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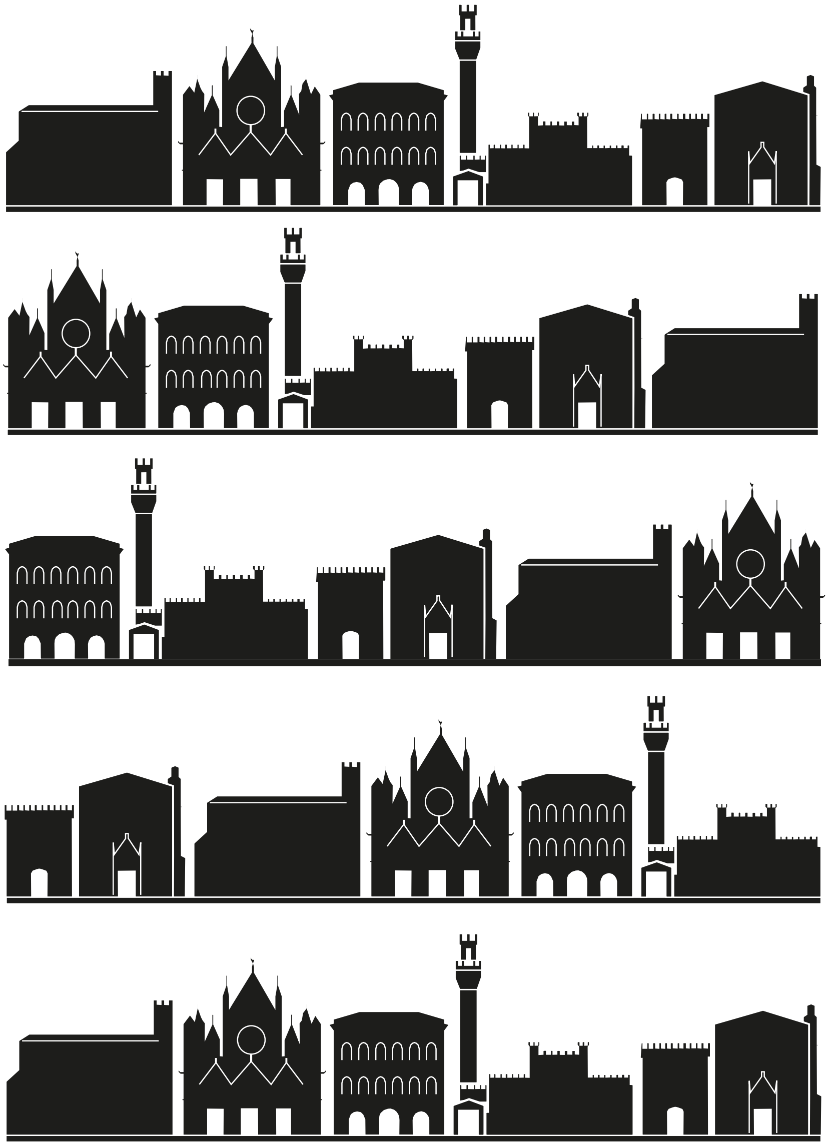

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Archaeoacoustics of Rock Art: Quantitative Approaches to the Acoustics and Soundscape of Rock Art

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Abstract: Archaeoacoustics refers to the field of study concerned with the effects of sound in past societies. Scholars interested in acoustics try to understand the human past beyond its materiality by recovering a set of less evident, less tangible cultural signs relating to the sense of hearing. Of the many contexts in which the intangible evidence of acoustics can be analysed, this paper pays attention to its expression in rock art. Our aim is to explore the quantitative analyses undertaken for the study of acoustics in rock art landscapes by focusing on the three main lines of evidence that rock art researchers are following: (i) landscapes with special naturally occurring sounds; (ii) lithophones, ringing rock, and rock gongs; (iii) intentionally produced sound. Three acoustic effects have been usually subjected to quantitative measurement: echoes, resonance, and reverberation. We will argue that not all lines of evidence have been explored in equal measure by scholars and that there are specific types of acoustic measurements and analysis, the potential of which are still to be assessed.

Keywords: Archaeoacoustics, Rock art, Quantitative analysis, Post-Palaeolithic, Soundscape

Introduction

Archaeoacoustics, or the combination of archaeology and acoustics, refers to the field of study that aims to investigate sound in the past. Scholars interested in acoustics try to understand the human past beyond its materiality by recovering a set of less evident and intangible cultural signs related to the sense of hearing. Of the many contexts in which the intangible evidence of acoustics can be analysed, this article will pay attention to rock art. The archaeoacoustics of rock art studies how past communities engaged with acoustics by choosing areas with particular acoustic properties to be decorated and/or to create acoustical environments in which to set all the activities related to the production and experiencing of rock art. Studies in this field usually reflect on why acoustics were sought after by past societies, and data are drawn from fields as diverse as psychology, iconography, and anthropology (see e.g. Lahelma 2012; Morley 2006). The spatial association of rock art and acoustic phenomena should not automatically be considered as significant, however, as it may be coincidental. It is important to analyse such a relationship through a landscape survey to test whether there is a positive association between the places where particular acoustic effects are present, and those where they do not exist or are of lesser importance. If a positive relationship is found, then it is reasonable to assume that acoustic effects were meaningful and desirable for the communities that produced the rock art in the past.

Methodologically this field of research is still in its infancy. Although the first articles on what we now call archaeoacoustics were produced in the 1950s and there has been a sharp increase in its study in the last decade, there is still much to do. Most authors looking at the connection between rock art and acoustics discuss the latter based on the perception of scholars. Those who attempt to quantify the acoustic properties valued by prehistoric communities are still in the minority. The point of departure is that the auditory experience sought by people in the past is measurable in terms of acoustic parameters. There are several acoustic phenomena, such as echoes, resonance, and reverberation, that are related to the transmission, reflection, refraction, interference, diffraction, scattering, absorption, and dispersion of sound (Rossing 2007: 16). These can be measured in terms of temporal pattering, spatial characterization, and frequency domain (Rossing 2007).

Echoes are the sound a listener hears reflected from a hard (usually vertical) surface. From an acoustical standpoint an echo signature is clearly visible when the digital file is converted into a graphic display (sonogram or echogram), but in order for it to be perceived by the human ear several conditions must be met. First of all, due to the psycho-acoustic phenomenon known as forward masking, the reflections will be inaudible if they arrive very soon after the direct sound and/or their level is very low in relation to the direct sound. Thus, there exists a threshold of audibility dependent on delay and direction of incidence relative to the direct sound. Only if the level of the reflection is above this threshold will the reflections have an audible effect, which again depends on their level, delay, and direction of incidence. Echo threshold is typically observed for delays beyond 50 ms and at high reflection levels (Rossing 2007: 305). If the delay is shorter, the direct signal and the reflection are perceptually merged, causing a variation in level, clarity, spaciousness, or change in localization direction (e.g. 'precedence effect' or 'Haas effect'; see Litovsky *et al*. 1999). Because human hearing is generally in the frequency range of 20Hz to 20 kHz (Levitin 2006: 22) and because sound travels at about 343 m (1125 feet) per second at typical temperatures and atmospheric pressures, the listener must be 17 m (55 ft) from the reflecting surface to hear echoes.

The second type of acoustic effect studied in the archaeoacoustics of rock art is resonance, a phenomenon that occurs in enclosed or semi-enclosed spaces, consisting of the amplification of a specific sound the frequency of which matches one of its own natural vibrational frequencies (Rossing 2007: 213). It is caused by standing waves that occur when the mirror sound images reflect off each side to set up a stationary pressure pattern in the space. This effect generates unexpected higher or lower levels of sound (dB) at some locations and a specific frequency because a standing wave is reinforcing or cancelling the sound pressure.

The third acoustic effect discussed by scholars looking at the relationship between acoustics and rock art is reverberation. This is defined as the build-up of sound within an enclosed or semi-enclosed space resulting from repeated sound wave reflections off all of its surfaces. It can increase sound levels up to 15 dBA and can also distort the perceived frequency of sound or the intelligibility of speech (Rossing 2007: 394), as the sound reflections lose important details (e.g. consonants or pitches) that are masked by louder, lingering sounds. Reverberation is described by a parameter known as the reverberation time (EDT, RT). For example, the RT60 can be physically defined as the time (in seconds) it takes for the sound pressure level of a sound source to decrease by a factor of 60 dB after that sound source has been silenced.

There are three major contexts in which rock art and acoustics can be discussed. Firstly, there are landscapes where scholars have observed the correlation between particular naturally occurring sounds and rock art. Secondly, there are resonant geological formations with rock art producing bell- or gong-like sounds when subjected to percussive impacts (lithophones, ringing rocks, rock gongs, or stone bells). Finally, there are decorated spaces where an intentionally produced sound may result in an exceptional number of echoes, or create abnormal resonance and reverberation. It will be the focus of the following pages to present an overview of the methods that have been followed in the quantitative study of acoustics in rock art areas, and to propose fields in which we believe further development is necessary.

1 Rock art landscapes with special naturally occurring sounds

Soundscapes, or the particular set of sounds that characterize a landscape, have recently been classified by the ecologist Almo Farina as sonotopes (Farina 2014). Sonotopes are the sonic combination of geophonies, biophonies, and anthrophonies in the landscape. Geophonies include all those sounds produced by non-biological natural agents such as winds, volcanoes, sea waves, running water, rain, thunderstorms, lightning, avalanches, earthquakes, and flooding. Biophonies are sounds coming from living beings such as animal vocalizations (song, contact and alarm calls, and voices). One particular type set of biophonies, which is treated as a third type of sound, are anthrophonies or human-produced sounds. In archaeology some recent attention has been paid to anthrophonies (Boivin *et al*. 2007; Mills 2005a; 2005b), whereas geophonies have been dealt with by scholars interested in rock art in Portugal (Blake and Cross 2015), Sweden and Scandinavia (Goldhahn 2002), South Africa (Mazel 2011), and Chile (Waller 2002: 12).

Geophonies have been analysed in Scandinavian rock art, where suggestions that the sound of water may have been equally as important as vision in locating rock art (Coles 1991: 133; Sognnes 1994: 39, see also Lødøen 2010: 45–46). The methodology used by the rock art specialist Joakim Goldhahn was to quantify the sound pressure level (SPL) created by running water at regular intervals along river sections in rock art areas. His results showed that rock art placement in proximity to loud roaring rapids and waterfalls was not just governed by the availability of a suitable surface to engrave, but was a deliberate choice to select places with loud noises. Goldhahn argued that the 'roaring' sound of water (up to 110 dB) played a vital part in shamans' desire to enter and return from an altered state of consciousness, as it acted as a liminal border between the person at the rock engravings and the rest of the world (Goldhahn 2002).

In the Côa Valley rock art area in Portugal, Elizabeth Blake and Ian Cross (2015) mentioned the method developed by Mills (2005b) to generate 'soundmaps'. Mills partitioned the modern soundscape of a Cornwall mining area into features deriving from the landscape, ranging from the faunal environment to human activities. He generated visual 'soundmaps' in which the predominant sound types were mapped in terms of long-term average spectrum (LTAS). Although Blake and Cross did not provide any direct field measurements in their study of the Côa Valley, they developed hypotheses of long-term average spectrum (LTAS) on the basis of landscape features and archaeological evidence. They found a highly differentiated landscape, ranging from scrub vegetation, that would probably be fairly acoustically absorbent, and river flow, with either moderate background noise levels affording masking effects (turbulent flow) or low background noise level affording refraction effects (regular flow, calm surface), to highly reflective granite and schist slabs. They argued that the locations of petroglyphs, at the boundary between the rocky valley slopes and the floodplain mostly on fluvial rock terraces in proximity to the river, could give rise to psycho-acoustic anomalies (reflections, resonances, or echoes, or — in still water conditions — refractions leading to relatively distant sound sources appearing nearer than they are), or aiding in the masking biophonies or anthrophonies by reinforcing river sounds when the flow is turbulent. Thus, the petroglyphs seem to have been placed on the edge of the soundscape, affording atypical, 'liminal', and diverse sonic experiences quite distinct from those in the rest of the surroundings.

Discussing the rock art of the Didima or Ndedema Gorge in South Africa, Aron Mazel has argued that the acoustics of thunderstorms was the reason for the selection of this landscape to be decorated. Inspired by the remarks made by Harald Pager (1971) regarding the concentration of rock art at Didima Gorge and its landscape acoustic properties during thunder, Riaan F. Rifkin's comments on the similarities between acoustic and spiritual phenomena (Rifkin 2009), and the growing interest in archaeoacoustics (Scarre and Lawson 2006), Mazel argued that Didima Gorge was a special place for hunter-gatherers. Although he did not make any quantification of the effects, he proposed that the excellent acoustics inside the rock art sites and the intense reverberation of the whole gorge after thunderstorms would have been considered as meaningful by the communities who produced the rock art. He observed that the original name of the gorge itself suggested the importance of acoustics, as 'Ndedema' could be translated as 'the reverberating one'; in the gorge the sound of thunder crashing produces a clattering vibration as it echoes through the steep sandstone cliffs (Mazel 2011).

2 Lithophones, ringing rock, and rock gongs

Rock art is not only found at places where naturally occurring sounds are common, but also at lithophones. Catherine Fagg defines them as 'naturally situated and naturally tuned rocks, boulders, exfoliations, stalactites and stalagmites which resonate when struck and show evidence of human use as idiophones' (Fagg 1997: 2). As lithophones are used as instruments, their study was considered much earlier in the history of archaeology than any of the other types of acoustic context. The existence of rock gongs was first pointed out in Africa by museum curator Bernard Fagg, who showed his surprise that they had not attracted attention before and explained that many were still in use.[1] As he put it:

'The contemporary uses of these rock gongs varies greatly though they are most frequently used in secret religious ceremonies, often in connexion with circumcision at initiation rites (Mbar, Bokkos, Daffo, Fobur). They are used at Nok in the ceremonies just prior to the harvest of the first acha [a cereal crop] when certain grass seeds are carried up to the cave by the unmarried girls and ground on the solid rock. Here and in several other places the gongs are closely associated with corn-grinding grooves worn down into the solid granite. At Kusarha Hill in Northern Cameroon they are said to be used for communicating with spirits whose reply is received in the form of echoes from the depths of the cave. At Nok and elsewhere in Jabaland they are said to have been used as warning signals of the approach of Fulani cavalry during the Holy Wars of the nineteenth century, and indeed the sound will carry up to two or three miles in favourable conditions. They are in addition used in many places also for merry-making, for they provide an excellent accompaniment for singing and dancing, resembling in sound and rhythmic use the conventional double hand-gongs of iron, which are so widespread in Equatorial Africa. They are frequently closely associated with rock slides, sometimes as long as 150 feet, on which the boys amuse themselves by sliding down on small rock sledges from the tops of bare granite hills' (Fagg 1956: 18).

Bernard Fagg discussed this evidence in several publications (Fagg 1957a; 1957b) but never made any attempt to quantify the sound produced by rock gongs. Farther to the south in Africa and many years later Sven Ouzman surveyed a sample of 762 San rock-engraving sites located in an area of over 800 000 km^2 and found that eighty-four sites (11% of sample) co-occurred with rock gongs, although only in six cases was the rock the same (Ouzman 2001). Following D.M.L. Fock (1972) and Catherine Fagg (1997: 35-40), he explained that:

'When struck, even with a bare hand, these gong rocks emit a harsh metallic sound rather like striking a blacksmith's anvil with a hammer. The sound is usually restricted in tone and timbre, though some gong rocks have a three-octave range.' (Ouzman 2001: 241)

In addition to Africa, ringing stones have been identified in most continents. Maja Hultman undertook a landscape survey of ringing stones in Sweden and even looked at how far the sound of a sonorous stone could travel, but as no method was explained in her publication, the assumption is that she just did this by listening without using any measuring instruments (Hultman 2010, 2014). Neither has any quantifying method been used to study the ringing stones connected to rock art in France (Hameau 2002: 80, 174), Portugal (Bastos 2010), India (Boivin 2004), the USA (Devereux 2008; Hedges 1993), or Sudan (Kleinitz 2004), although in the latter sound samples were taken, but no musicological study was ever carried out (Kleinitz 2008: 136). Only Hans-Joachim Ulbrich had attempted a quantitative investigation of a lithophone by measuring the acoustics of Peña de Luis Cabrera basalt-stone formation in Lanzarote (Canary Islands, Spain). He recorded the percussive sound produced a stone pebble by means of a Cardioid Microphone Uher Report Mod. 4400, and he analysed the frequency spectrum running the Blackman-Harris algorithm in Syntrillium's Cool Edit Pro software. With such methods, and a set of samples obtained from percussions of different intensities, the frequency-curves exhibit a median resonance frequency at 6550 Hz (Ulbrich 2003).

Bernard Fagg's studies had an impact beyond ringing stones and included other types of lithophones such as stalactites and stalagmites. He explained that on returning to England he decided to check whether the connection between rock art and rock gongs could be seen in France. He visited the Palaeolithic caves of Cougnac in the Dordogne where he noticed an 'infinite variety of "metallic" notes which could be produced by tapping the stalactites with a pebble, and also by the presence — not far from the paintings — of horizontal fragments of stalactite with new vertical growths forming on top of them' (Fagg 1957c: 30). He argued that 'this naturally suggests the possibility that they were broken in antiquity, perhaps by the men who made the paintings' and suggested that this could have also happened at Font-de-Gaume (Fagg 1957c: 30). A few years later his proposal was followed up by the French rock art specialist, Abbé André Glory at the caves of Cougnac, Pêche-Merle, and Fieux in France, as well as in Nerja, Spain (Glory 1964, 1965) and the caves of Escoural in Portugal (Glory *et al*. 1965). Neither Glory nor Lya Dams (Dams 1984, 1985), who revisited the caves, quantified the sounds, although Dams published some staves with the tones obtained when striking the lithophones (Dams 1985: 43).

In summary, despite the interest raised by lithophones, only one quantitative study has so far been carried out.

3 The archaeoacoustics of intentionally produced sound in rock art landscapes

The universal importance of acoustics and music in society (Trehub *et al*. 2015) has led scholars reasonably to assume that some communities in the past may have purposely prospected, surveyed, and located the places in the landscape — including the subsoil — with better acoustics. It also seems reasonable to consider that, even if not deliberately sought, the astonishing acoustic response of some places (caves, boulders, shelters, or rock surfaces) would have not gone unnoticed and would have been used for ritual and/or other purposes. Some communities then selected these acoustically optimum sites to be decorated.

3.1 Echoes

There is ethnographic information about the importance of echoes for a wide range of small-scale societies around the world (Waller 2002). The positive relationship between the

[1] Only a decade later, but in a different part of the country, no memory of their use remained (Jackson *et al*. 1965).

presence of rock art and echoes in several rock art sites and landscapes has been noted by many scholars in Spain (Díaz-Andreu and García Benito 2012, 2015; Díaz-Andreu *et al*. 2014), Finland (Lahelma 2010), Canada (Waller and Arsenault 2008) and the USA (Waller 2002; Waller *et al*. 1999).

Most authors note the number of echoes without using special devices for this, but there are some exceptions. The methodology followed by Steve Waller consisted in producing a single loud percussion noise via a spring-loaded device (duration < 0.1 sec, mean 53 dB, standard deviation 9 dB). Each experiment at each location was conducted in triplicate to assess the reproducibility of the impulse. The ambient sound before, during, and after each impulse was recorded on a portable cassette recorder using an omnidirectional microphone placed 1 m from the impulse generating device. These recordings were then digitized at a sampling rate of 22 kH and quantitatively analysed for sound intensity as a function of time and frequency, using computer software (Waller 2002).

A different sound source has been used at Lakes Nuuksionjärvi, Vitträsk and Juusjärvi in Helsinki (Finland). In an article published in 1995, Iégor Reznikoff explained his tests with voice used from D2 to D3, with a powerful open-air singing technique (100–110 dB at the source), in order to obtain a good echo effect at a given point, in front of a picture and facing the lake (Reznikoff 1995: 551). Two decades later a project undertaken by a Finnish team decided to use a 6 mm cal. starting pistol as an impulse sound, the sound of handclap, and a wooden percussion plate at the Värikallio rock art site at Somerjärvi Lake (Finland). Sound was recorded with a Zoom H4n portable recorder (48 kHz/16 bit), coupled with two Neumann KM 183 microphones that were used as an AB stereo pair pointed upwards and separated by 22 cm, that is, roughly equivalent to the typical distance from ear-to-ear on a human head. The AB stereo pair allowed the researchers to measure the angle of arrival of the reflected impulses based on the time difference of the respective impulse and then to the point of origin of echoes (Rainio *et al*. 2014: 144). It seems that the massive smooth rock surface with paintings is the most efficient sound reflector in the area, as it reproduces the impulse rather accurately in respect of the intensity, structure, duration, and spectrum of the sound, even from afar, on the other side of the lake. It also reinforces and prolongs the echo from the opposite shore by creating a repetitive flutter echo between parallel shorelines. It also provides a strong argument in support of the significance of echoes in rock paintings, as during the fieldwork they identified a probable depiction of a drummer that had been overlooked in the previous documentation work carried out at Värikallio (Rainio *et al*. 2014: 144).

3.2 Resonance

In the late 1980s the acoustic specialist Iegor Reznikoff and the archaeologist Michel Dauvois analysed the intensity and duration of resonance in painted caves in France. Although they used non-technological devices to produce impulse sound, such as the voice in a continuous register ranging from C1 to G3 complemented by the high harmonic emission and whistles up to G5 (Reznikoff and Dauvois 1988: 240), they were able to superimpose the resonance map of the cave on the motifs, arguing that there was a coincidence between resonant places and specific iconographies (Reznikoff and Dauvois 1988).

More recently new research has been undertaken in the El Castillo cave system in northern Spain, where Jose Miguel Gaona Cartolano and his team measured the variation in sound pressure level (SPL) using a set of 31 audio tones of different frequencies from 80 Hz to 1kHz, pink noise, and sine sweep driven by an omnidirectional speaker (Gaona *et al*. 2014), recorded with a condenser microphone and converted to digital files with a sampling rate of 48 kHz/16 bit. A distinct increase in sound level was observed as the frequency of the emitted tone shifted towards the 100 Hz range, reaching a maximum peak at 108 and 110 Hz (-1 dB). This simple finding is remarkably consistent with other archaeoacoustics investigations of megalithic structures (Devereux *et al*. 2007; Jahn *et al*. 1995; Manaud and Barrandon, forthcoming 2015), which have shown significant sonic resonance features within this precise range of frequencies (Gaona *et al*. 2014).

3.3 Reverberation

Reverberation has been measured in archaeoacoustics studies undertaken in Spain. Díaz-Andreu and García Benito explored the reverberation of post-Palaeolithic rock art sites using as sound sources repeated clapping (to create percussive sound), wind devices (two whistles with frequencies of C7/C#7 and G7/G#7 played together; the G7/G#7 whistle played at intervals), and vocal music (male and female voices together using the 'a' sound as in mat; a solo male voice and a solo female voice). Digital recordings were made and comments on the results were noted *in situ* in a purpose-built acoustics recording form. Reverberation was measured from 0 to 2 — no reverberation (0), short and soft reverberation of one second duration or less (1), and longer reverberation (2). Tests included locations where rock art had been created and other places in the landscape with an apparently similar geological nature (i.e. shelters) where, despite their relatively large number, no rock art had been found. The results of the recordings were analysed using Sonic Visualiser software and included in a database that served as a basis for comparison between sites with more or fewer motifs and areas with and without rock art. In this way four areas were tested, three with Levantine rock art (Díaz-Andreu and García Benito 2012, 2015) and one with schematic art (Díaz-Andreu *et al*. 2014), all with positive results, especially those with Levantine art.

Rupert Till and his team have very recently begun to investigate the acoustics of a series of caves where art was produced during the Upper Palaeolithic. Their studies in the Tito Bustillo cave in Asturias (Spain) aimed to assess, analyse, and interpret the affordances these acoustics offered to human sound production and music-making in the cave (Till *et al*. 2013; Till 2014). They captured the impulse responses through the use of a sine sweep signal played through an omnidirectional loudspeaker. This signal sweeps through all the frequencies within the range of human hearing, from 16 Hz up to 20000 Hz, systematically stimulating the response of the space to each frequency. They used both a calibrated measurement microphone attached to a laptop computer to record the acoustics and a Soundfield microphone, capable of capturing sound arriving from all directions, which provides a useful insight into the 3D direction of arrival of reflections. From this impulse response numerous acoustical parameters were calculated, including metrics for reverberation (T20, T30, EDT) and speech intelligibility (STI), as well as those often used to characterize the acoustics of enclosed spaces and concert halls, such as Definition or

Deutlichkeit (D50), Clarity (C80), Lateral energy (LEF), and Envelopment (LG80). They argued that there are some significant matches in the Tito Bustillo cave between large painted motifs and distinct and delayed reverberation effects, which sound like an echo. This provides support for the idea that rock art producers would have been aware if the space was acoustically 'live' (with reverberation) or 'dead' (without reverberation), and that the acoustics of a place could well have had some influence on whether it was selected as the position for a painting or engraving.

4 Further developments

Archaeoacoustics is now facing new challenges in establishing itself as a proper traceable tool, which can provide the necessary scientific evidence to support archaeologists and historic theories.

So far no rock art studies have explored the methods indicated by acoustics experts for measuring sounds in sonotopes. These consist of measuring the long-term average spectra (LTAS) of sonotopes (Ge *et al*. 2009) typically expressed as Leq (the continuous sound that contains the same sound energy as a time-varying sound over a given time period, expressed as a single value in dB) or LAeq (the same as Leq but referring to the differential sensitivities of the human auditory system to different frequency ranges). In addition to Leq and LAeq, another type of measuring method includes the modulation transfer function, a measure of how well the temporal envelope of a sound signal is preserved in a given acoustical environment (Houtgast *et al*. 1980). A final method of measuring sonotopes proposed by the ecologists Mark Naguib and R. Haven Wiley is attenuation, which calculates the sound pressure level in a particular environment at a distance from a sound source and corrected for air absorption (Naguib and Wiley 2001).

Further developments in the field of lithophones, ringing rock, and rock gongs are needed because, as explained, to date only one quantitative analysis has been made of them. Many different studies can be proposed. Regarding cave lithophones we suggest that an analysis of the resonance frequency obtained when playing both the painted and unpainted areas of the lithophone with different percussion tools should be done. The results of this study should be then compared with the frequencies obtained in other undecorated stalactites and stalagmites. Techniques used for the study of megalithic structures could be applied to lithopones in caves (Devereux and Jahn 1996: 665: Jahn *et al*. 1995; Watson 2006; Watson and Keating 1999). Regarding ringing rocks, in addition to similar comparisons of resonance frequency between decorated and undecorated rocks, the acoustic coherence could also be tested.

Concerning the archaeoacoustics of intentionally produced sound in rock art landscapes, we would like to suggest three new areas of research development: (i) the investigation of the 3D spatial properties of sound to gain a better understanding of the acoustic prospecting of past rock art producers; (ii) the simulation of past soundscapes through the use of GIS tools for noise evaluation combined with palaeoenvironmental data; and (iii) the prediction of the acoustic conditions of rock art sites using auralization virtually to recreate the behaviour of any type of sound.

The first future possible avenue of research, the 3D sound characterization, would allow to ascertain scientifically the direction from which the sound, including that of echoes, arrives. This has been put in practice in a range of other archaeological contexts: these are the Chavín De Huántar Archaeological Acoustic Project (Abel *et al*. 2009), the Stonehenge acoustical investigation (Fazenda and Drumm 2013); the acoustical study of a sample of historical monuments (including the megalithic structure of Maes Howe, Orkney) (Murphy 2006); and, finally, the project related to historical opera houses (Farina and Tronchin 2011). All four of these projects have been addressed at developing new microphone arrays combining omnidirectional, binaural, and hybrid Ambisonic microphones. It is important to add that Tronchin and Farina have developed a MatLab program that allows a very simple and cost-effective post-processing of the 3D spatial analysis of sound. This works in a very similar way to the very high-priced acoustic camera (Heilmann *et al*. 2014), creating both a false-colour map of the arrival of sound reflections (Fig. 1) and an animated colour video rendering of the sound map, overplotted on the 360° x 180° panoramic image (Farina and Tronchin 2011).

The second method is the modelling noise propagation tools developed for GIS software. This can be a useful procedure to study past soundscapes or to investigate whether or not rock art sites are acoustically connected in a sort of signalling/communication network. The GIS modelling of noise propagation was first devised for studying noise pollution in human-dominated ecosystems, including noise from urban and industrial areas or aircraft and highway traffic. It incorporates important factors, however, that are likely to affect the sound propagation in natural ecosystems, such as changes in topography, weather conditions, vegetation cover, etc. which allow for alternate frequency weighting better to represent the way a different noise can be heard. Among the various available tools we should mention SPreAD-GIS, a very flexible, open-source software for incorporating field measurements and model noise propagation for any type of source and environment (Fig. 2) (Reed *et al*. 2012). This GIS tool has been applied to the analysis of sound propagation in Levantine, macro-schematic, and schematic rock art sites in the Alicante area (Valencia, Spain) (Díaz-Andreu *et al*. forthcoming).

The third and final research carried out for a different type of project, but that could be applied to analysing the archaeoacoustics of rock art with intentionally produced sound, relates to the exploration of the possibilities offered by the 'auralization' of high-quality Impulse Response (IR) measurements by the convolution-based reverberation technique developed and refined in Farina's recent acoustic measurement work (Farina and Ayalon 2003; Farina and Tronchin 2004). From such an accurate IR dataset there is no longer any need to test different types of sound impulse at the rock art sites, as it is possible to recreate virtually (or 'auralize') the behaviour of any type of frequency or to extract the sound of virtually all acoustical parameters.

5 Conclusion

The archaeoacoustics of rock art is a multidisciplinary field of research, as there is no single discipline that can be drawn on to understand the acoustic and auditory aspects of past human behaviour. Archaeologists are usually well prepared to deal

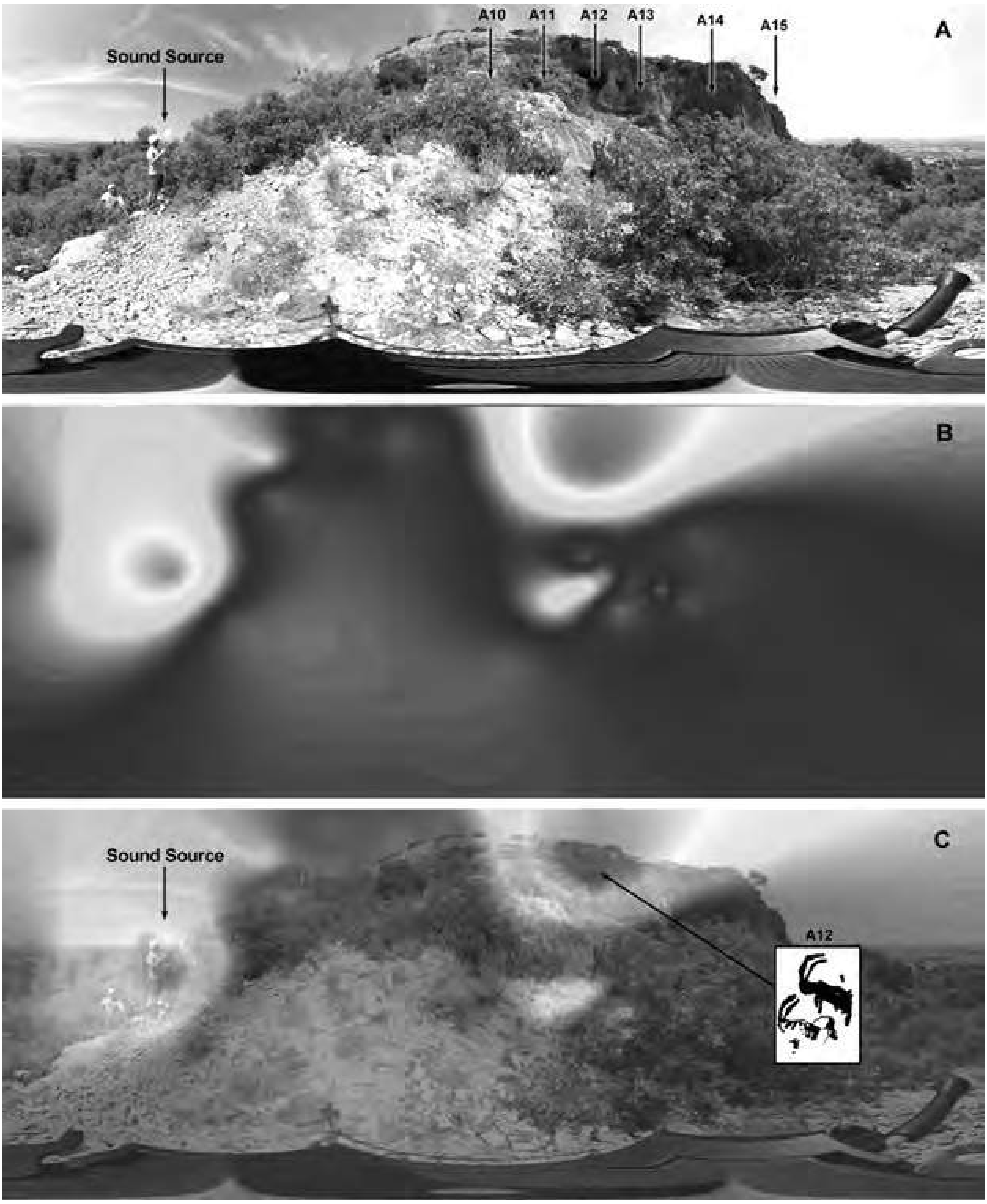

Fig. 1. An example of a false colour map of the IR (Impulse Response) analysis carried out in July 2015 by M. Díaz-Andreu, T. Mattioli, and P. Hameau in the rock art site of Baume Brune (Joucas, Provence-Alpes-Côte d'Azur, France) using an air-balloon as impulse sound. The acoustic recordings were made by Ambisonic microphone array and data were processed by IR Spatial Analysis MathLab software: (a) 360° picture of a section of the Baume Brune cliff; numbers refer to shelters; only shelter no. 12 has rock art; (b) false colour map of the impulse sound and acoustic reflections; (c) overlapping of images (a) and (b) onto one another, the main motifs painted in shelter no. 12 have been added in the bottom right section of the figure.

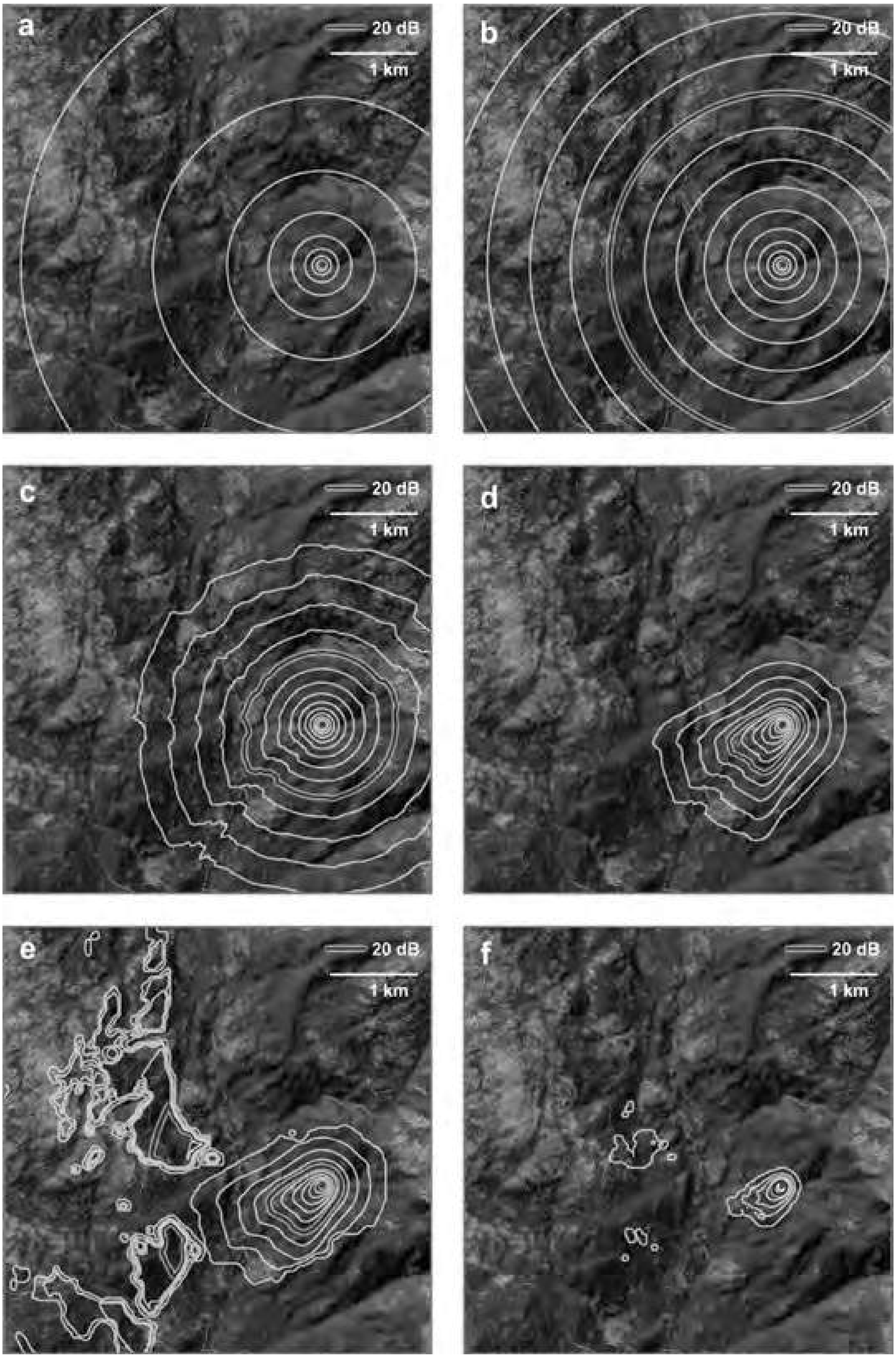

Fig. 2. An example of model calculation of sound propagation using the Spread-GIS tool: (a) spherical spreading loss; (b) atmospheric absorption loss; (c) foliage and ground cover loss; (d) downwind and upwind loss; (e) terrain effects; and (f) summary results, including predicted sound propagation patterns and excess sound levels. In (f), areas where introduced noise is likely to be audible can be identified (from Reed *et al.* 2012).

with the qualitative aspects of research, being well trained to read literature produced by a diverse set of other disciplines such as anthropology and psychology. The technicalities of the quantitative aspects of measuring acoustics are usually further apart from their specialization, however, as the techniques come from the disciplines of music, physics, and engineering. That is why interdisciplinary teams are desirable for rock art projects willing to deal with the quantitative aspect of acoustics.

In this article we have surveyed the different quantitative analyses made so far in the study of rock art acoustics. We have divided the research into three main areas according to the sound source, natural or human, and the sound producer, a geological formation or sound produced by instruments or voices. The resulting three clusters of studies are the rock art landscapes with naturally occurring sounds, lithophones, and the archaeoacoustics of intentionally produced sound in rock art landscapes. In them different acoustic effects have been the subject of measurements: echoes, resonance, reverberation, variation in sound pressure level (SPL), the direction of arrival of reflections, and the long-term average spectrum (LTAS). As a result of our survey we can say that the study of lithophones is in urgent need of quantitative analysis. A similar situation has been found in the studies of rock art landscapes with naturally occurring sounds, with the exception of an analysis of the sound pressure level. The state of the art in the last group of studies — the archaeoacoustics of intentionally produced sound in rock art landscapes — is somewhat healthier, as there are quantitative analyses of echoes, resonance, and reverberation. As we have argued in the 'further developments' section, however, much more could be done. We have proposed several avenues for future research.

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