colored Devonian sandstone with beds located perpendicular to the working surface were used in these experiments. The traceological analysis of experimental percussion traces on this rock helped establish a combination of indicators reliably distinguishing direct and indirect percussion, regardless of the material from which the tool was made. The first of these refers to the boundaries of the petroglyph. The outline of the image executed by indirect percussion is normally clear-cut and relatively even regardless of line width. By contrast, blows made by direct percussion are less controllable, so the rock surface frequently demonstrates dints outside the contour. A line of dense percussion with distinct borders and overlapping peck marks can also be produced by direct percussion. The line in this case is wider (about 1.5–2.0 mm). Direct percussion with sparse (non-overlapping) peck marks produced vague outlines and abundant isolated dints. This technique is suitable for filling in the background of an image, although contour petroglyphs executed in this technique have also been recorded. A distinctive feature of direct percussion is considerable variation in the size of dints occurring within a single area. The reason for this is that the trajectory of the tool movement and the striking force are poorly controlled and so the resulting dints differ from one another. A heavy blow results in a deeper penetration of the tool tip into the rock surface, the dint being usually broader than in the case of a gentle blow leaving but a shallow mark on the rock surface. In addition, the shape of dints resulting from direct percussion is less standard than in the case of indirect percussion. This is related to the different kinematics of the movements of the striking tool. Blows can be direct and tangential to the rock surface (similar kinematics is typical of the
adze). The resulting peck marks are often oblong and their depth varies within the dint.

Over the course of experiments into indirect percussion technique, a set of features typical of this technique was established. Firstly, the resulting lines have distinct boundaries; there are virtually no peck marks occurring beyond the lines. This technique is laborious and time-consuming. The artist is able to control the blows and thus to locate every dint in its proper place. Therefore the artist must be very careful in arranging the marks on the rock surface. Another feature of this technique, closely connected to the above, is the order of dints. A special location of peck marks, as in the case when the outline is made in one or two rows of dints located close to one another, likely points to a particular strategy of image creation. This is illustrated by certain petroglyphs in the Minusinsk Basin (Fig. 1, 1, 5). Lines made by dense indirect percussion are often narrow – just one of two dints wide versus comparatively broad lines made by direct percussion. The depth of peck marks is another diagnostic indicator not only of the technique used but also of the tool. Dints produced by indirect pecking are usually deeper than those produced by direct percussion.

The purpose of our series of experiments was to establish the characteristic features of traces of percussion executed using various techniques and tools. The objectives and conditions of these experiments were determined on the basis of previous experimental findings (Zotkina, 2012).

Experiments suggest that the robustness of the tool is an important factor. A thin metal tool such as a small pointed rod, even one made of hardened steel, does not produce deep dints when direct percussion is used. In this case, the dints are small and very shallow (less than 1 mm deep). These marks are clearly identifiable and unlikely to be confused with other kinds of marking. They are rare in southern Siberian petroglyphs. However, when such a thin, hard metal instrument is used as a mediator, small but deep dints result. This serves as a diagnostic feature for determining the use of such tools as mediators in indirect percussion (Girya, Devlet, 2010; Girya et al., 2011) (Fig. 2, 3–5).

A heavy metal tool with a robust working end, like a pickaxe, used directly, produces medium-depth peck marks because a heavy tool intensifies the striking force (Fig. 2, 1, 2). The metric parameters are important. A heavy tool with a thick working end penetrates relatively deeply into the rock surface. Dints in this case are usually wider than those produced by a thin rod because the contact surface of a larger instrument is usually greater. The resulting peck marks show a combination of universal characteristics indicative of direct percussion.

A thick metal tool used as a mediator produces the deepest dints (Fig. 3, 2). Deep isolated marks can be seen, for instance, at the Malaya Boyarskaya rock art site (Fig. 3, 1). Our experiments have enabled us to reconstruct how deep dints are produced. Direct percussion with a pointed robust tool such as a rod or a pickaxe does not produce deep or regularly shaped dints. When we used a specially pointed steel pickaxe like those employed by stove makers as a mediator, and a hammer with a steel working part as a striker, the resulting dints were similar in depth and shape to large dints found at Malaya Boyarskaya (Fig. 3, 2, 3). The latter, however, are slightly narrower and longer. The reason for this may lie in the ancient tool being grinded at a more acute angle. The pattern of cracking on the right side of virtually all peck marks is identical in both cases and demonstrates the direction of the blow (Fig. 3, 1–4). Also, some dints at Malaya Boyarskaya are crescent-shaped like those obtained in our experiment (Fig. 3, 4).

One of the objectives of the 2012 experiments was to study percussion marks produced by tools made of various materials. It was demonstrated that both stone and metal instruments must be very hard, firm, and wear resistant in order to leave marks on red Devonian sandstone. Metal instruments should also be plastic enough to prevent breaking. Traces left by stone and metal instruments were compared. The efficiency and technological capacity of tools of various shapes made of various rocks and metals were assessed.

In previous experiments mostly flint and quartzite tools were employed (Girya, Devlet, 2008; Girya et al., 2011; Zotkina, 2012). Quartzite with a high quartz content is harder and more durable than flint. Both rocks are mostly isotropic and suitable for knapping, resulting in pointed blanks with various trimming angles. In the 2012 experiments Shalabolino local pebbles were used.

The Shalabolino petroglyphic gallery, near to which the experiments were conducted, is located on the right bank of the Tuba, the right tributary of the Yenisei. Pebbles collected near the river are composed of debris of various sedimentary and
Fig. 1. Shalabolino gallery petroglyphs and experimental peck marks comparable to ancient prototypes. 1 – zoomorphic image in area 4; 2 – details of the zoomorphic image (head and neck of an animal); 3 – indirect pecking marks experimentally made using a relatively small metal chisel; 4 – representation of a reindeer in area 4; 5 – details of the reindeer representation (the animal’s neck); 6 – indirect pecking marks experimentally made using a pebble tool as a mediator.
Fig. 2. Peck marks experimentally produced with metal tools.
1 – direct peck marks left by a robust metal tool; 2 – robust metal pickaxe used in experiments; 3, 4 – peck marks left by relatively small metal mediators with variously shaped tips, and tools used in experiments; 5, 6 – peck marks left by relatively small metal mediators after prolonged work.
Fig. 3. Examples of Malaya Boyarskaya rock art.
1 – large dints; 2 – experimental peck marks left by a steel pickaxe used as a mediator; 3 – 3D model of peck marks (by H. Plisson); 4 – dints left by pickaxe blows overlying the image of a house; 5 – fragment of a zoomorphic representation with peculiarly shaped peck marks.
volcanic rocks. This material is hard and durable, yet much less isotropic and fragile compared to quartzite with a high quartz content or flint. The hardness of most rocks of which the Yenisei and Tuba pebbles are composed ranges from 5.5 to 6.5 on the Mohs scale. The hardness of flint is about 7. Flint is more fragile and therefore easier to knap. The knapping of Shalabolino pebbles requires more physical force than in the case of flint because of the higher viscosity and hardness of rocks found in the Yenisei basin. However, precisely these features ensure the wear resistance and efficiency of tools made of these rocks when softer local sandstone is processed. Points made of Donets flint and local pebbles were used in our first level experiments. For the sake of stringency and to make the results more comparable, only indirect percussion was used because direct percussion rapidly rendered the flint tools unusable.

Experiments demonstrated that points made of various rocks show different patterns of wear. The shape of the working part of a flint tool changes rather rapidly, affecting the marks it leaves as well (Fig. 4, 4). Dints produced at the early and final stage of replication may show considerable differences in both shape and size. The flint point wears rapidly, becoming chisel-like (Girya, Devlet, 2010). A similar effect is observed in quartzite tools although quartzite is more durable. Percussion may last longer, yet the pattern of wear is the same. Peck marks are similar too. The main feature of percussion executed with a fragile tool is that the shape of dints varies within a single image (Girya et al., 2011; Devlet, Girya, 2012).

Tools made of the local viscous rocks are affected differently. At the first stage of experiments, fine chips may crumble out at the place of contact between the tool tip and the rock surface. Eventually the working part solidifies and becomes less subject to wear. The wear slows down because the tip gets smoother, not because its shape changes in any radical way. Therefore percussion with tools made of local pebbles from the Yenisei alluvium results in a different wear pattern on flint and quartzite tools because the shape of the working tip is more stable.

Experiments have revealed traceologically meaningful percussion signs on rock surfaces with tools made of various stones. Tools made of local pebbles were shown to be more robust when used on the Devonian red sandstone.

Further studies explored the technological capacities and features of peck marks resulting from direct and indirect percussion. For this purpose four tools were manufactured from common pebbles from the Tuba alluvium (the rocks were neither rare nor distinctive). These tools can be classified as handaxes (Fig. 4, 1, 3). The working tip was prepared through alternating bifacial percussion using a large hard hammerstone made of syenite. The rest of the stone surface retained the pebble cortex. Tool 1 was made of a viscous coarse-grained rock of magmatic origin. The grains vary in size*. Physical properties of the rock such as viscosity and hardness (5.5–6.0 on Mohs scale) ensure long-term use against the red sandstone. On the other hand, variable grain size accounts for fragility because the pressure on the grain differs. Because the material is isotropic, knapping is possible and a working end of a specified shape can be achieved.

Tools 2 and 3 were made of rocks with similar physical properties. Their hardness likewise measures 5.5–6.0 on Mohs scale. Both rocks are heterogenous. Rock 1 contains a comparatively large amount of quartz grains accounting for extra hardness; rock 2 shows admixtures of feldspar. The rock is viscous, and detaching even small flakes requires considerable force. Variable size of grains accounts for fragility.

Tool 4 was made of metamorphosed fine-grain sandstone with the admixture of micaceous cement. This is a hard rock measuring 6 on Mohs scale. It shows smaller grain size and higher isotropy compared to materials of tools 1–3. The high content of mica cementing the grains accounts for viscosity, homogeneity, and firmness.

The following conclusions were made with regard to percussion scars resulting from direct and indirect pecking with tools made from Tuba pebbles. Hard hammerstones can be used for several hours without losing efficiency. The tip of the tools was gradually worn out and the rock at this part became denser. Trimming of the working part was mostly impossible because this part is very dense. Dints resulting from indirect percussion may be rather deep with irregular (ragged) outlines, yet their shape is stable (Fig. 4, 5). The outlines of peck marks can be changed due to the changing position of the hammerstone in the hand or relative to the rock surface. Much less often this is

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*We thank N.A. Kulik for a petrographic analysis of the experimental pebble tools.
Fig. 4. Experimental peck marks left by stone tools.
1 – marks of direct percussion with stone tools made from Shalabolino pebbles and experimental tools; 2 – marks of direct percussion using pebble tools made from the Shalabolino pebbles (detailed photos of specimens and tools used in experiments); 3 – points made from Shalabolino pebbles; 4 – marks of indirect pecking using a flint tool as mediator and an experimental tool; 5 – peck marks left by tools made from Shalabolino pebbles as mediators.
due to abrupt changes in the configuration of the tool tip resulting in breakage.

Experiments revealed distinctive signs of direct percussion using Tuba pebble tools (Fig. 4, 2). This technique of pecking was shown to be efficient when replicated on red sandstone. Dints resulting from direct pecking have regular outlines, often almost round. They show the combination of universal features listed above. Traces of direct percussion with a heavy metal tool and a pebble tool share certain characteristics: irregular depth and shape of peck marks, comparatively deeper dints minimally necessary to obtain an even line consisting of densely placed marks (Fig. 2, 1; 4, 1, 2). These features suggest similar kinematics of tool movements. However, at present it is impossible to distinguish marks left by a thick metal tool from those left by a viscous, durable stone tool. Additional experimental studies are required to establish relevant criteria.

Experiments with indirect percussion with tools made from local pebbles produced comparatively deep peck marks with irregular outlines (Fig. 4, 5). The technique makes it possible to fix the working tip of the stone chisel on the rock surface and control the pecking. This technique enables one to arrange the dints in a specific order. Experimental dints resemble those observed in certain petroglyphs such as the deer image on area 4 in A.L. Zaika’s nomenclature (2007) of the Shalabolino rock art gallery (Fig. 1, 4–6).

Another area of our experiments was focused on studying metal tool percussion. It was found that the best tools for this purpose are those made of “crumbly” brass and hard steel. This experiment was aimed at establishing features that are optimal for pecking the rock surface. However, our results do not preclude the possibility of the use of other metals with similar properties. The tasks for further experiments were specified.

For the first series of experiments we made short metal tools fastened to wooden hafts. However, the experiments demonstrated that hafts reduce the blow force, making the technique less efficient. This result was taken into account in further experiments, aimed at reconstructing the process of indirect percussion using short weak blows against the surface of the red Devonian sandstone. Some 12 cm long metal rods made of hard steel with variously shaped working parts (Fig. 2, 3–6) were used as chisels. The hammer consisted of a steel working part and a wooden haft.

E.Y. Giryä and E.G. Devlet pointed to the importance of the shape of peck marks in studying percussion with metal tools. The shape is mostly rounded (Giryä, Devlet, 2010; Giryä et al., 2011) (Fig. 1, 3). However, our experimental findings and data concerning various rock art sites show that peck marks indicating the use of metal tools are not necessarily round (Fig. 2, 3–6; 3, 5). The task for future experiments was formulated based on the results of former studies and the preliminary traceological analysis of petroglyphs at Shalabolino and Malaya Boyarskaya and consists in analyzing marks left by steel chisels with variously shaped points and with various degrees of wear.

Experiments in replication showed that the working end of steel chisels rapidly gets worn out and flattens regardless of the shape of the tip. However, in contrast to chisels made of more fragile or more plastic metals, this change does not impede further pecking. Percussion marks mostly retain their shape defined by the shaped of the chisel’s working end (Fig. 2, 3, 4).

After prolonged work even a very strong steel chisel will wear out. There are two main techniques of percussion in which a relatively small metal chisel is used. In the first technique, the chisel is held perpendicular to the rock surface. In this case, the tip becomes blunt and making continued work impossible. The heavily worn tool leaves large peck marks, which are shallower than those left by a tool with a sharp tip. The outlines of the dints are regular, and their shape may resemble that of dints left by a sharp chisel (Fig. 2, 5, 6).

The second technique guarantees durability of the tool because its position relative to the rock surface is oblique. Experiments have shown that, when the chisel is placed in this way, the sides of the tip become flattened resulting in natural trimming. The peck marks are mostly round, oblique in profile, and mainly equally deep (rather deep, in fact). They remain narrow even after prolonged use of the tool. This technique appears to be the most rational, which accounts for its frequent use by ancient artists.

However, petroglyphs in the Minusinsk Basin show peck marks of various shapes from sub-triangular and sub-rectangular to oblong linear. All these marks retain features suggestive of the use of a metal tool such as stability of shape and regular outlines (Fig. 3, 5). These features likely suggest the use of the first technique for a short duration.
One of the problems in the study of peck marks is desquamation. Immediately after percussion the rock surface differs from that affected by prolonged weathering. Fresh dints may contain a finely-dispersed fraction that is difficult to remove even with a coarse brush. Observations demonstrate that a period of a few months may suffice for the dints to deepen (Fig. 3, 2). Therefore it may be useful to examine the weathering of peck marks after experimental percussion. This aspect has to our knowledge not yet been studied and the comparison of real and experimentally-derived peck marks has invariably been conducted shortly after the experiments. Future studies must include monitoring of the results of experiments carried out several years previously.

Examination of the rock surface is equally important for the recognition of weathering effects. Traceological features of peck marks largely depend on the presence and condition of the rock cortex. When the rock cortex is heavily weathered, minimal efforts are needed to leave peck marks, but regular contours and even dints with regular outlines cannot be produced because of the cracking of the cortex. Some dints are larger than the tip of the tool, and have uneven outlines. The difference between peck marks on weathered and non-weathered surfaces is considerable and must be taken into account in experiments replicating petroglyphs.

Summing up the findings of experiments and the preliminary traceological analysis of pecked petroglyphs in the Minusinsk Basin, certain technologic features should be mentioned. Direct percussion was widely used in silhouette and outlined images, while indirect percussion was more often employed in drafts and in the additional elaboration of outlines. Tools made of local viscous pebbles and of durable metals like hard steel or metals with similar properties were preferred. Robustness represented an important feature of metal chisels. Judging by dints made by direct percussion, the ancient artists frequently employed robust and well-sharpened metal tools.

Our experiments mostly replicated peck marks on the Devonian red sandstone. Many features of the experimental petroglyphs match those of actual petroglyphs at Shalabolino and Malaya Boyarskaya rock art sites. However, at the present stage, our main objective was to determine technological regularities associated with petroglyphic art rather than to replicate specific ancient representations. In the future, it is hoped that percussion marks will be produced that are identical to ancient percussion marks, thereby providing new opportunities for the attribution of rock art images in the Minusinsk Basin.

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