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Possibilities of Direct Dating of Rock Art in the Khakass-Minusinsk Basin

The study addresses modern methods of absolute dating of rock art. We review prospective approaches to dating petroglyphs under various conditions: AMS, OSL, uranium-thorium, and cosmogenic isotope. Not so much methods per se are discussed as principles of their application to certain reliably dated rock art sites of various periods in Europe, Asia, America, and Australia. Examples of satisfactory outcomes in international practice are cited alongside our assessment of prospects and limitations to be considered with regard to the method of dating the earliest petroglyphs and rock paintings in the Khakass-Minusinsk Basin. The review suggests that the basic conditions for the use of the uranium-thorium method are not met, the AMS method requires a preliminary analysis of the context, whereas OSL and cosmogenic isotope method are the most prospective.

Keywords: *Rock art, direct dating, Khakass-Minusinsk Basin.*

Introduction

In the Khakass-Minusinsk Basin, dated rock art images from almost all historical periods are known: the Early Bronze Age is represented by Okunev art, the Late Bronze Age by petroglyphs of the Karasuk tradition, the Iron Age by Tagar, Tes, and Tashtyk art, the medieval period by a peculiar figurative tradition of the Yenisey Kyrgyz. The association of these art styles with the archaeological cultures of the region is considered proven; however, the correlation of the rock images with certain ancient periods, without reliable connection to the archaeological context, is not well grounded.

Most researchers consider the "Minusinsk" style to be the earliest in the region (Podolsky, 1973; Miklashevich, 2020). They argue that the petroglyphs of this style are made in an archaic manner, which is atypical of the younger periods, for example, the Bronze Age. The subject (wild animals, often large in size) also indicate an old age (Miklashevich, 2015). In palimpsests, images of the "Minusinsk" style are always overlaid with later petroglyphs (Sher, 1980: 191; Zotkina, 2019). However, this evidence can only be considered as circumstantial.

There are various hypotheses concerning the chronology of the "Minusinsk" style. N.L. Podolsky proposed to date it to the Neolithic–Late Bronze Age (1973); Y.A. Sher did not exclude the possibility of an Upper Paleolithic age for this style (1980). N.B. Pyatkin and A.I. Martynov attributed the "Minusinsk" style to the Stone Age (1985), and E.A. Miklashevich (2015) agreed with this attribution. Y.N. Esin and I.D. Rusakova dated this style to the Early Bronze Age and attributed it to the Afanasyevo culture (Esin, 2010; Rusakova, 2005). I.V. Kovtun correlated the "Minusinsk figurative type" with the

Late Bronze Age (2001: 152–153). However, none of these hypotheses has been fully justified (Miklashevich, 2020). Thus, the time of emergence and existence of the "Minusinsk" style, as well as the origins of the rock art in the Khakass-Minusinsk Basin, are still debatable.

Until recently, petroglyphs on open surfaces were dated exclusively through the method of analogs or stratigraphic analysis. Twenty years ago, most of the absolute dating techniques were almost unused to determine the age of discovered rock art sites (Devlet, 2002: 64–70). Modern approaches to dating have led to qualitative changes in the strategy of rock art studies and chronological attribution. Direct dating of the earliest rock art of the Minusinsk Basin can be one of the techniques to solve the issue of its age.

This article provides an overview of effective methods and approaches to rock art dating, which have been tested at sites in various parts of the world. The presented information provides the basis for correlating the available research experience with the tasks of dating the earliest rock art of the Khakass-Minusinsk Basin and other areas, with respect to the regional specifics.

Dating techniques

Radiocarbon analysis. The age (time of death) of the studied organism is determined by comparing the initial (at the moment of equilibrium with the concentration of atmospheric carbon) and the residual amount of ^{14}C therein. Under normal circumstances, the limit for measuring the ^{14}C decay rate is eight half-lives (5730 ± 40 years), i.e. approximately 45 thousand years (Walker, 2005: 19). The AMS-dating technique is suitable for charcoal rock paintings (Valladas, 2003). Any other organic residues detectable in the composition of the pigments (binders) can also be dated by the AMS method. In most cases, the organic components of ancient dyes have not survived, but sometimes it is possible to identify the products of their decomposition—calcium oxalates, which can be used to establish radiocarbon dates.

One of the main limitations of the radiocarbon method is the half-life limit of ^{14}C (Walker, 2005: 19; Lowe, Walker, 1997); it does not apply to most rock art sites known to date, because in only very few of them can the estimated age fall outside this limit*.

Uranium-thorium (U-Th) dating. The technique is based on the measurement of the ^{230}Th–^{234}U isotope ratio in the carbonate formation ($^{238}U = {}^{234}U + {}^{230}Th$). Uranium dissolves in water and is easily transferred to calcite; thorium does not dissolve, it is the product of uranium decay in the rock. The dating materials are various carbonate formations. This method is used in studies of objects aged in the range of 10 thousand to 350–400 thousand years (Kuzmin, 2017: 187–191).

Limitations are associated with detrital contamination of samples—microscopic particles of clay and dust, adsorbing radioactive substances, which can provide additional supply and leaching of uranium. In this case, the system is not closed, and its dating may lead to an incorrect age estimation of the sample. The considerable thickness of the sample does not guarantee a closed system, since the process of uranium supply or leaching could be restarted, and not simultaneously (Pons-Branchu et al., 2020). Sampling in stratigraphic order can prove that the sample is stable, if the dates derived are chronologically consistent (Ochoa et al., 2021: 96–97).

Optically stimulated luminescence (OSL) dating. This method is used to determine the time elapsed since the object under study was last exposed to radiation (sunlight), and the duration of the object's exposure to light. The method is based on measuring the intensity of luminescence (sunlight) resulting from the release of energy accumulating in the crystal structure of minerals (namely quartz and feldspar) being part of the rocks. The usability of quartz and feldspars for dating is based on two main processes: energy accumulation and its zeroing or illumination (Panin, 2010; Duller, 2008; Murray et al., 2021). When using quartz as a dosimeter mineral, the OSL-method is applicable for dating the samples from 1 year to 120–150 thousand years old; using feldspar, up to 300–500 thousand years old (Kuzmin, 2017: 207–211).

The OSL-method is used mainly for dating loose deposits. This technique can be used for determining the age of rock art in the case where sedimentation took place under special conditions, and the deposits at least partially overlap the images. OSL-dating of the rock itself involves more complex sample preparation (Brill et al., 2020). Fragments of the rocky surface associated with various episodes of the geological history of the studied object can be used as samples (Sohbati et al., 2012).

Cosmogenic isotope dating (based on terrestrial cosmogenic nuclides (TCN)). This method is based on measuring the amount of daughter nuclides formed in the surface layers of the rock during splitting of the

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*Today, the oldest reliably proven age of rock art in the world is 45 thousand years (Sulawesi Island, Indonesia) (see, e.g., (Finch et al., 2021)).

atoms that make up the minerals of quartz, feldspar, beryllium, chlorine, etc., due to the interaction of high-energy particles, entering the atmosphere from space, with atoms of air gases. The amount of terrestrial nuclides determines the age of rock outcrops (Granger, 2014; Fujioka et al., 2022). The TCN-method is used to obtain the age of rock exposure in the range from 100 years to 5 million years (Akçar, Ivy-Ochs, Schlüchter, 2008).

The limitations of this method are associated with erosion processes, which lead to the loss of nuclides accumulated in the rock's surface, and with rock's shielding from cosmic radiation by vegetation, snow cover, and loose deposits (Panin, 2010: 51).

Benefits and limitations of direct dating of rock art

AMS-dating. There are many known cases of successful determination of the age of rock paintings by the charcoal used. These are associated mainly with classic cave art sites in Europe, such as Chauvet-Pont d'Arc, Niaux, Gargas, Cosquer, Altamira, and others (Valladas et al., 1992, 2010, 2017; Atlas…, 2020; García-Diez et al., 2013: Tab. 2). The method of direct AMS-dating of pigment has proven to be very effective, and gives the possibility of determining the time of creation of charcoal paintings with great accuracy. Today, this approach is broadly used for chronological attribution of rock art sites all over the world (O'Regan et al., 2019; Moya-Canoles et al., 2021; Šefčáková, Levchenko, 2021; Rowe et al., 2021; Bonneau et al., 2022). However, until recently, direct radiocarbon dating of many paintings made with mineral pigments has been considered impossible. In some cases, the composition of pigments shows organics: for example, fibers, surviving components of binders, or their decomposition products (calcium oxalates); these substances can be dated by the AMS-method (Ochoa et al., 2021). An important advantage of this approach is that it is applicable to many paintings made with manganese or iron oxide, and even to those on open surfaces (Pecchioni et al., 2019). Organic substances are most often not detected in the composition of pigments; however, some binders (for example, animal fat, blood, etc.) might have been converted into calcium oxalates—a product of microbial activity (Watchman, 1993; Arocena, Hall, Meiklejohn, 2008; Lofrumento et al., 2011). An important preparatory stage for this dating includes comparative analysis of the chemical composition of the analyzed pigments, substrate, and deposits at the site (Pecchioni et al., 2019: 333). In such a way it is established whether the formation of calcium oxalate at a given locality is related to environmental features (Livingston, Robinson, Armitage, 2009). If it can be proven that the calcium oxalate in the dye is a product of the decomposition of organic binders intentionally added by humans, the pigment can be successfully dated by the AMS-method (Brook et al., 2018; Pecchioni et al., 2019; Steelman, Boyd, Allen, 2021).

Spanish researchers used a rather peculiar approach to the dating of calcium oxalates of painted images on the walls of the rock shelters of Sierra de las Cuerdas and Cueva del Tío Modesto (Hernanz, Gavira-Vallejo, Ruiz-López, 2007). The red pigment contained no organic components, but the overlapping bluish-gray crust associated with lichen activity yielded calcium oxalates. Microstratigraphy of the samples taken showed that the pigment had been applied more than once, and had been repeatedly overgrown with lichen (Ibid.: 515, 518). The rock paintings were shown to have been created between 5000 and 1000 BC (Ruiz et al., 2009).

U-Th-dating. In recent years, Indonesian rock art has been reliably dated through a series of predominantly U-Th dates (Aubert et al., 2014, 2018, 2019; Ilmi et al., 2021; Brumm et al., 2021). By now, the proven oldest age of rock art in the world has been established on the basis of coralloid speleothems overlaying naturalistic images of Javan pigs in the caves of Leang Bulu' Sipong-4 (43,900 BP) and Leang Tedongnge (45,500 BP) on Sulawesi. An important advantage of speleothems from Indonesian sites (as compared, for example, with calcites from sites in other regions of the world) is the closed system, which is reliably proven by the stratigraphy.

AMS- and U-Th-dating of images has been used successfully in cave sites on the Iberian Peninsula. More than 100 radiocarbon and more than 130 uranium-thorium dates provide solid evidence of the appearance of parietal art in this area as early as in the Aurignacian (Ochoa et al., 2021). The age of the images in La Pasiega Cave—64,800 BP (U-Th)—arouses considerable debate (Hoffmann et al., 2018). Such an early date caused great doubt in the scientific community (Slimak, Fietzke, Geneste, 2018; White et al., 2019). The study of rock paintings in Nerja Cave has convincingly proven that speleothems of great thickness may have been an open system, in which the processes of uranium input or leaching were restarted, so the dates obtained are not reliable (Pons-Branchu et al., 2020).

AMS-dating was used to determine the age of the charcoal paintings in Altamira Cave in the range from 19,000 to 15,000 BP, which suggested attribution of the images to the Magdalenian period (Valladas et al., 1992; Moure et al., 1996; Moure, Gonzalez Sainz, 2000). At the same time, as based on the stratigraphy of archaeological layers, the period of human occupation of the cave was determined by the radiocarbon method in the range of 26,784–16,866 BP (Gravette to Middle Magdalenian). Later, eight U-Th dates were derived from a thin calcite coat covering most of the polychrome paintings; the dates show the lower chronological boundary of 35,559, and the upper of 15,204 BP. Thus, the most ancient examples of the art of Altamira belong to the Aurignacian, the archaeological evidence of which was not found in the cave. The period of creation of the pieces of prehistoric art spans 20 thousand years (García-Diez et al., 2013). This example proves the importance of cross-dating rock art sites by different methods.

The thickness of successfully dated carbonate formations at most of the described sites is at least 1 cm, and often even exceeds this size. However, as shown by the studies of the Spanish caves of La Pasiega and Nerja, even a large thickness of calcite deposits does not guarantee the closeness of the system of dated material.

OSL-dating. The study of the famous Fariseu site in the Côa Valley (Portugal), with specific sedimentation conditions, was one of the first cases of successful application of the OSL-method in the study of open-air rock art sites (Aubry et al., 2010). The surface with petroglyphs was covered by undisturbed deposits, including archaeological layers; these were dated by OSL-method. On the basis of the derived dates, two periods of human occupation were identified: 18,400–15,000 BC and 12,000–11,000 BC. Judging by the location of the dated deposits, the rock images were made prior to the period corresponding to the lower boundary of the sedimentation process—18,400 BC (Ibid.: 3309).

Another example of successful OSL-dating of rock images by covering sediments is associated with the open-air site of Qurta in northern Egypt. Researchers determined the age of eolian deposits, partially overlapping the surfaces bearing images of bovids, as ca 15 ka BP (Huyge et al., 2011; Huyge, Vandenberghe 2011). An important advantage of this method is that the presence of overlapping cultural layers is not a prerequisite for dating the petroglyphs; any deposits are sufficient, although such situations are quite rare at rock art sites.

An unusual dating strategy was chosen to determine the age of rock images on the ceilings of rock shelters and small caves in the Kimberley region in northern Australia. Dating samples were collected from seven petrified nests of mud-wasps covering the images. Nests usually consist of organic remains (pollen, spores, phytoliths) and mineral components. The results of OSL-dating of quartz grains have shown that two of the five samples date back to 16,400 and 17,500 BP (Roberts et al., 1997). Subsequently, a more representative series of samples was analyzed by the AMS-method. Dating of 15 samples from mud-wasp nests covering ten images, collected from six rock art sites in the region, has shown that the images had been made over a rather long period—from 17,500 to 13,000 BP (Finch et al., 2021). The described approach cannot be defined as universal for open-air sites, since it can be used to determine the age of images only in localities where the probability of survival of ancient nests of mud-wasps is higher. However, that study demonstrates the importance of assessing the local conditions and possibilities for dating at each particular site.

OSL-dating of exposed rock surfaces has been successfully used to determine the age of rock paintings (Liritzis, Evangelia, Mihalis, 2017). The Great Gallery site in Canyonlands National Park in southeastern Utah, USA, is a classic example of such research. Geological events that took place undoubtedly after the creation of the rock images were dated: the age of the alluvial deposits and the time of the rock fall, which partially damaged some of the images, were established; the period of exposure of the painted surface of the Great Gallery was determined. The period, during which the rock paintings on this large panel were made, was comparatively short—1000–1100 years AD; it corresponds to the period of the Fremont culture of pre-Columbian America (Chapot et al., 2012; Pederson et al., 2014).

The method of OSL-dating of the rocky surface by a sandstone block with deep grooves and holes is described in detail; the block was found during excavations at the entry zone of Daraki-Chattan Cave at the Rewa River in India. The derived date of 13 ka BP, according to the researchers, is the lower chronological boundary, marking the time of the block's fall; this time coincided with a sharp climate change in the Early Holocene and the associated intense denudation processes (Liritzis et al., 2019).

Apparently, this approach suits well for dating open panels with petroglyphs containing no pigments. It does not require sampling directly from images, and hence minimizes the possibility of destructive impact. The only limitation is the probability of establishing a too broad time range between the lower (the age of the panel) and the upper (geological event) chronological boundaries.

Cosmogenic isotope dating. This dating method started to be used in rock art studies with the attempts to determine the time of exposure of panels with images from the three sites of Ribeira de Piscos, Canada do Inferno, and Penascosa in the Côa River valley. The analysis of ^{36}Cl isotope has shown that the rock surfaces were accessible for making the petroglyphs in the Paleolithic (136,000–16,000 BP) (Philips et al., 1997; Stuart, 2001). The derived data, albeit indirectly, confirmed, for the first time, the assumption of the oldest age of the Foz Côa rock images, which was later convincingly proven (Aubry et al., 2010).

Cosmogenic dating of the blocks forming the rock shelters in the Borologa locality (Kimberley, Australia) showed that the processes of destruction and subsequent downslope movement of these giant boulders took place 130,000–90,000 BP, and formed the landscape at the site. According to the geomorphological study, some rather large slabs were deliberately split and subsequently moved by man. A radiocarbon date of ca 9500–9300 BP was derived by a sample of an mud-wasps' nest from one of the panels with rock art, from which the slab was removed (Finch et al., 2019). The age of the eolian deposits partially overlapping this surface with images is 2700–2500 BP. Since the slab lay on top of Late Holocene deposits, it was concluded that in the range of 9300–2500 BP, it was deliberately moved (Delannoy et al., 2020). That study proved the effectiveness of a comprehensive consideration of geomorphological context of rock art sites.

An unusual approach to the use of the TCN-method was proposed to determine the lower chronological boundary of Western Australian rock art. Measurement of the amount of nuclides in granophyres and gabbro rocks (16 samples, ^{10}Be in quartz composition) with petroglyphs, found on the Burrup Peninsula and the adjacent area of the Dampier Archipelago, indicated an extremely slow erosion process (on average, ca 0.30–0.40 mm/1000 years) (Pillans, Fifield,

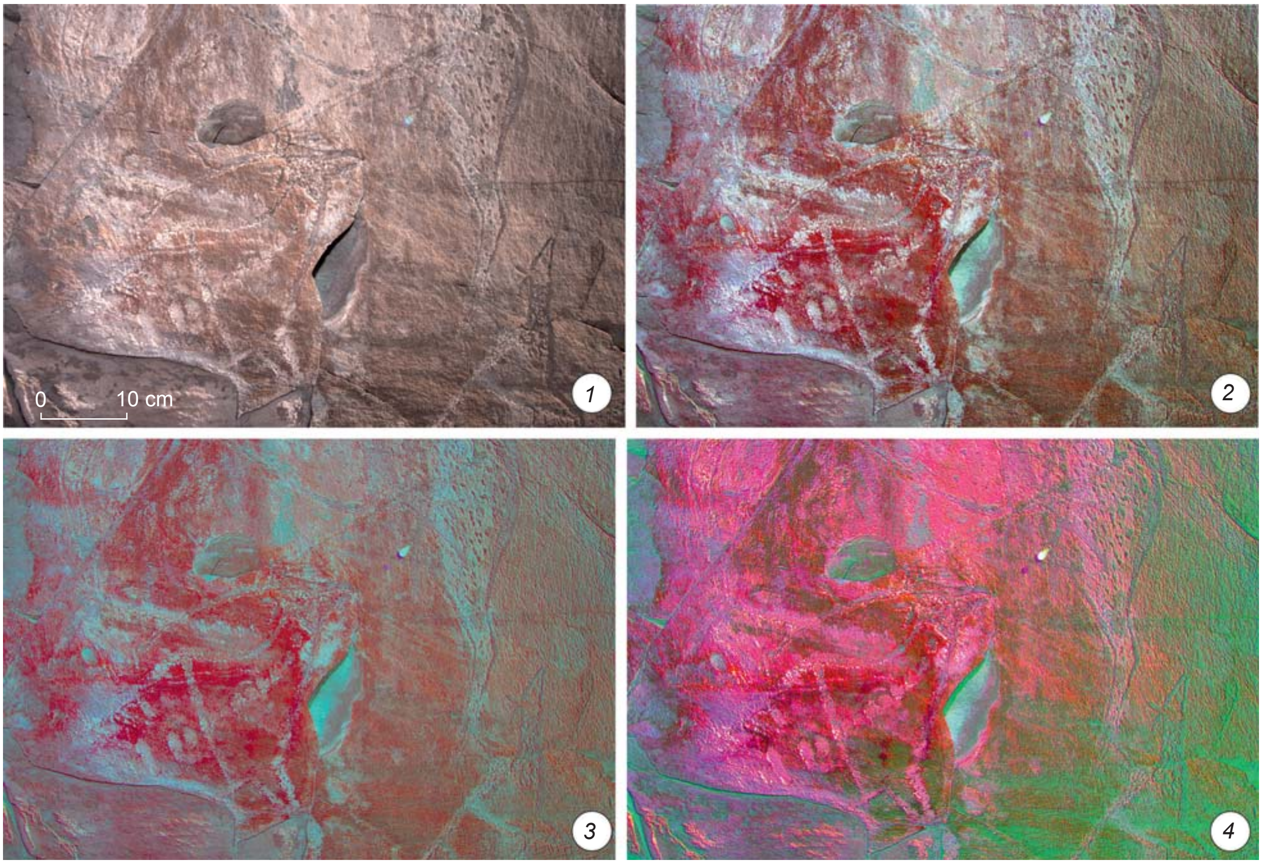

Fig. 1. Zoomorphic image in the "Minusinsk" style, whose pecked contours show red pigment thereunder. Sukhanikha I, panel 7.
1 – general view, photo with natural diffused light; *2–4* – photo 1 treatment by DStrech.

2013). Experts came to the conclusion that these data indirectly confirm the radiocarbon date of 18,000 BP obtained from mollusk shells from the cultural layer of the Gum Tree Valley site, where fragments of slabs with petroglyphs were found (Lorblanchet, 1992: 42), but suggested an older lower chronological boundary, with an age limit of 60,000 years (Pillans, Fifield, 2013: 105). However, this assumption looks disputable, because it is hardly possible to take into account the screening factors and climatic changes over such a long period, which increases the likelihood of an error in estimating the age by erosion processes (Watchman, Taçon, Aubert, 2014). The approach based on measurements of erosion dynamics is useful for solving the issues of conservation and restoration of petroglyphs, but can hardly be used for indirect dating.

Benefits and limitations of direct dating of the rock art in the Khakass-Minusinsk Basin

The proposed review leads to the conclusion that the considered methods can be used to determine the age of the earliest rock art in the Khakass-Minusinsk Basin. About 15 localities with ancient images are known in this region. The most significant are the rock art sites of Oglakhty, Tepsey, Ust-Tuba, Shalabolino, Boyary I, Georgievskaya Gora, Moiseikha, Sukhanikha, and Maidashinskaya.

The earliest examples of rock art in the region are dominated by rock carvings, mostly pecked images. Paintings or petroglyphs, containing the remains of red pigment, have been found at the sites of Tepsey I, Sukhanikha I, Oglakhty (Mount "Sorok Zubyev"), and the Shalabolino rock art site (Fig. 1, 2). Some images

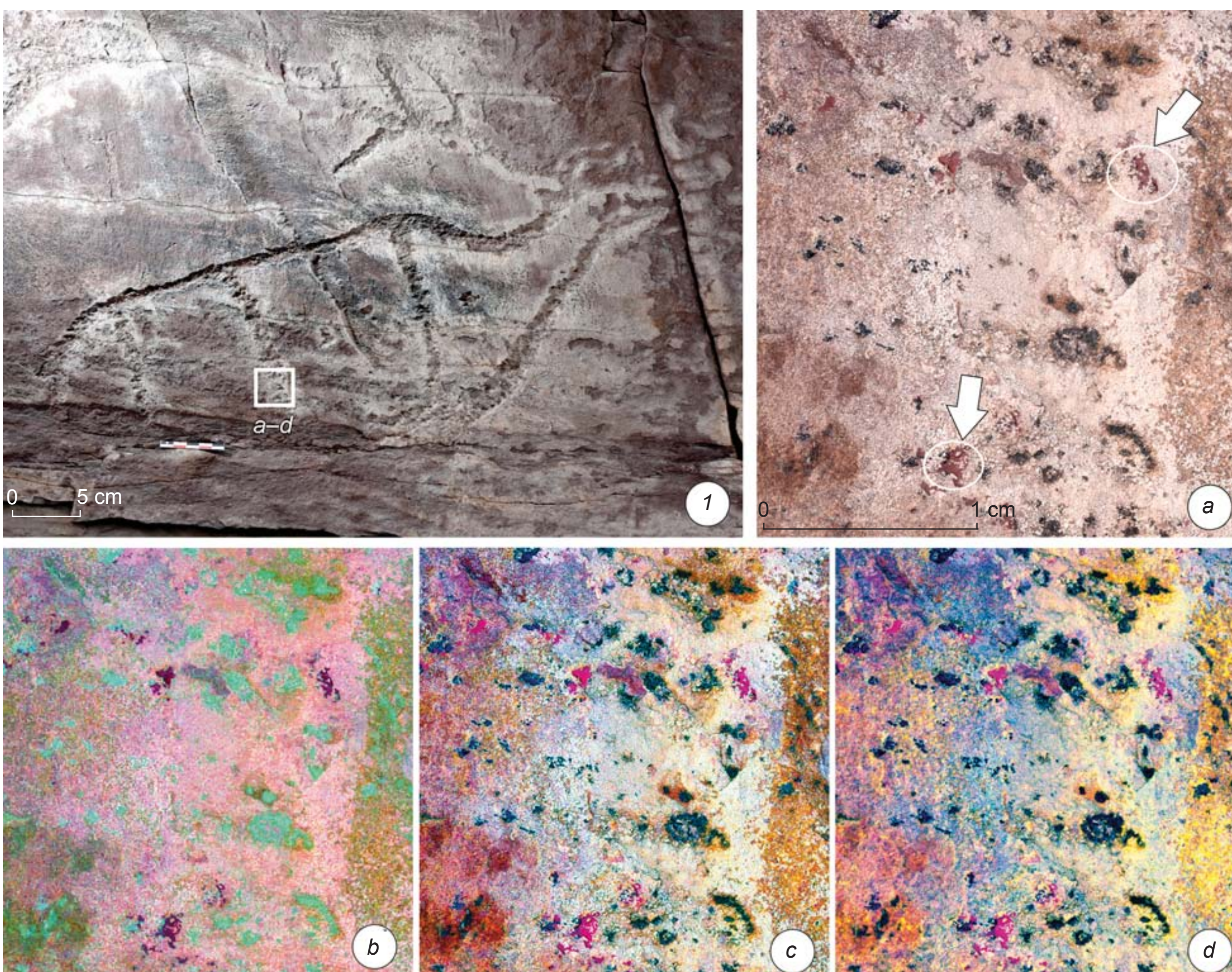

Fig. 2. Image of a deer in the "Minusinsk" style; the protruding areas of its pecked contours show red pigment. Oglakhty IV. "Pervy Zub".
1 – general view, with macrophoto area marked (flash photo): *a* – macrophoto of the area with particles of red pigment; arrows show calcite overlapping pigment; *b–d* – macrophoto *a* treatment by DStrech.

are partially covered with calcite deposits. It is possible that the mineral pigments on the images from the above-mentioned sites may contain calcium oxalates, which today can be dated by the AMS-method. To check this possibility, the chemical composition of both the pigment and the rock's surface without images and deposits closest to them should be analyzed. This will exclude accidental admixture of organic substances from the environment into the pigment, and prove that the dated calcium oxalate is a product of decomposition of an organic binder deliberately added by an ancient artist (see, e.g., (Pecchioni et al., 2019; Steelman, Boyd, Allen, 2021)) if it is the case. On exposed surfaces, the likelihood of organic contamination is high, and calcium oxalate could have formed in the pigmented area both before and after the image's creation (Sauvet, 2015: 214). To determine the possibility of using the AMS-dating of calcium oxalates, a series of preliminary chemical analyses should be conducted for each locality where the earliest rock paintings are present.

It was found that the thickness of calcite deposits and crusts overlying the earliest rock images at Tepsey I, Sukhanikha I, and Oglakhty is insufficient for sampling for U-Th dating. In all the cases known to us, calcite forms crusts no thicker than a few millimeters (Fig. 3), which is not enough to conduct the U-Th analysis. In addition, open-air rock surfaces are most likely affected by detrital contamination. Thus, the application of this method to the sites in the Khakass-Minusinsk Basin is impossible owing to the lack of basic conditions.

The methods of cosmogenic and OSL-dating of rock surface fragments can be considered the most suitable for the issues set out here. Both methods are carried out on rocks. These methods of dating do not require sampling directly from the surfaces of images, i.e., the risk of damage is minor. The purpose of the study is to establish the lower chronological boundary—the time of the surface's exposure, and the upper one—the geological event that followed the creation of the image. These methods do not

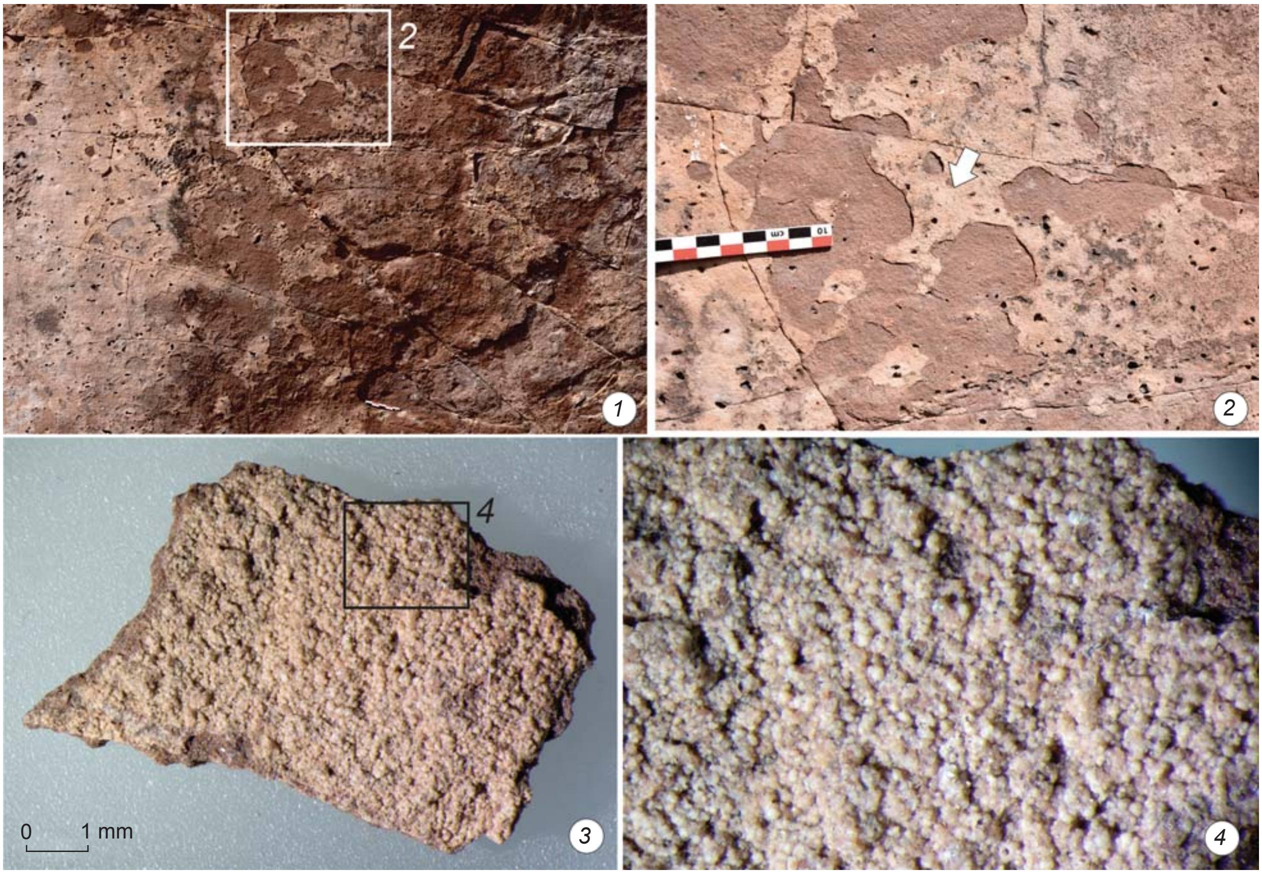

Fig. 3. Panel with earliest petroglyphs, covered with calcite crust. Georgievskaya Gora.
1 – zoomorphic image (general view), with calcite sampling area marked; *2* – macrophoto of the area with exfoliated calcite crust; arrow shows the sampling area; *3*, *4* – macrophoto of the calcite sample less than 1 mm thick (×20 and ×56 magnification, respectively).

determine the absolute age, but establish the period when a petroglyph was created. A preliminary test for the traces of penetration of light into quartz granules of red-colored Devonian sandstone from the Khakass-Minusinsk Basin (on a block from the vicinity of the Shalabolino rock art site) showed that this rock transmits light and, therefore, is promising for OSL-dating (Zotkina et al., 2022: Fig. 1).

The method of rock age estimation by the cosmogenic ^{10}Be isotope is applicable for dating the Middle Yenisey sandstone, which contains a high proportion of quartz. Such dating is most suitable for the reconstruction of the chronology of geomorphological processes at the site, when the access to the panels with rock art is destroyed and the platforms under and over the rock are missing. The dates obtained for these geological events can be younger than the "upper" dates of the time of images creation. Taking into account that many earliest petroglyphs are located at high tiers, dating the process of destruction of the ways of access to them can be promising in terms of revealing the most ancient images.

Conclusions

The above review does not claim to be complete or cover all the recent works on the absolute dating of rock art, if only because the number of such studies is growing every year, qualitatively new changes appear in the mechanisms of method application: problems that were earlier considered insurmountable are solved and errors are corrected. Nevertheless, the review of methods and approaches in terms of benefits and limitations with regard to specific scientific tasks and region can be useful for choosing a strategy of dating rock art sites in the Khakass-Minusinsk Basin and elsewhere.

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