Acoustic measurements and digital image processing suggest a link between sound rituals and sacred sites in northern Finland

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Abstract

In northern Finland, near the canyon lakes of Julma-Ölkky, Somerjärvi and Rotkojärvi, steep rock cliffs produce distinctive acoustic spaces. On these cliffs, prehistoric rock paintings (5200 to 1000 BC) as well as an ancient Sámi offering site (circa 1100 to present) can be found. Ethnographic sources describe that the Sámi used to sing and listen to echoes while making offerings there. This article presents the results of an archaeoacoustic research project that seeks to explore the role of sound in the development and use of these archaeological sites. The innovative set of methods includes multichannel impulse response recording, angle-of-arrival estimation of early reflections, spectrum analysis, digital image processing and 3D laser scanning. On the basis of the analyses, it is concluded that the cliffs that have been painted or held as sacred are efficient sound reflectors. They create discrete echoes and, accordingly, phantom sound sources. Especially at the Värikallio cliff near Lake Somerjärvi, the sound appears to emanate directly from the painted figures. These results, together with previously unnoticed drumming figures in the Värikallio painting, provide a clue to the significance of the sound rituals at these sacred sites.

Keywords: Rock art; *sieidi*; echoes; archaeoacoustics; northern Europe

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1. Introduction

Though the premise that sound and music were just as important to past human societies as they are to contemporary societies seems easy to accept, it has taken a long time for practical archaeological research to adopt this perspective. Although sounds may be ephemeral *per se*, the acoustic environments and instruments used to produce them persevere, making the reconstruction of aural experiences and phenomena a legitimate object of study. The pioneering works of scholars such as Bernard Fagg (1956) in the United Kingdom, Cajsa Lund (1974; 1981) in Sweden, Iégor Reznikoff and Michel Dauvois (1987a–b; 1988) in France, and Steven Waller (1993) in the United States have brought about the emergence of a new sub-discipline known as archaeoacoustics, a discipline that is dedicated to the study of ancient music, sounds and, particularly, acoustics of archaeological sites (Scarre and Lawson 2006; Kolar 2013b; Eneix 2014; Till 2014; Blake & Cross 2015).

In tandem with its growth in popularity, concerns have been raised regarding the perceived lack of scientific rigor in archaeoacoustic research (Drake 2012). In a prologue to the proceedings of a recent major conference on archaeoacoustics, Ezra Zubrow (2014) writes that the sub-discipline is currently in a pre-paradigmatic stage. “There are no generally accepted theories, generally accepted methodologies or generally accepted data…yet.” The present paper aims to address some of these concerns by developing new methodology related to the precise scientific documentation and analysis of acoustic phenomena at three sacred sites in northern Finland, namely, two prehistoric rock paintings and one Sámi offering site (*sieidi*) from the historical period. Both the rock art sites and the *sieidi* in Finland have been associated with exceptional acoustic environments (e.g., Reznikoff 1995; Lahelma 2010). However, whereas in the case of the rock paintings, this association has been based on simple acoustic tests (singing, clapping of hands and counting the echoes) or subjective experiences by modern observers, in the case of the *sieidi*, there is actual ethnographic evidence that links them with sound rituals and a particularly strong echo (cf. Paulaharju 1932; Itkonen 1948). By comparing the acoustic properties of the *sieidi* and the rock paintings, we argue that it may be possible to identify acoustic phenomena that were singled out by past human populations in northern Finland as being particularly significant.

Our approach is to capture the impulse response of the chosen sacred sites through controlled field recordings by using mapped recording points and custom-designed recording equipment. The echoes, i.e., reflected sound waves, are then characterized by using various quantifiable features such as time delay, distance from the reflecting surface, angle of arrival, amplitude, sound pressure level and frequency spectrum. Particularly, the angle-of-arrival estimation of early reflections, providing a tool for localizing the echoes, is a novel method in the field of archaeoacoustics. The aim is to accurately characterize the acoustics of the spaces and explore what this information might suggest, for example, about the ritual activities that once occurred at these sites. Similar types of rock art sites in open gorge landscapes have been studied earlier by Reznikoff (1995; 2002), Waller (1993; 2006), Margarita Díaz-Andreu and Carlos García Benito (2012; 2013) and Díaz-Andreu and Tommaso Mattioli (2016), who all report exceptional acoustic phenomena, such as echoes and reverberation, in the vicinity of the engravings or paintings.

The rock paintings and the *sieidi* admittedly differ in many ways, the most obvious being the fact that the *sieidi* do not feature painted images. The types of locations of the *sieidi* often differ from those of rock paintings, and the temporal difference is also considerable. Although the dating of the rock paintings in northern Finland is unknown, similar paintings in the central and southern parts of the country are dated using shore displacement chronology and are determined to have been created between 5200 and 1000 BC (Lahelma 2008). Because of their stylistic similarities, it is reasonable to date the northern paintings within the same timeframe, at least until proven otherwise. Thus, they were probably made by Neolithic hunter-fishermen of the Finnish interior. The *sieidi*, however, are connected to the ethnic religion of the indigenous Sámi people who, in the historical period, practised a livelihood based largely on reindeer herding, hunting and fishing. Though the prehistoric roots of the *sieidi* tradition are not well understood, in Finland, offerings found at the sites are dated between the 11th and 17th centuries, with ethnographic records and modern finds bearing evidence of the still-continuing use of some of the sites (Äikäs 2015). Thus, given the archaeological records, the tradition is only 1000 years old, suggesting that there is a gap of at least 1500 years between the youngest rock paintings and the oldest *sieidi* sites. However, some have argued that despite the temporal gap, the *sieidi* continue the same tradition as the rock paintings (e.g., Luho 1971; Núñez 1995; Lahelma 2012), as evidenced by the similar sacrificial practices associated with them, or the similarities between the rock painting motifs and the iconography of the Sámi shaman drums. Although the practises and rituals at the rock paintings may have differed from those at the *sieidi*, they seem to have included elements of communicating with another world, thus giving a special meaning to these locations. Hence, we refer to these places as sacred sites in this text.

2. Study sites

2.1. The rock paintings of Värikallio and Julma-Ölkky

All of the sites we studied are located on steep cliffs rising on the shores of long, canyon-like lakes in largely uninhabited wilderness areas. The paintings are located close to each other in north-eastern Finland near the small town of Suomussalmi and the Russian border, while the *sieidi* is located approximately 300 km to the north-west in Finnish Lapland. In both regions, the terrain is fairly similar in that it is rugged sub-arctic taiga forested land dotted with lakes and occasional exposures of pre-Cambric granitic bedrock. Background hum from traffic and other human activities is non-existent in these wilderness areas.

The painted site of Värikallio is one of the largest of its type in Finland, with at least 60 distinguishable images. The paintings have been crafted in a tight cluster on the face of a smallish cliff at the eastern end of Lake Somerjärvi, where they cover an area approximately 10.5 m wide and 2.3 m high. Much of the painted area is covered by a wash of red ochre, which makes it difficult to identify and record some of the paintings that include characteristic figures of triangle-headed humans, stick-figure elk or deer, geometric motifs and non-cervid animals that may represent lizards or beavers. Taavitsainen (1979), who first recorded the site, suggested that its motifs bear evidence of contact with the famous Neolithic carving sites of Nämforsen (see Hallström 1960) in northern Sweden and Zalavruga (see Savvateyev 1970) in north-western Russia. Because the direct tracing published by Taavitsainen misses much of the finer details, the site was re-documented in the course of our fieldwork using digital photography and the CPED toolset (for a description of CPED, see Hollman and Crause 2011). This documented work was not central to our acoustic research and thus is not described in any detail, but because it yielded some surprising results, in particular, several drumming human figures previously unknown in Finnish rock art, it will be briefly touched upon in the discussion section.

The painting of Julma-Ölkky lies approximately 3.5 km to the north-east of Värikallio, on a tall fractured cliff rising on the eastern shore of a lake similarly called Julma-Ölkky (**Fig. 1**) (Kivikäs 1995; Lahelma 2008, appendix 3). With just three or four faint images, it is a much humbler site than Värikallio. There is a small painting of an elk (21 cm long) facing right and two stick-figure humans of roughly the same size. A fourth figure, perhaps another elk, may be present to the right of the elk. The cliff itself, however, is more imposing than Värikallio. Both of the painted sites rise directly from the water and can therefore be accessed only by boat or, during the winter, over the frozen surface of the lake. As the paintings are between 0.2 m and 2.5 m above the present surface of the lakes, i.e., within reach of a boat or lake ice, it indicates that the water levels have not changed greatly throughout the past millennia.[1] This was a prime reason for choosing these sites for acoustic testing, because the acoustics of the sites have very likely remained essentially unchanged. Moreover, it is unlikely that other features of the past environment, such as vegetation or climate, would have influenced the acoustic properties of the bare vertical cliff faces, the main subject of this study.

[1] As a rule, Finnish rock paintings are located immediately on shorelines, often on steep cliffs that rise directly from the water (see Lahelma 2008). It is therefore safe to assume that most of them were originally painted from a boat or the frozen lake surface. Nowadays the majority of the paintings are several metres above the current water level and, when the hydrological history of the lake is known, they can be dated using the shore displacement chronology. That is the single most important means of dating Finnish rock art.

2.2 The *sieidi* of Taatsi and Taatsinkirkko

Taatsinkirkko (the church of Taatsi) is a smooth cliff surface rising on the northern shore of a narrow gorge lake called Rotkojärvi in the municipality of Kittilä (**Fig. 2**) (Äikäs 2015). On its eastern side, an approximate 10-m-high tower-like rock formation rises that is known as the offering stone of Taatsi. Archaeological excavations at the formation have revealed the oldest bone material found yet in Sámi offering places of Finland. A pike bone found near the eastern side of the offering stone was dated to 900 ± 25 BP (Hela-1878), or 1040 to 1180 cal AD (Äikäs 2015). Early 20th century written sources describe Taatsinkirkko as an offering place where fish and reindeer were sacrificed (Fellman 1906; Paulaharju 1932). Important for the purpose of our study, these sources indicate that echoing was perceived to be fundamental to the sanctity of the site. One of the anonymous informants of Samuli Paulaharju, a school teacher and collector of ethnographic knowledge, describes the site thusly:

> "Water runs and drops there and echoes, as if someone was preaching. It is like a room […] [The Sámi] sang their *sieidi*-prayers there because the cliff resounded" (Paulaharju 1932, 50, our translation).

Itkonen (1948, 320) reports a similar attentiveness to acoustic phenomena related to a *sieidi* called Algažjáurpáht (Sacred Lake Cliff) located on the Kola Peninsula in north-western Russia, which suggests that such interest in acoustic wonders was widespread among the Sámi of northern Fennoscandia. Tradition held that this lakeshore cliff, deemed particularly sacred by the Skolt Sámi, was inhabited by the people of the underworld and that on a still summer night, one could hear them talking inside the cliff. Making any type of noise while passing the cliff was strictly forbidden. Yet, in a ritual context, singing and other types of sounds produced at a *sieidi* could be a central part of the observance, as indicated by Paulaharju's informant quoted above. The expression '*sieidi*-prayer' (in the Finnish original, *seitarukous*) is significant as it undoubtedly refers to what, in Sámi culture, is known as *joik*, a type of magical singing that, according to traditional belief, was given to mankind by the people of the underworld (Qvigstad 1929). *Joiking* is expressly mentioned in association with other *sieidi* sites, such as Noitakallio (the shaman rock), which is approximately 70 km to the south of Taatsinkirkko, where the shamans (*noiadi*) would go to lie down and sing themselves into a trance (Paulaharju 1932, 53). Due to its magical nature, *joik* was closely associated with the profession of the *noaidi* and could be accompanied by the beating of a shaman drum during a shamanic séance.

3. Methods

3.1 Fieldwork at the sites

The fieldwork was conducted in two phases. The first phase was performed in the summer of 2013 and the second in wintertime between 2014 and 2016. In both phases, the fieldwork included GPS mapping as well as audio recordings. The first phase also included digital photography and 3D laser scanning. The first phase recordings focused on gaining overall information of the acoustical spaces, whereas the second phase recordings concentrated specifically on angle-of-arrival estimation. Moreover, the results gained from the first recordings were used for designing a more extensive set of recording equipment for wintertime conditions. The summertime recordings were made from on board a rowboat or a motorboat (see also Rainio et al. 2014), while the wintertime recordings were performed from a frozen lake surface.

In the summer, 15 recording points were selected from around the painted or sacrificial cliffs as well as from farther away along the canyon lakes. All points were marked with floating buoys. The buoys were then mapped using a handheld GPS device. More accurate maps and 3D models of the entire study sites were created using a Leica ScanStation 2 laser scanner that was positioned on the shores opposite the Värikallio, Julma-Ölkky and Taatsinkirkko cliffs. The 3D models were used for visualizing the topographic features of the sites. In the winter, the recording points centred more around the painted or sacrificial cliffs and had fixed positions on ice. The locations were mapped using a real time kinetic GPS with an accuracy of 1 cm. Due to the deep cliffs surrounding the measurement area, an additional aerial was needed. Finally, the acoustic data from each recording point were combined with the location information in ArcGIS.

3.2 Audio recording equipment

The summertime field recordings were made with a compact boat-mountable recording system that consisted of a Zoom H4n four-channel portable digital audio recorder and two Neumann KM 183 omnidirectional microphones positioned on the prow of the boat. A 48 kHz sampling rate and a bit depth of 16 bits were used for the recordings. The KM 183 microphones were set up as an AB stereo pair, and the H4n internal microphone was placed in the front to form an equilateral triangle with a 22 cm mutual distance, i.e., roughly equal to the inter-aural distance of a human head. In this composite microphone array arrangement, the KM 183 pair served as the main microphones for measuring the reverberation time and spectrum as well as for estimating the arrival angles of the early reflections in the audio space. The H4n internal microphone was used as a supporting microphone to provide a reference signal for arrival angle calculations as well as to record an additional XY stereo image for audio demonstrations. Starter revolver shots, handclaps, wooden percussion plates, bone pipes and short human shouts were used as excitation signals. The starter revolver shots were used to record the impulse responses of various locations at the sites for acoustic measurements, whereas the other signals were used as reference signals or used for audio demonstrations. All signals were produced in the rear of the boat.

While providing adequately high-precision measurement signals, the boat-mountable recording system fulfilled the practical requirements of transportability, freedom of mains power, durability and moderate cost. The most notable limitation of the method, known in advance of the field tests, was that the direct signal of the starter revolver was too loud to be recorded without clipping. However, the early reflections from the cliffs as well as reverberation were captured without distortion.

With respect to the wintertime recordings, a new system with several improvements was designed (**Fig. 3**). To provide a wider variety of excitation signals, a custom-built omnidirectional dodecahedron loudspeaker driven by a battery-powered amplifier was used. The Zoom H4n was used as the playback device for the excitation signals. The recording setup consisted of a custom-built microphone stand with an array of four KM 183 microphones arranged in a tetrahedron with a 40 cm inter-microphone distance. A Zoom H6 multichannel recorder was used as the recording device with a 96 kHz sampling rate and 24-bit depth. The tetrahedron microphone array allowed for measuring the arrival angles of the echoes in a three-dimensional space. The drawbacks of the new system were that it required a steady surface, such as lake ice, and required greater effort to transport and set up, particularly in deep snow and cold temperatures. For these reasons, the number of recording points was reduced to only a few. Depending on the prevailing conditions, the microphone stand was positioned 5–10 m from the loudspeaker, in most cases between the loudspeaker and the studied cliff (cf. **Fig. 3**).

The main excitation signal in the wintertime recordings with the new system was a logarithmic sine sweep. Other excitation signals included sine tone and noise bursts as well as a recorded female voice, calls, laughter and drumbeats. The latter were intended for demonstration purposes. The sine sweeps were post-processed using a deconvolution method introduced by Angelo Farina (2000). The deconvolution process yields an impulse response of the recorded acoustic environment with a much improved dynamic range over an instantaneous impulse such as a revolver shot.

3.3 Acoustic analysis

The recorded sound files were analysed using the Spectutils sound analysis and visualization software toolkit (Lassfolk and Uimonen 2008). Based on the GNU Octave numerical computation language, Spectutils provides functions for creating oscillograms, sound pressure level plots and Short-Time Fourier Transform based spectrograms and sonograms. In addition, specialized signal processing Octave functions were written during the project for angle-of-arrival calculation.

Both the impulse responses made with revolver shots and the deconvolved sine sweeps were used for analysing the frequency spectrum and the reverberation time of the spaces at each recording location. By examining both the oscillograms and the spectrograms, we found that the cliffs produced distinctive and discrete early reflections with a clearly definable angle of arrival with respect to the microphone array. The arrival angles of the early reflections were calculated using the arrival time difference of the reflected impulse with respect to each pair of microphones in the microphone arrays. The angle of arrival was calculated using the following equation:

$$\theta = \cos^{-1}\left(\frac{\Delta t_{AB}}{\Delta t_{MAX}}\right)$$

where Δt_{AB} is the inter-microphone time difference of the impulse (in seconds) and Δt_{MAX} is the maximum inter-microphone time difference as determined by the inter-microphone distance (in cm) and speed of sound (in cm/s). The summertime composite array recordings allowed for the angle-of-arrival estimation in a 360° horizontal plane. The impulses were estimated visually from the oscillograms, and the angles were calculated manually from the KM 183 microphone signals by using the Zoom H4n internal microphone reference signal to distinguish between front and back arrival angles. With respect to the tetrahedron array recordings, an analysis program was written to automatically calculate the angle of arrival in both horizontal and vertical planes by applying inter-channel cross correlation as well as a scaled version of the angle calculation equation. For each analysed reflection, the analysis program outputs the ±180° azimuth and ±90° elevation angles relative to the excitation signal sound source, i.e., the dodecahedron loudspeaker. There, the azimuth angle is calculated directly from the arrival time differences between microphone pairs in the bottom triangle of the tetrahedron array. The elevation angle is calculated from the arrival time of the top microphone and the mean arrival time of the bottom triangle with Δt_{MAX} scaled accordingly.

4. Results

4.1 Echoes from the sacred cliffs

When reproducing the excitation signal at the foot of the painted Värikallio and Julma-Ölkky cliffs and the *sieidi* of Taatsinkirkko, the sound is forcibly reflected. This reflection or echo is heard with the ear (**Sound samples 1, 2**) and seen in the sound analysis plots, where it seems to repeat the excitation signal fairly accurately. In the sound pressure level plots and oscillograms, the spike representing the echo is high and simple, which indicates that the sound is loud and structurally similar to the given signal (**Figs. 4a, 4b**). In the sonograms, it is observed that the echo closely resembles the audio spectrum (c. 100–10 000 Hz) of the excitation signal reproduced by the dodecahedron loudspeaker (**Fig. 5a**), even from a distance of 50–60 m **(Fig. 5b)**. The time delay of this echo varies with the recording point and corresponds to the distance from that particular point to the studied cliff. From approximately 10 m off the cliff, the sound reflects so quickly (approximately 0.06 s) that it is difficult to distinguish it from the excitation signal. Farther away, however, the sound reflects more slowly and with a lower sound pressure level (**Fig. 4c**). At distances beyond 10 m, the sound pressure level of the echo still exceeds the "echo threshold" defined in psychoacoustical listening tests for pulse-like signals (cf. Blauert 1997, 222–235). Therefore, it can be argued that the echo visualized in the sound analysis plots is audible as a separate sound event. The best distance for listening to the echo appears to be 30–50 m with a time delay of 0.2–0.3 s. Arrival time differences between the microphones indicate that this echo arrives from the direction of the Värikallio, Julma-Ölkky and Taatsinkirkko cliffs, or more precisely, from these specific cliffs (**Figs. 6a, 6b, 6c**). In the field, this direction was clearly observable with the ear, though systematic and controlled auditory localization experiments would be needed to verify our subjective and potentially biased observations (cf. Kutruff 2000, 189–190; Kolar 2013a–b). Such a strong response from the studied cliffs is indeed not surprising given that smooth, hard wall-like surfaces are generally highly reflective and tend to reflect nearly all impinging sound energy (cf. Waller et al. 1999, 180–182; Egan 2007, 52, 89, 93). The large area (130–400 m^2) and the slight inclination (approximately 100°) of the cliffs ensure that a large amount of energy is reflected back to the sender, also in winter, when snow covers everything except for these vertical surfaces. As a consequence, the early reflection caused by the cliff forms a phantom sound source with an arrival angle which is both audible and measurable.

4.2 Other echoes at the sites

The echoes from the Värikallio, Julma-Ölkky and Taatsinkirkko cliffs are not the only echoes at the studied sites. Rather, on the contrary, especially in the summer, several other echoes can be heard and captured in the vicinity of these cliffs as well as farther away along the narrow canyon lakes. None of our recording points proved to be wholly echoless (**Fig. 7**). According to the sound analysis plots, these echoes are not accurate repetitions of the excitation signal, but are a great deal softer (**Fig. 4c**), more complex or diffuse in structure (**Fig. 4c**) and restricted in frequency range (**Fig. 5a**). In particular, the highest and the lowest frequencies fade quickly, being only observable in the reflections with a short time delay (< 0.1 s) (**Fig. 5b**). Both our subjective auditory observations and angle-of-arrival calculations indicate that these echoes arrive from two opposite shores of the canyon lakes, which in the studied places are 40–100 m in breadth (**Figs. 6b, 6c**). In the middle of the lakes, the two echoes overlap each other, whereas on the shorelines, they can be heard in succession. On the shore, the echo from that specific shore coincides with the excitation signal and is therefore inaudible. This type of resounding acoustics may be typical of narrow canyon lakes where both shores are somewhat steep and rocky. These rugged surfaces, however, are less reflective than the outstandingly smooth cliffs of Värikallio, Julma-Ölkky and Taatsinkirkko. Moreover, in winter, these rugged surfaces are almost unresponsive due to the thick mantle of snow. Thus, the average echoes on these acoustically anomalous lakes are less pronounced than the strong, accurate and invariable responses from the sacred cliffs (cf. **Fig. 7**).

4.3 Flutter echoes between the shorelines

At Värikallio and Taatsinkirkko, more complex, multiple echoes were captured. At the foot of these painted or sacrificial cliffs, the sound reflects from the cliff and the opposite shore, but the oscillograms and sonograms show that these reflections also have a long reverberant tail (**Fig. 8**). Furthermore, the tail has intensity peaks at more or less regular intervals. These peaks or level boosts suggest that the sound actually consists of a series of echoes, the rearmost of which are not resolvable by the human ear but are heard as a slight flutter in the aftermath of the first strong reflections. At Värikallio, the duration of this repeating echo is 1.2–1.5 s (cf. **Fig. 5a**). The pattern indicates a flutter echo, where the sound bounces back and forth between opposite lake shores (cf. Egan 2007, 61, 109, 112). At least four successive turns can be counted at Värikallio as well as at Taatsinkirkko. At Julma-Ölkky, this type of re-reflection is missing from the plots. However, this is expected because the painted cliff is not facing the opposite shoreline. Although flutter echoes in general are not exceptional phenomena, these observations strengthen the impression that the studied cliffs are efficient sound reflectors. In addition to strong true echoes, they seem to produce repetitive flutter-type echoes between themselves and the parallel shorelines.

4.4 Auditory illusions

All of above-mentioned echoes are impressive as such, but something exceptional, and at the same time hardly measurable, could also be heard at the foot of the Värikallio, Julma-Ölkky and Taatsinkirkko cliffs. Apart from the energetic excitation signals, these cliffs reflect soft conversation, laughter and footsteps, that is, outcomes of social intercourse and casual activities. What is startling is that at Värikallio, the sound appears occasionally to derive straight from the painted figures, as if they were speaking or laughing, as if they were alive. This audio-visual impression arose most likely as the result of the excitation voice, whisper or laughter from the loudspeaker, when the researcher-observers stood by the microphones in the middle between the loudspeaker and the cliff. The elevation angle calculation, projected to a still picture of the 3D model, also indicates that the sound emanates from the lower part of the cliff, i.e., from the level of the paintings (**Fig. 9**). However, here again, systematic auditory localization experiments would be needed to verify our subjective observations, as the visual stimuli from the paintings might have guided them (cf. McGurk & MacDonald 1976). Furthermore, the sound reflects not only back to the sender but also to other observers who stand or move at suitable angles in front of these cliffs. In this sense, these observers hear the sound simultaneously from two different directions, specifically, from the actual source and from the cliff face. This stereo effect is confusing because it creates an illusion that the cliff is suddenly interfering or participating in the discussion. Despite the sensation of magic (cf. Cross & Watson 2006), these effects have a logical explanation. They all stem from the same law of reflection, which states that the angle of the incident sound wave equals the angle of the reflected sound wave (Kuttruff 2000, 33–37, 90–97, Figs. 2.1, 2.4). This means that a performer at a right angle to the cliff can hear his/her own voice as an echo, while the others can hear a reflection of the same sound when standing at a certain oblique angle to the cliff (**Fig. 10**). Almost simultaneously, these receivers also catch the direct sound.

5. Discussion

Our field recordings at Värikallio, Julma-Ölkky and Taatsinkirkko demonstrate that the acoustical phenomena at all of these sites are considerably resounding. Several echoes can be heard in the immediate as well as in the more distant surroundings of the studied cliffs, especially in the summer. Throughout the year, the strongest and most pronounced echoes are reflected from the painted or sacrificial cliffs, which, in addition to true echoes, are reflective enough to create flutter-type echoes, auditory illusions as well as phantom sound sources. In this sense, the studied sacred cliffs can be considered to be the ear-catchers of the acoustically anomalous lakes. Furthermore, similar smooth wall-like cliffs, featuring almost all Finnish rock art sites, can be considered among the most efficient sound reflectors found in the natural constructions in Finland, or known by the past hunter-fishermen or reindeer herders. As a rule, the dwelling sites and huts of these people were situated at a distance of several kilometres from this type of sacred sites: on gently sloping sandy heaths and beaches, where the acoustics was very different (**Fig. 11**). If any discrete echoes were heard at the dwelling sites, they arrived from rather distant and therefore indefinable sources, for example, from the other side of the lake. On the whole, the results of our measurements certainly support the hypothesis that sound played some role in the development and use of the studied sites. It seems reasonable to assume that auditory effects and experiences, such as the ones discussed herein, had an influence on the meanings people gave to these places: remote cliffs and canyon lakes (see also Goldhahn 2002 on the connection between rock art and rush of water). However, other elements too might be important to them. The same smooth, hard, large walls that had the greatest capacity to reflect sound waves provided the most attractive or favourable surfaces for painting. In many cases, the best reflectors were also visually the most impressive rocks of the lakes. Thus, the identification of the original or primary reasons for painting and ritualizing certain cliffs seems difficult. Because the reflectivity of the sacred cliffs appears to remain unchanged throughout the year, the acoustic research does not help to determine whether the paintings were crafted during the summer or the winter, i.e., from a boat or from a frozen surface of the lake.

Unexpected but important evidence for the significance of sound rituals in the context of the rock paintings was discovered when the painting of Värikallio was redocumented in the course of our fieldwork. We took a systematic photomosaic of the panel using a tripod-mounted system camera to take high-resolution RAW images (altogether 1.5 GB). The photographs were then processed by the South African photographer and software engineer Kevin Crause using the CPED toolset, which has produced outstanding results in revealing ‘invisible’ images at badly weathered rock painting sites (e.g., Challis et al. 2013). The enhanced images made it possible to identify several previously unrecognized figures, including three human figures that appear to be beating a drum (**Fig. 12**) and a bow lady that has its closest resemblance in Sámi tradition of *Juksáhkka*, the Sámi goddess of childbirth. The drumming figures seem to hold a round object in one hand, while the other hand is raised in a striking position. Stylistically similar drumming figures are depicted, for example, at the rock carvings of Alta in northern Norway (**Fig. 13**) (Helskog 1988, 53, 133), but in Finland, they are, thus far, unique. The identification of *Juksáhkka* is based on the emblematic bow in the left hand of the figure and the fact that the figure is clearly female as both breasts and a *mons pubis* appear to be depicted. This motif is also very rare, but individual instances can be found in rock art throughout northern Fennoscandia (see Lahelma 2012), and similar figure also occurs on Sámi shaman drums of the historical period. Together with the drumming figures, they suggest that the rock paintings may be more directly associated with Sámi culture than generally thought, thus highlighting the relevance of Sámi ethnographic sources for interpreting north Fennoscandian rock art.

With respect to the *sieidi* sites, the ethnographic sources clearly link them with sound rituals. In the Sámi ethnic religion, the *sieidi* were perceived as animate beings that could have emotions, consume offerings given to them, and communicate in different ways (Äimä 1903; Paulaharju 1932; Äikäs 2015). As noted, an echo could be one of the ways in which *sieidi* replied. Priest Jacob Fellman (1906, 230) has described a chant to the *sieidi* of Taatsi promising it antlers in return for hunting luck, and later, Paulaharju (1932, 16) describes how the *sieidi* of Taatsinkirkko was approached by singing magical songs. The existence of such pieces is only evidenced in written sources, so there is no information available about their musical form. However, on the basis of our investigations, it can be assumed that some of the verses or words echoed from the cliff around the canyon lake. Testing this with recorded or live *joiking*, either in the field or in a simulated acoustic space, would be an interesting follow-up to the project. As noted, Paulaharju also states that the Sámi shamans used to *joik* at *sieidi* sites to attract reindeer or to enter into a trance. Although ethno-historical records do not mention drums in connection with the *sieidi*, they could well have been part of the rituals that occurred at the sites of both rock paintings and *sieidi*. Sharp impulses, such as drumbeats, would have been particularly compatible with the sites' acoustics, because they make the echoes clearly audible. They also enable to play a rhythmic dialogue or duet with the cliff by beating and listening in turns. Using music and song that was given to mankind by the people of the underworld, the sites and the painted figures could be brought to life, thus enabling ritual communications with the cliffs and the spirits thought to dwell within those cliffs.

6. Conclusions

Our archaeoacoustic investigations at Värikallio, Julma-Ölkky and Taatsinkirkko indicate that these sacred sites have a distinct acoustic character. Steep and rocky canyon lakes give rise to several echoes, especially in the summer, when the rugged landscape is free of snow. However, in both summer and winter, the most pronounced echoes are reflected from the smooth vertical cliffs that have been painted or held as sacred. According to our audio analysis, these cliffs forcibly reflect sound, repeat the excitation signal relatively accurately, and create auditory illusions as well as phantom sound sources. At Värikallio, the sound appears to emanate from the painted figures as if they were talking or answering back. Although the association between rock art and echoes, in general, is not a new discovery, this case study is the first to measure that the sound emanates directly from the paintings. It is also the first to discuss the unique Sámi traditions in the context of archaeoacoustics. Acoustic scapes, such as the ones discussed herein, would have offered favourable prerequisites for ritual communications with the cliffs or with spirits dwelling within them. Probable depictions of drummers, identified during the fieldwork in the Värikallio painting, provide a clue to possible instruments used in these auditory performances. On the other hand, ethnographic accounts of Taatsinkirkko describe that the Sámi invoked specific chants or *joiks* while making offerings there.

Compliance with Ethical Standards

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Conflict of interest: The authors declare that they have no conflict of interest.

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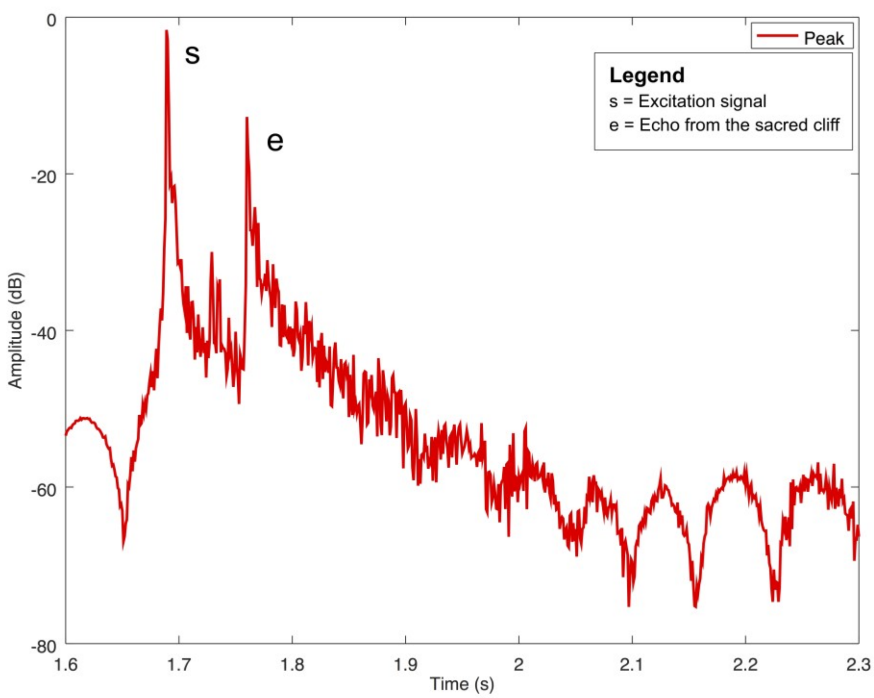
Fig. 1 Painted cliff of Julma-Ölkky as seen from the south. The paintings lie 1.2 m above water. Photograph: Riitta Rainio

Fig. 2 Sacred cliff of Taatsinkirkko with the offering stone of Taatsi in the foreground. Photograph: Anssi Malinen

Fig. 3 Recording setup on ice in front of the Värikallio cliff. From left: the dodecahedron loudspeaker, the snow mobile with a sledge, the recording and playback devices, researchers Tiina Äikäs and Annu Mikkonen, the tetrahedron microphone array, the spectator pier and the painted cliff. Photograph: Riitta Rainio



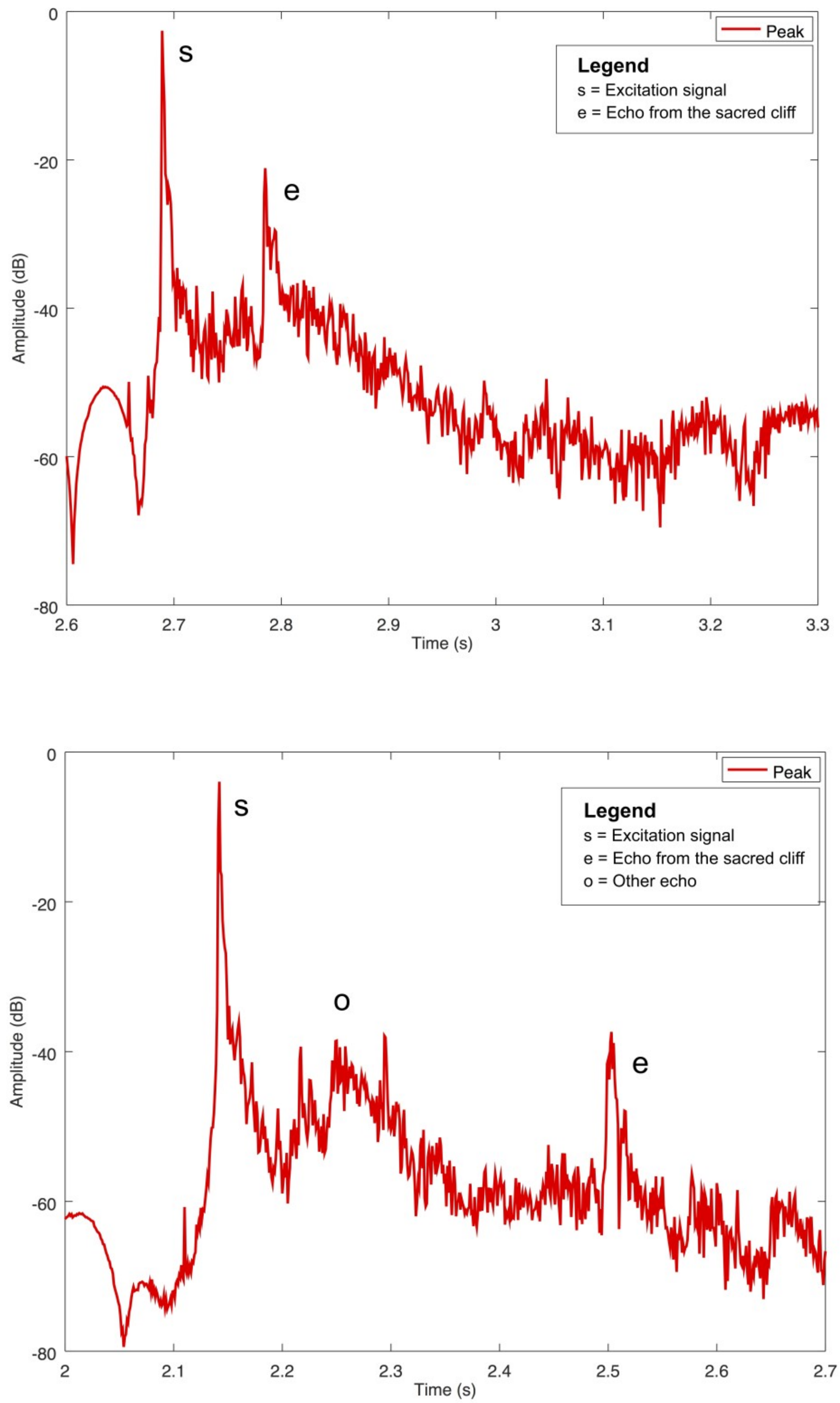
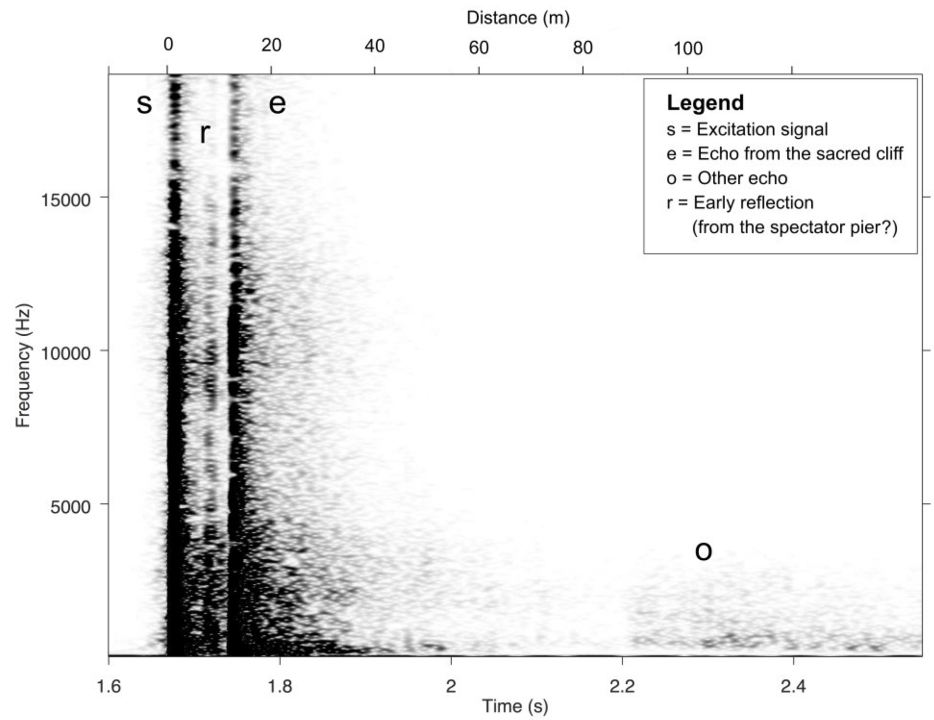


Fig. 4 Unweighted peak sound pressure level plots showing the excitation signal, the echo from the sacred cliff and other echoes at **a)** Värikallio (the microphone stand 12 m off the cliff at a temperature of +2° C), **b)** Julma-Ölkky (the microphone stand 16 m off the cliff at a temperature of +2° C) and **c)** Julma-Ölkky (the microphone stand 58 m off the cliff at a temperature of -13° C)



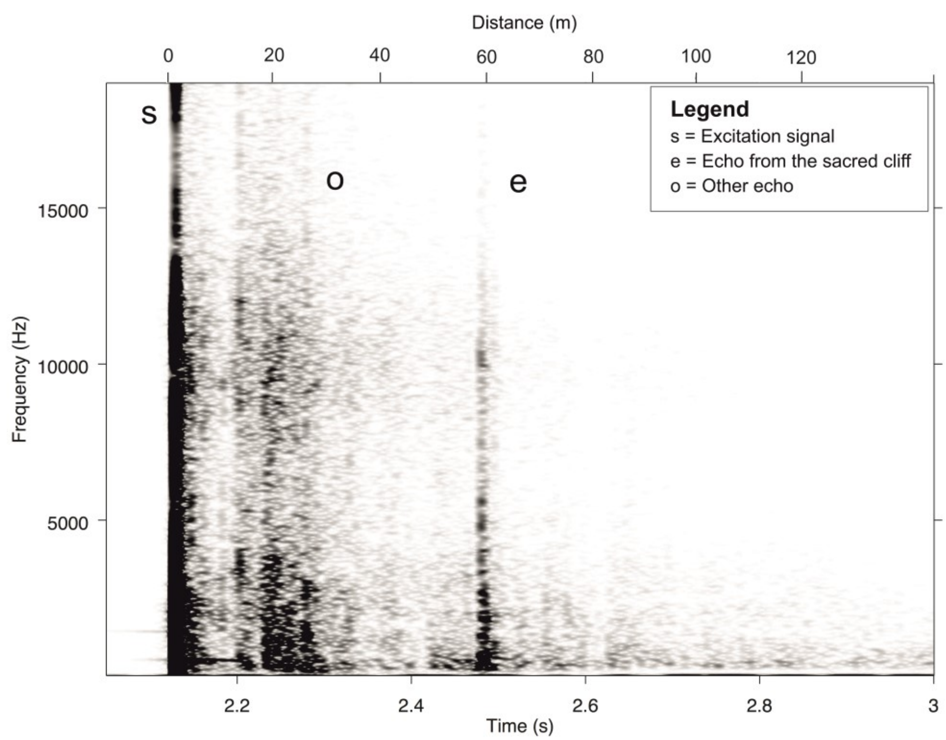
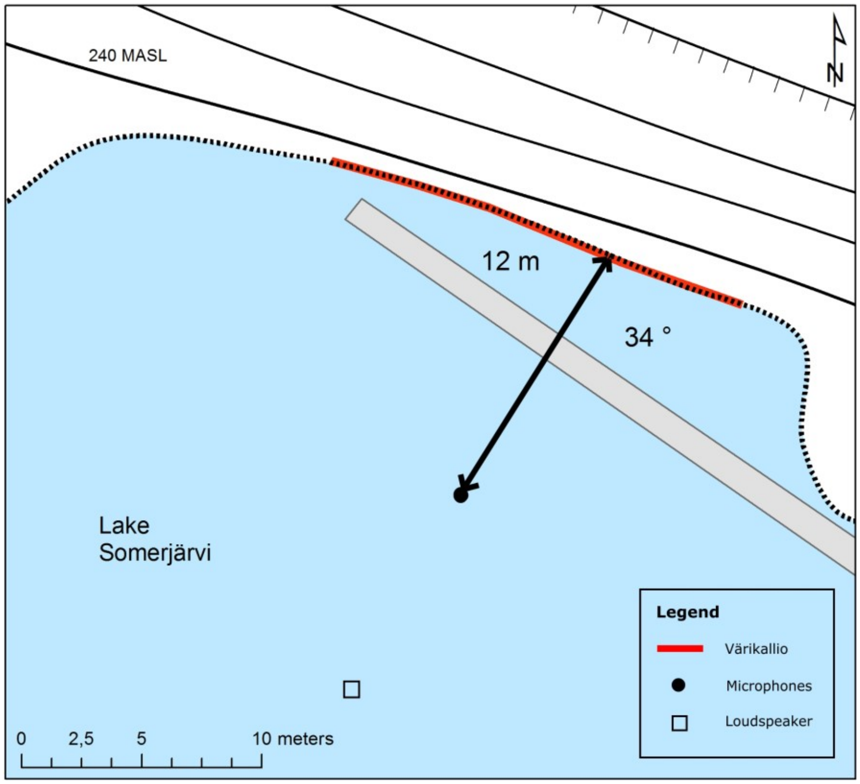


Fig. 5 Sonograms showing the excitation signal, the echo from the sacred cliff and other echoes or reflections at **a)** Värikallio (the microphone stand 12 m off the cliff at a temperature of +2° C) and **b)** Julma-Ölkky (the microphone stand 58 m off the cliff at a temperature of -13° C). The amplitude of the frequencies is represented by the intensity of the greyscale. The distance from the reflecting surface is calculated with the formula T/2 x c, where T is the time delay of the echo (in s) and c is the speed of sound (in m/s) at a given temperature of the air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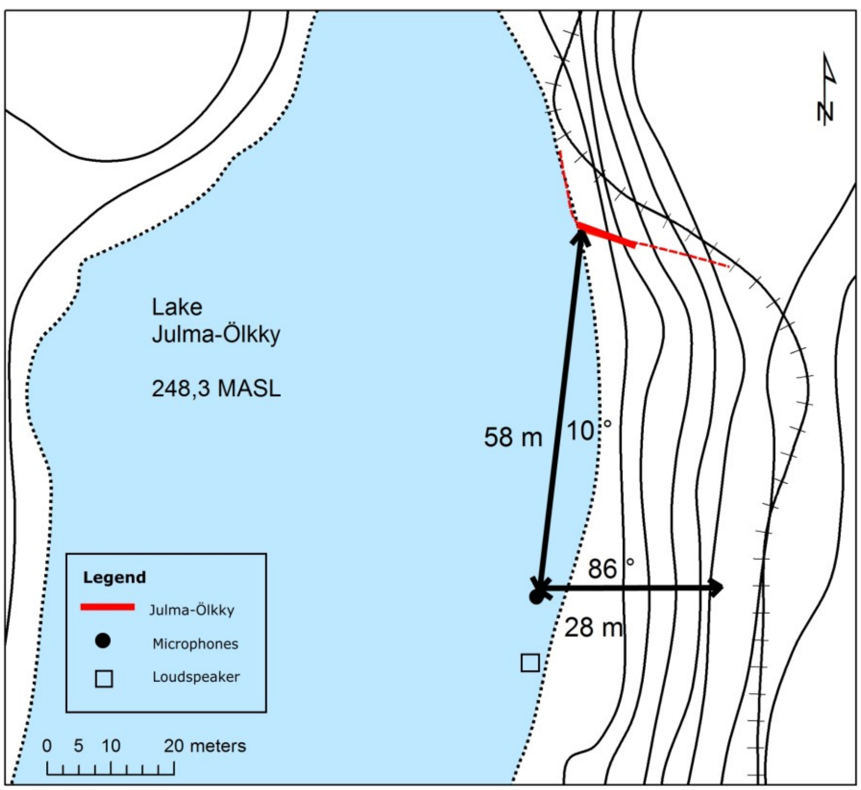
12 m
34 °
Lake
Somerjärvi
Legend
Värikallio
Microphones
Loudspeaker
0 2,5 5 10 meters


Lake
Julma-Ölkky
248,3 MASL
58 m
10 °
86 °
28 m
Legend
Julma-Ölkky
Microphones
Loudspeaker
0 5 10 20 meters

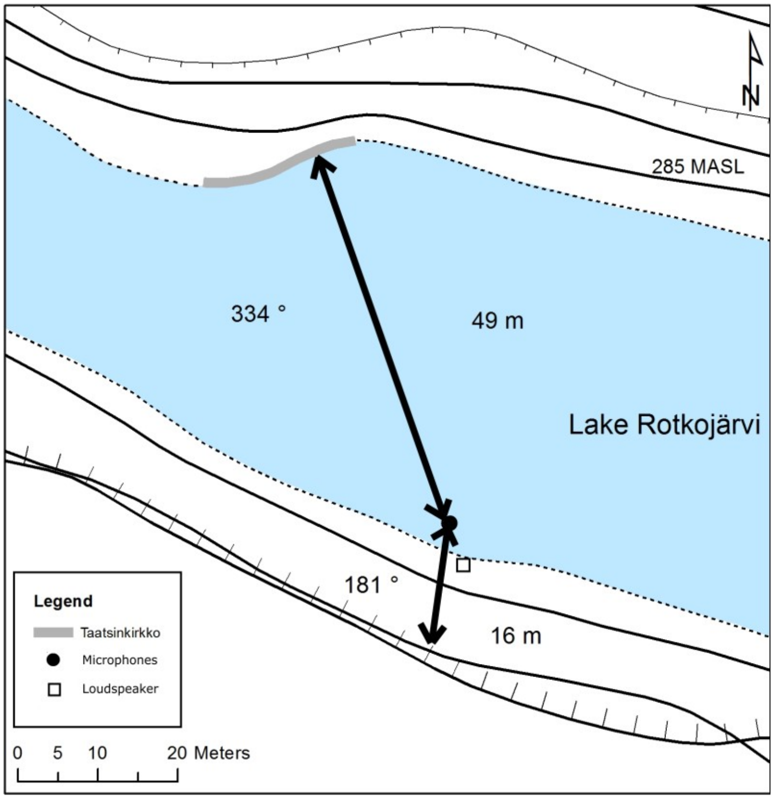


Fig. 6 Maps showing the calculated angle of arrival and distance of the early reflections or echoes at **a)** Värikallio (the microphone stand 12 m off the cliff at a temperature of +2° C), **b)** Julma-Ölkky (the microphone stand 58 m off the cliff at a temperature of -13° C) and **c)** Taatsinkirkko (the microphone stand 49 m off the cliff at a temperature of +8° C). Direction of the arrow = calculated angle of arrival; length of the arrow = calculated distance from the reflecting surface

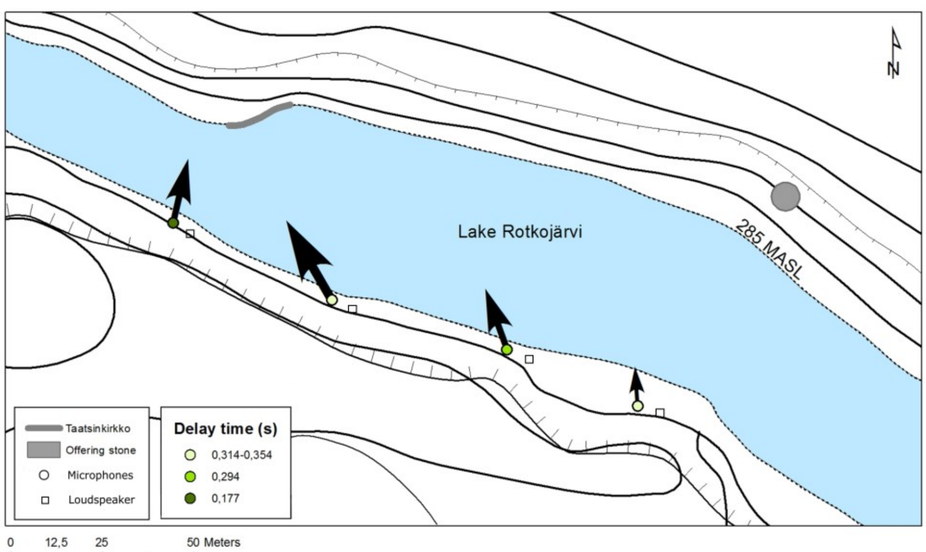


Fig. 7 Map showing the discrete echoes at four different recording points on the southern shore of Lake Rotkojärvi (at a temperature of 0° C). Direction of the arrow = calculated angle of arrival of the echo; size of the arrow = amplitude of the echo using three scales (0.09, 0.15−0.25, 0.4); colour of the recording point = time delay of the echo

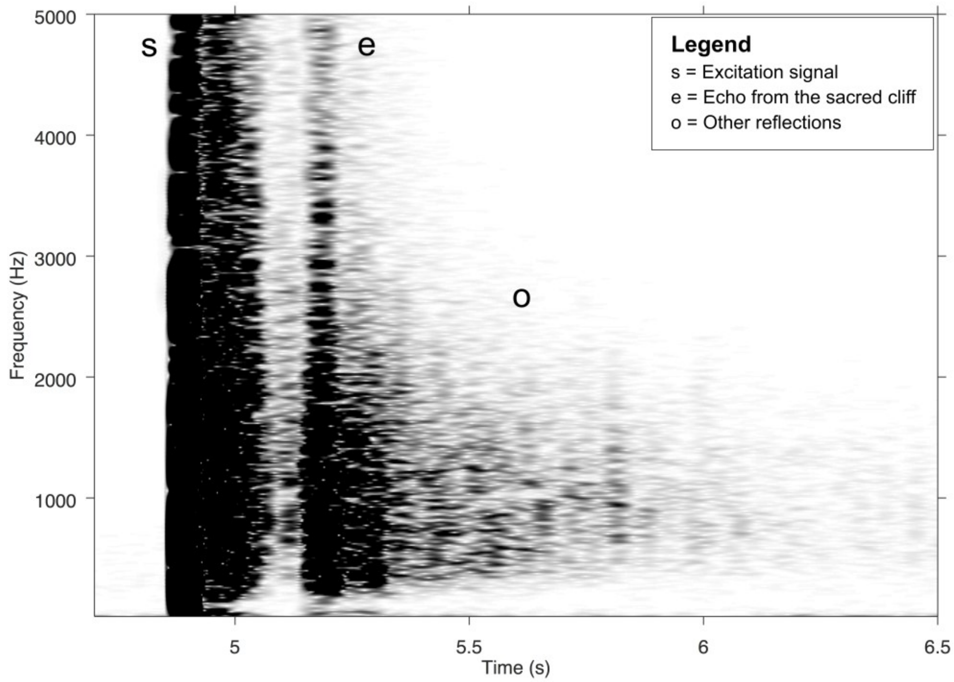


Fig. 8 Sonogram showing the excitation signal, the echo from the sacred cliff and all other reflections at Taatsinkirkko (the microphone stand 49 m off the cliff at a temperature of +8° C). The amplitude of the frequencies is represented by the intensity of the greyscale

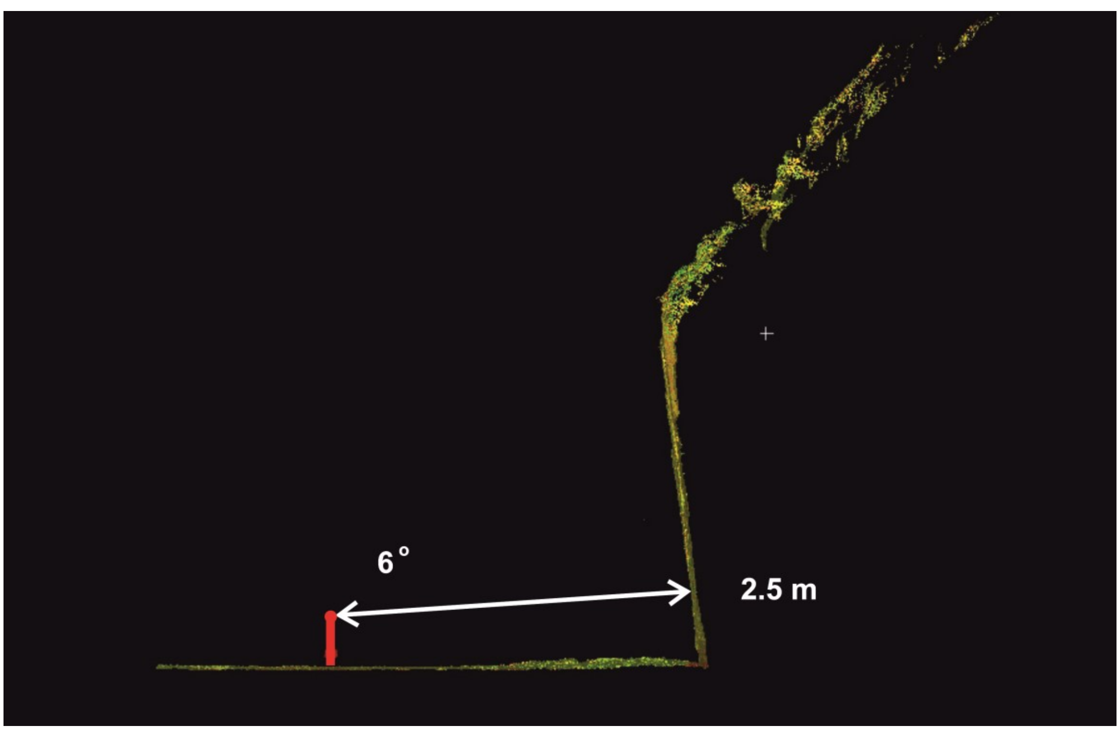


Fig. 9 Still picture of the 3D model showing the smooth inclined form of the Värikallio cliff, the microphone stand and the calculated angle of arrival of the echo in a vertical plane (the microphone stand 12 m off the cliff and the loudspeaker 22 m off the cliff behind the microphones at a temperature of +2° C). The paintings lie 0.2–2.5 m above the present level of the lake

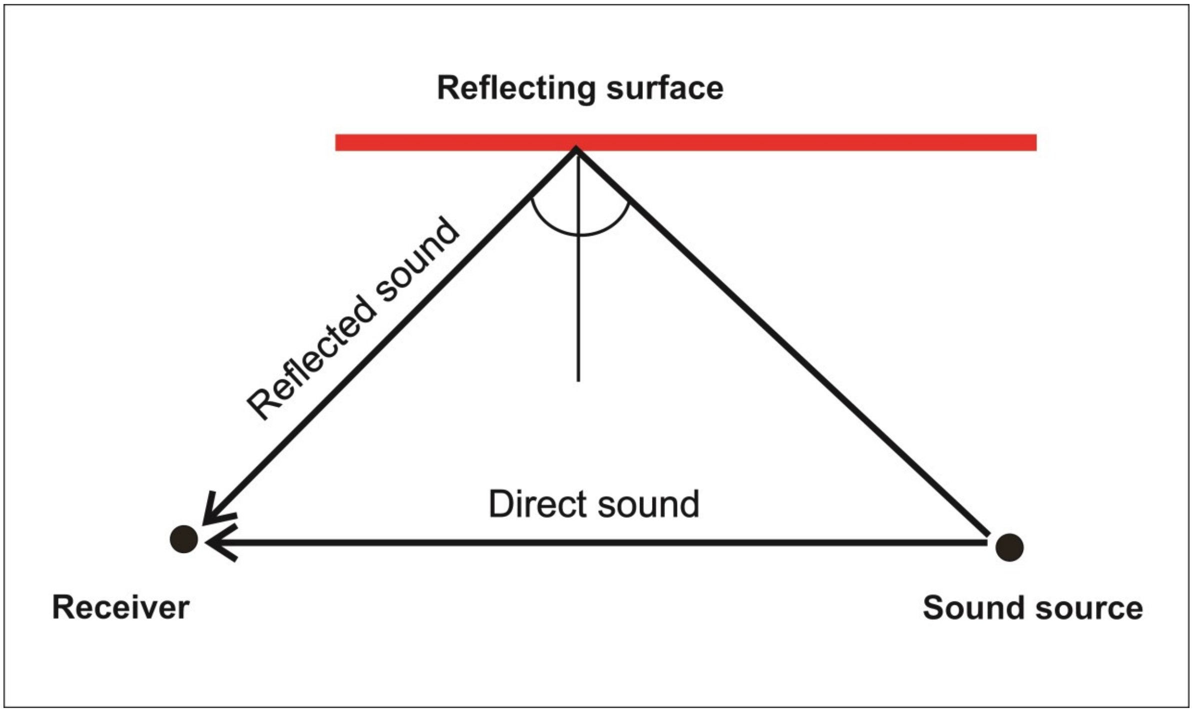


Fig. 10 Example of possible sound source and receiver positions giving rise to the stereo effect in front of a reflective surface

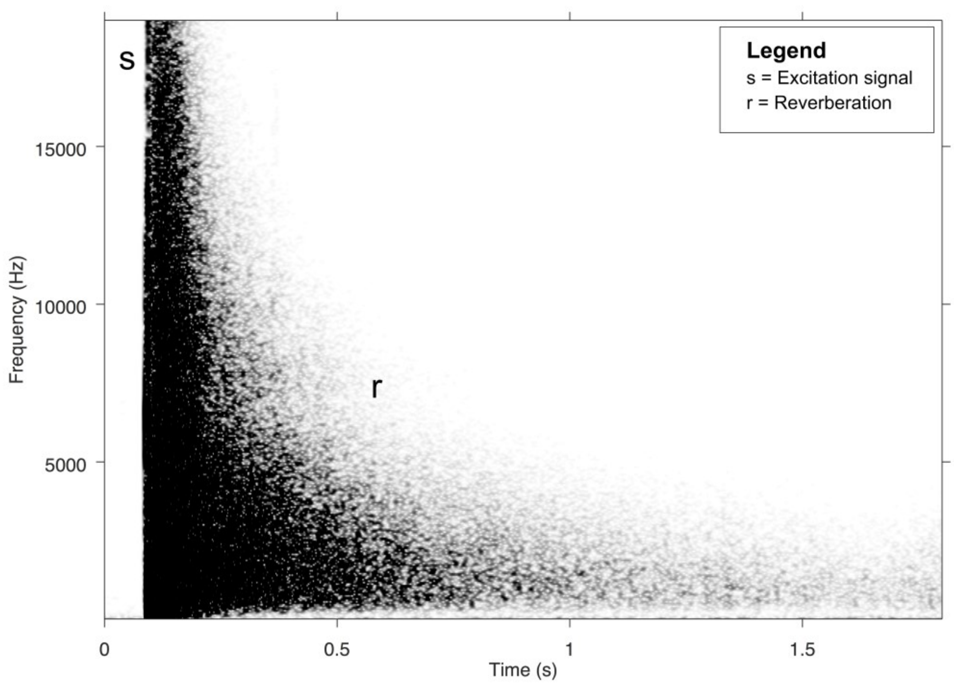


Fig. 11 Sonogram showing the excitation signal and the resulting reverberation (without discrete echoes) at Muikkupuro, a typical Stone Age dwelling site located approximately 5.5 km to the south-east from Värikallio (at a temperature of +17° C). The amplitude of the frequencies is represented by the intensity of the greyscale

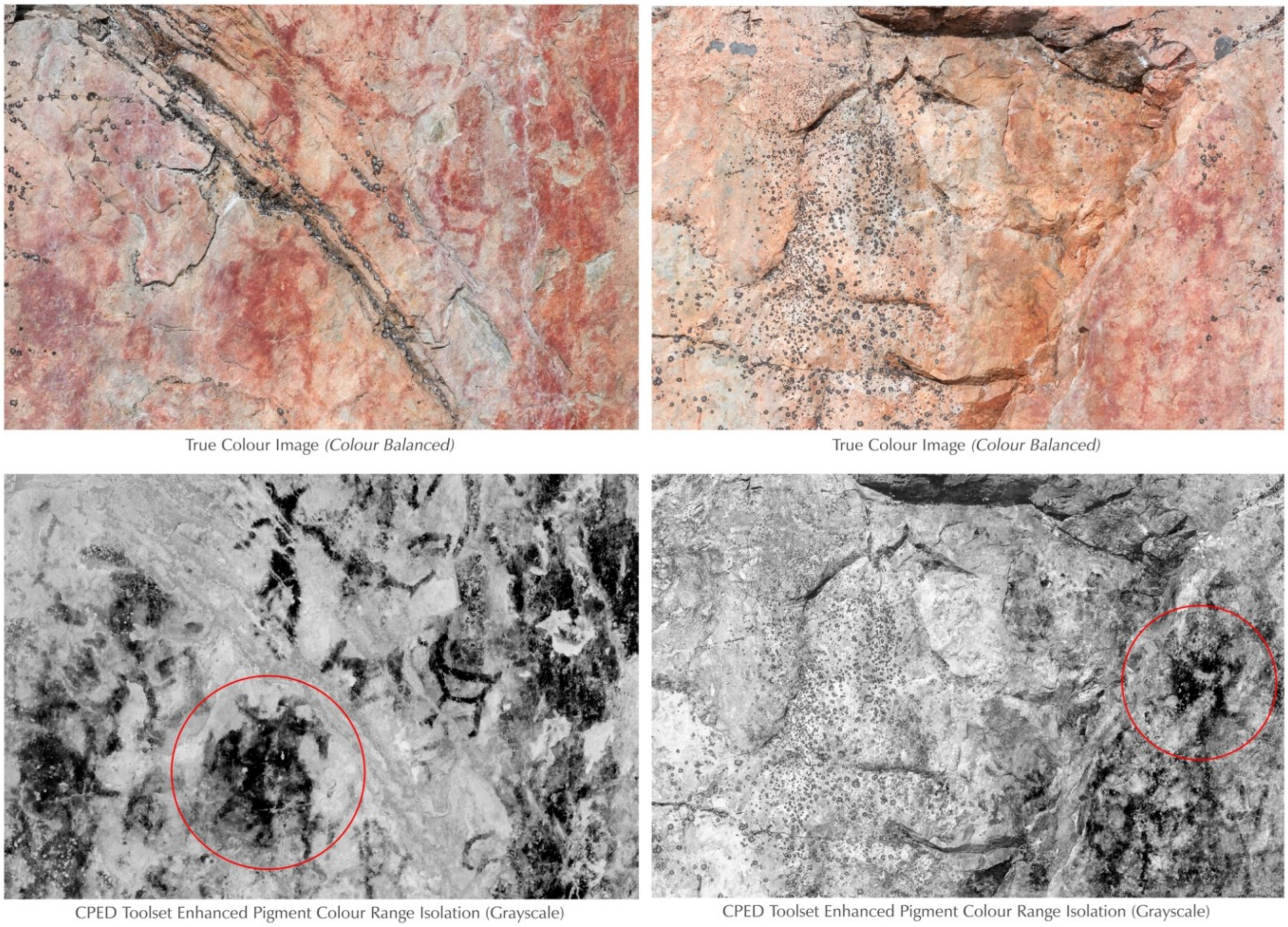


Fig. 12 Two pairs of images from Värikallio showing possible drumming figures (two partially superimposed figures on the left, one figure on the right). The images in the upper row are unretouched true colour images, whereas those in the lower row have been modified with the CPED toolset. Photographs: Antti Lahelma. Digital enhancement: Kevin Crause

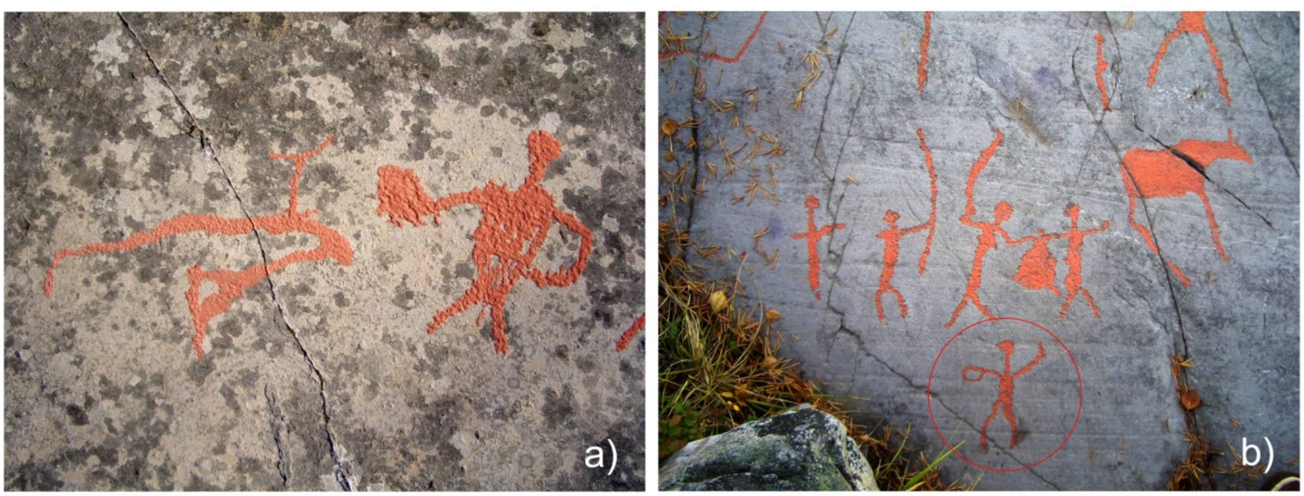


Fig. 13 Two examples of drumming figures from the rock carvings of Alta in northern Norway: a) a scene from the Bergheim panel and b) a scene from the Ole Pedersen IX panel. Photographs: Antti Lahelma

Sound sample 1 Noise burst and the echo from the painted cliff of Julma-Ölkky (the microphone stand 58 m off the cliff at a temperature of -13° C), repeated four times

Sound sample 2 Drumbeat and the echo from the sacred cliff of Taatsinkirkko (the microphone stand 49 m off the cliff at a temperature of +8° C), repeated four times