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GIS, sight and sound. Exploring the rock art landscapes of the Santa Teresa Canyon (Baja California Sur, Mexico) as a case study

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A R T I C L E I N F O

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A B S T R A C T

This article explores the senses of sight and hearing in Santa Teresa Canyon, Sierra de San Francisco (Baja California, Mexico), where there is a large number of rock art sites of the Great Mural style. This rock art tradition is characterized by the presence of sizeable prehistoric murals depicting large figures. Departing from previous research in which the acoustical properties of the rock art landscape of the canyon were appraised, in this study we look at this in conjunction with visibility. Through the use of a series of tools and procedures implemented through GIS, viewsheds and soundsheds are modelled and assessed in relation to the surrounding landscape. The comparative analysis of emblematic, principal and secondary sites allows us to propose that these categories may have played a complementary role in the construction of a socialized landscape by the native communities that inhabited the Baja California peninsula.

1. Introduction

All our senses are part of our cultural understanding of the world (Skeates, 2010; Thomas, 2008). However, archaeology has focused mainly on sight, a bias largely due to the importance given in the Western world to that sense. Importantly, however, sight is usually combined with, and even at times substituted by, other senses, in particular hearing, which is the best counterpart of vision for spatial awareness (Letowski and Letowski, 2012) and, particularly, for undertaking localisation tasks (Kells, 2001; Blesser and Salter, 2007; Neuhoff, 2011). Hearing even has advantages over sight, as it allows events of moving objects that are not within sight to be anticipated and greatly enhances experiences and remembering places (Pocock, 1989). The lack of importance given to the sense hearing in archaeology is partly related to today's audible experience characterized by a high degree of background noise. This constant acoustic interference prevents use of the sense of hearing to its full potential in the modern world. In the 1970s Murray Schafer was already arguing that pre-industrial

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societies lived – and still do in some places – in what he called 'hi-fi soundscapes', in which discrete sounds can be heard clearly thanks to the low ambient noise level (Schafer, 1977 (1994)).

Both sight and hearing, as well as our other senses, are important in the phenomenological perception of the world. They shape a corporeal connection to our surroundings. The manner in which we value what we see is, however, cultural. Some communities will appreciate a place for what it looks like and what can be seen from it, but others may welcome the opposite. In a similar vein, the manner in which sound is dispersed from a place may be considered positively or, on the contrary, it may be expected that nothing is heard from outside, or that no sounds from the outside disturb the place. In any case, the way we feel a place is often the result of the integration of multiple sensory inputs that create emotional responses to it. Positive sensory experiences can enhance our well-being and create a sense of belonging. Through the senses identity is created, reinforced and challenged. They are also a useful source of practical information on how to act to control the territory in situations of danger and for economic reasons (Stocker, 2013).

Interest in the senses of sight and hearing emerged in relation to rock art landscapes in the 1990s, when the first commentaries and analyzes were published. These dealt with sight (Bradley, 1991; Bradley et al., 1994), hearing (Steinbring, 1992; Reznikoff, 1995) or both (Hedges, 1993). However, whereas visibility was easier to investigate, the analysis of sound presented more challenges. To begin with the first studies of sound were truly inspiring but technically poor. One of their major deficiencies was that they were not repeatable, a basic requirement of a sound scientific method. This deficiency has been overcome thanks to new analytical procedures that, over time, have become more sophisticated with the adoption of methodologies developed for other sciences (Díaz-Andreu and Mattioli, 2016; Díaz-Andreu et al., 2023). As pointed out in the latter article, two major types of method have been followed for the study of rock art soundscapes, one based on the quantification of acoustic parameters and the other on Geographic Information Systems (GIS). Both approaches have been used by the authors of this article in their previous work, although only the former in relation to the rock art landscapes of Baja California (Díaz-Andreu et al., 2021).

In 2018, a team from the University of Barcelona, the INAH and the National Autonomous University of Mexico (UNAM) analyzed the acoustical properties of Santa Teresa Canyon, in the Arroyo de San Pablo, located in a central area of the Sierra de San Francisco mountains. On the basis of the acoustic tests taken in situ in Santa Teresa Canyon, it was argued that the area with the most favourable acoustic conditions was Cueva Pintada, located in the lower part of the canyon, close to its bed. The analysis also showed that the rock art shelters themselves had not been chosen for their special acoustic conditions, given that the acoustic tests carried out in both decorated and undecorated rock shelters provided similar values (Díaz-Andreu et al., 2021). The authors argued that this result was in keeping with the information from the ethnohistoric sources that mention collective dances being performed in the ravines by several ethnic groups from the peninsula, including the Cochimí communities of the study area (Clavijero, 1782–1982–: 65; Sales, 1794–2003–: 66–72).

Would the use of GIS enhance the results of the acoustic tests in Santa Teresa Canyon? Space is a crucial factor in understanding ancient sites and human interaction with the environment, so it is unsurprising that it holds such significance in our field. The analysis at this scale of observation has advanced considerably in recent decades, particularly with the implementation of GIS. The primary advantage of using GIS in archaeology is its capacity to analyze vast amounts of spatial data, which can be integrated with other types of information. Additionally, when appropriate procedures are followed, GIS can also be used to create or convert mathematical models (Gillings et al., 2020) based on historical or archaeological data. These models represent various variables related to geography, such as topography, as well as human perceptions of that geography, including visibility and sound propagation from a specific location or as perceived within its immediate surroundings (Gillings, 2012).

The use of GIS in the study of rock art has a notable tradition in Mexican archaeology and, more broadly, in Mesoamerican archaeology. For example, in the central region of Chiapas (Mexico), Acosta Ochoa et al. (2011) employed GIS technology as a planning tool for the survey and identification of rock art sites. Similarly, in El Salvador, Costa (2017) used GIS to map the geographical distribution of rock art traditions. These studies highlight the potential of GIS as a tool for managing and presenting archaeological data. However, GIS also offers analytical capabilities that allow for a deeper understanding of the relationship between rock art sites and their surrounding geographical and social landscapes. A good example of this analytical use can be found in the work of Martínez Moreno and Viramontes Anzures, 2015, who analyzed rock art sites in the northeastern area of the state of Guanajuato (Mexico). Their use of GIS focused not only on the spatial distribution of the sites but also on approximating their visual fields, analyzing their relationship with communication paths, and examining the economic potential of their immediate surroundings. Another example is Gutiérrez Martínez's analysis of the Gran Mural tradition. Using GIS, the author explored the relationship between primary and secondary sites and assessed their connection to various natural resource catchments, such as the volcanic zone of Tres Vírgenes (Gutiérrez Martínez, 2013: 421).

The validity of GIS for assessing sensory variables has also been demonstrated in several studies, including those by Primeau and Witt (2018), Witt and Primeau (2019), and Van Dyke et al. (2024). These works examine the propagation of sound from diverse settlements associated with Chacoan great-house communities in New Mexico (USA) and highlight its significance as a tool for fostering social cohesion. Several authors of this article have also tested the effectiveness of this methodology in the analysis of rock art shelters in the Iberian Peninsula (Díaz-Andreu et al., 2017; García Atiénzar et al., 2022; Mattioli et al., 2019).

Following the approach we developed in a different rock art area (García Atiénzar et al., 2022), the main objective of this article is to analyze, from a spatial and sensorial perspective, the rock art of the Santa Teresa Canyon in the Sierra de San Francisco, where a large number of sites painted in the Great Mural tradition are found. Using GIS as a method, we expanded our previous study (Díaz-Andreu et al., 2021) through the modelling and analysis of visibility and audibility associated with the rock art sites. The aim is to attempt an approach to the way in which the communities that painted the Great Mural rock art sensed the landscape. In this article three objectives are followed: first, to analyze the senses of sight and hearing through an analysis of the viewsheds and soundsheds in our study area; second, to explore whether there are distinctions between sites taking into account the great disparities between them as regards the number of motifs, among other elements; and finally, to compare the results of the two previous analyses in order to assess the different ways in which the senses were being used.

2. The great mural rock art tradition

The Great Mural rock art tradition is located in the central region of the Baja California Peninsula in northwestern Mexico. From north to south, it is found in rock art shelters (known locally as *cuevas* or caves) in the San Borja, San Juan, San Francisco, and Guadalupe *sierras* (mountain ranges) (Gutiérrez Martínez, 2017) (Fig. 1). This spectacular rock art style includes paintings and some carvings.

Some of the decorated panels are more than 10 m high. The painted motifs sometimes exceed 2 m in size, which implies that ladders[1] or scaffolding would have been used for their execution (Hambleton, 1979: 28–30; Viñas, 2013: 22). The paintings were made with red, black, white and yellow pigments, which were possibly obtained from the Tres

[1] There is a ladder found in "a cave site in the Sierra de Guadalupe" (Gutiérrez Martínez, 2013, Fig. 9.1).

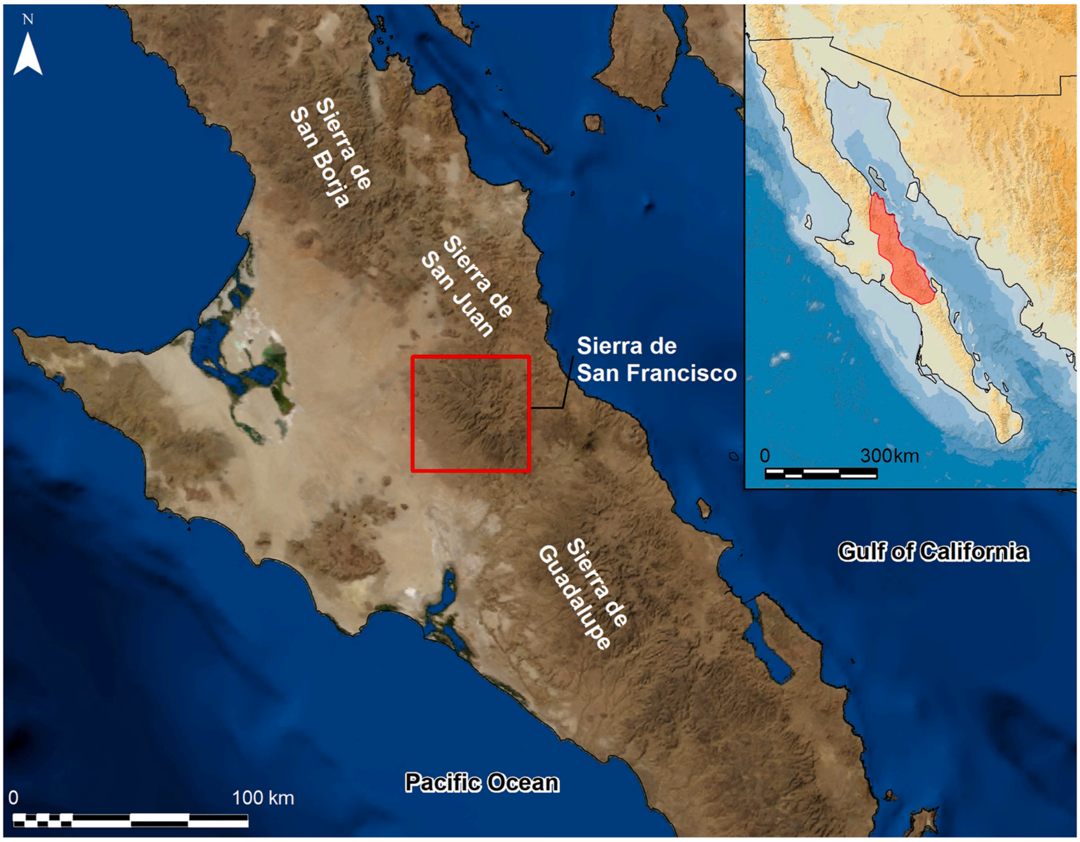

Fig. 1. Map of Baja California with the location of Santa Teresa Canyon in the Sierra de San Francisco mountains. In red, the area of distribution of the Great Mural rock art tradition, according to Ritter (1991). Prepared by the authors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Vírgenes volcanic area, located in the southwestern area of the Sierra de San Francisco (Gutiérrez Martínez, 2019a). These pigments were used to depict anthropomorphic and zoomorphic figures such as deer, bighorn sheep, pronghorn, birds, fish and whales, as well as various types of implements, including arrows, spears and projectile points. Additionally, geometric elements such as circles, spirals and lines were also represented. Within this thematic repertoire, the anthropomorphic figures, including males, females and asexual individuals, are typically depicted with their arms raised in a position of prayer, reverence or dance. Some of these figures have body painting and adornment and there is also a wide diversity of headdresses (Gutiérrez Martínez, 2013: 387–414; Viñas, 2013, Fig.41; Rubio, 2014: 124–125) (Fig. 2).

The paintings were first mentioned by the missionary Miguel del Barco, who lived in the area in the 18th century and gathered information from two other missionaries living in San Ignacio and Santa Rosalía (del Barco, 1988 (1773-1780)). The earliest synthesis of what was known about them was published by Léon Diguet, a French chemist working for a mine in Santa Rosalía located to the south of the Sierra de San Francisco (Diguet, 1895). After him, little was published about the art except for a few works in the mid-twentieth century (Dahlgren and Romero, 1951; Dahlgren, 1954; Meighan, 1966). The number of publications began to grow in the 1970s, first authored by North American archaeologists and then by Spaniards and especially Mexicans. This led to a significant increase in the bibliography and interest that ultimately led to their inclusion on the UNESCO World Heritage List in 1993. Several recent graduate and MA degree (e.g. Mendoza Straffon, 2004; González Vázquez, 2022) and PhD (Gutiérrez Martínez, 2013; Viñas, 2013; Rubio, 2014) theses have now significantly expanded our knowledge of the Great Mural rock art.

One of the major advances of the research undertaken in the last few years has been the establishment of a chronological framework for the archaeological and artistic context of this rock art tradition. Radiocarbon dating indicates that the first artistic impulse may have occurred after 1300 cal BC and reached its peak sometime after 500 AD (Gutiérrez Martínez and Hyland, 2002: 344). The researchers conclude that the Great Mural tradition can be linked to the cultures that still inhabited the area at the time of the missionary contacts.

Recent research has not only recorded the sites, sometimes in great detail (see especially Viñas, 2013; Rubio, 2014), but has also focused on a variety of aspects including gender (Smith, 1986; Ritter, 1994; Gutiérrez Martínez, 2007; González Vázquez, 2022) and the relationship with nearby sites, such as the Tres Vírgenes volcanoes resource catchment area (Gutiérrez Martínez, 2013, 2019b). Moreover, subjects such as astronomy (Smith, 1985; Moore, 1986; Viñas et al., 2018) and heritage issues (Gutiérrez Martínez et al., 1996; Gutiérrez Martínez and Hyland, 2002; Conway et al., 2010; Conway, 2014) have also been explored. Regarding landscape, attention has focused on the relationship between rock art sites and the presence of wells and springs, the difficulty of walking through the terrain and the location of some of the most emblematic cave sites (Crosby, 1997; Viñas, 2013).

These works had led to different interpretations of the murals' use and themes. Meighan (1969), one of the first to question their possible meaning, pointed out that the paintings might be related to magic ritual associated with hunting (Meighan, 1969, 66). Crosby (1997) recognized some murals related to war or conflict but also suggested that all shelters were used in collective religious ceremonies. Gutiérrez and Hyland concluded that the murals were associated to ancestors' veneration rituals, clan identity, and also the possible role of shamans. They argued that the clan organization significantly influenced the social geography of the central sierras. Subsequently, Gutiérrez Martínez (2019b), in her PhD thesis, continued exploring these topics, focusing on lineage territory organization, suggesting that anthropomorphic figures with

Fig. 2. Cave paintings of the Great Mural tradition. a) Boca de San Julio; b) Cueva de la Música or Los Músicos; c) Cueva de las Flechas; d) Cueva Pintada (Photographs: Natalia González and Margarita Díaz-Andreu).

hairdressers represented specific lineages and that the landscape was organized according to the social groups and the position of the rock art shelters. Moreover, Viñas (2013) in his research on Cueva Pintada, concluded that the characters depicted could personify deities, mythical beings or ancestors, viewing the site as a space for communication with entities, social cohesion and the transmission of values. In a different direction, Rubio (2014), who made a detailed study about the site El Ratón, considered that this mural could have also been related to astronomical observations and rituals related to the summer solstice.

María de la Luz Gutiérrez Martínez's Ph.D. thesis represented a great step forward in the study of the Great Mural tradition. Her thesis revolved around four sites, Cueva Pintada and Cuesta Palmarito in the Sierra de San Francisco and Cueva San Borjitas and Monos de San Juan in the Sierra Guadalupe. She described them as exceptional because of the dimensions of the shelters, their visibility in the landscape and the type of motifs painted in them. She argued that the four sites were characterized by similar features: each represented a different substyle of the Great Mural tradition; they contained a large number of figures; there were many superimpositions in the motifs; and some may have been special as they were repainted several times. Moreover, the art at these sites depicted a large number of different types of headdress and combinations of colored patterns on human motifs (Gutiérrez Martínez, 2013: 10). These emblematic sites were at the center of exclusive territories and would have acted as aggregation sites (Gutiérrez Martínez, 2013: 481–482). Thus, she argued, multiple nuclear families consisting of five to ten individuals would have gathered in them, forming groups of between 50 and 200 people (Aschmann, 1959; Gutiérrez Martínez, 2013, p. 421). Gutiérrez Martínez also assessed the relationship between rock art sites and various natural resource catchment areas, such as the Tres Vírgenes volcanic zone (Gutiérrez Martínez, 2013). To achieve this, she employed GIS and also used the same method to explore the relationship between emblematic sites and the remaining of sites, which she referred to as secondary.

3. Study area, selection of sites and site typology

This article focuses on a selection of thirteen sites with Great Mural style paintings located in Santa Teresa Canyon. We have only selected those whose location we are certain of and for which we have enough information about their murals. We exclude sites with petroglyphs – such as La Cuevona and La Piedra de Chuy – because their characteristics are clearly different to those of paintings, a factor that merits further analysis elsewhere (see Fig. 3). In addition to the sites analyzed in 2021, there are new ones located outside our previous study area. In 2021 we explored 8 km of Santa Teresa Canyon, a sector of the gorge that did not encompass the sites in La Soledad Ravine and the Santa Teresa area. Two new sites are now considered from both areas: La Soledad and El Torote. Regarding the Santa Teresa area, we are now adding the sites of Banco de Santa Teresa and La Palma de Santa Teresa to our study [2]

In contrast to the sites analyzed in 2021, in this article we decided to subdivide sites on the basis of two different types of criteria. The first can be defined as **hierarchy**. It distinguished between emblematic, principal and secondary sites. Following Gutiérrez Martínez (2019b), we consider Cueva Pintada as an emblematic site, given its central location in the

[2] As noted in the 2021 article, there is considerable confusion about the site names, given that some sites have been given alternative names depending on the author. For example, Santa Teresa I instead of La Palma de Santa Teresa, La Soledad is also known as Pájaro Negro and Las Águilas, whereas Banco de Santa Teresa is also known as Borrego I and la Cueva de la Música as Los Músicos or even Boca de San Julio II. Finally, regarding the two sites at the Cacarizo area: the site El Cacarizo is also found in the literature with the names of Cacarizo I, Cerro del Cacarizo and Cueva de la Cañada del Cacarizo. Moreover, The site of Cacarizo II is also known as Morro del Cacarizo and Cueva de los Monos Blancos. In this article we have decided to use the official names of the sites in the INAH registry.

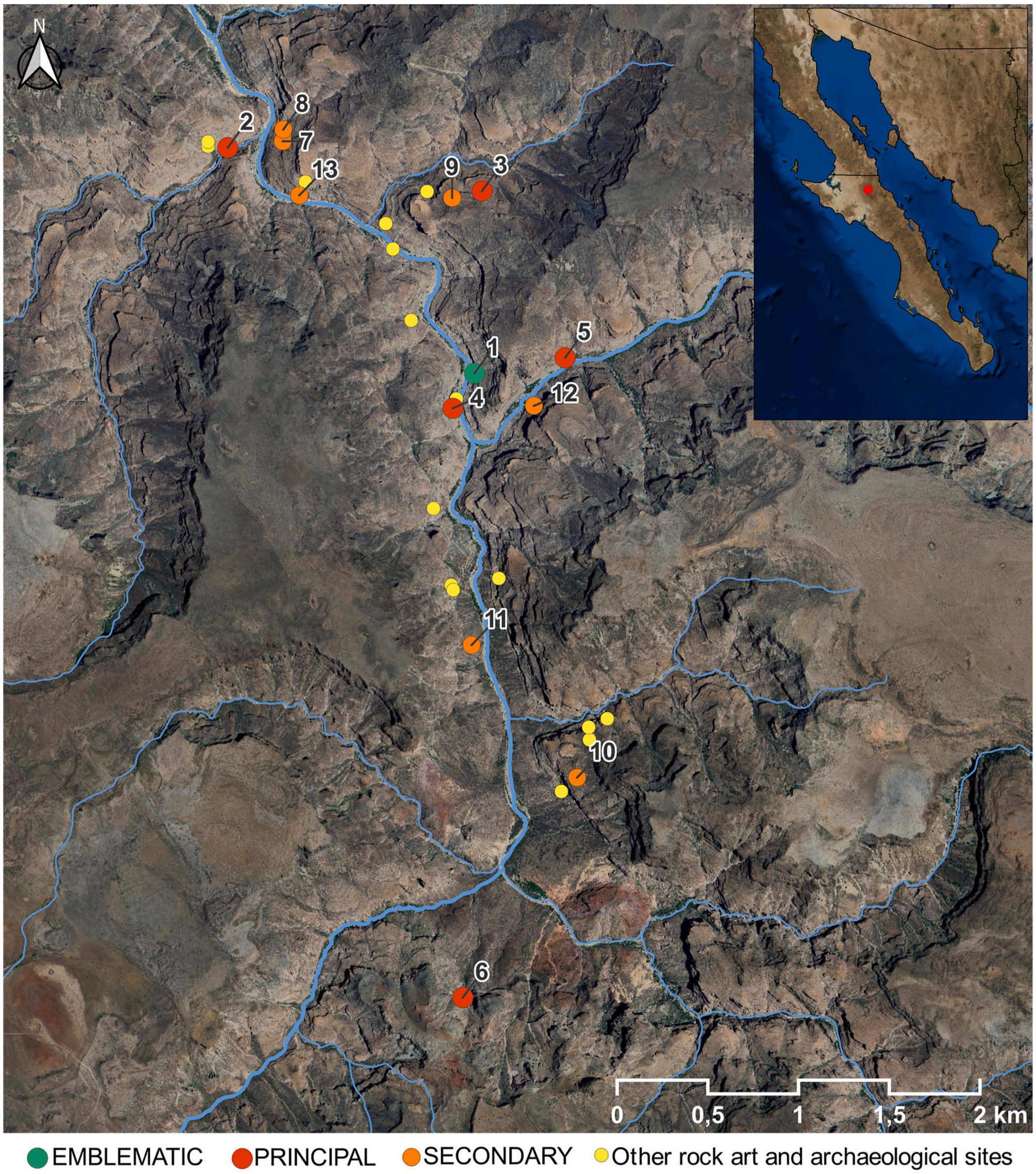

Fig. 3. Location of sites with rock art in the Santa Teresa area. Emblematic sites: 1: Cueva Pintada; Principal sites: 2: Boca de San Julio; 3: El Cacarizo; 4: Cueva de las Flechas; 5: La Soledad; 6: La Palma de Santa Teresa. Secondary sites: 7: Cueva de la Música; 8: La Venada; 9: Cacarizo II; 10: Banco de Santa Teresa; 11: Cueva de la Rata; 12: El Torote; 13: Zopilote y Pez. Yellow dots: other rock art and archaeological sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

canyon and, in particular, its large number of motifs (1121 according to Viñas' study), the most numerous in the area (Viñas, 2013). It may be worth mentioning that the number of motifs at Cueva Pintada is only comparable to the other emblematic sites she considered – Cuesta Palmarito, Cueva San Borjitas and Monos de San Juan – all located beyond our study area. Gutiérrez Martínez also considered other elements to distinguish these sites, including a wide variety of anthropomorphs in terms of their chromatic composition and the presence of different types of headdress (Gutiérrez Martínez, 2013: 14, 26–27). In contrast to Gutiérrez Martínez (2019b), however, we do not consider the remaining sites as a single type and we divide them into principal and secondary sites. Principal sites are distinguished firstly by the number of motifs in them, more than 20 and less than 200; secondly, by the superimpositions they present, suggesting repeated and/or prolonged use over time; and finally, they have all three of the most common motif types of this tradition – zoomorphic, anthropomorphic and geometric. Secondary sites are those that do not fulfil one or more of the aforementioned conditions. In our analyses we will compare emblematic and principal sites with secondary sites.

In addition to hierarchy, a second type of site subdivision criterion we have taken into account is their location in the canyon – i.e. whether the site is situated in the lower, middle or upper sector of the canyon. To distinguish between these three location types we have followed the topographic model shown by our initial GIS study of the area. This revealed a sharp contrast between the upper and lower parts of the valley, with a significant difference between the plateaus (Mesa Corra, Mesa San Jorge, Mesa El Datil, etc.) and both Santa Teresa Canyon and its tributary ravines. The plateaus are flat with gradients in the upper area of always less than 5%, while the walls of the canyon and its tributary ravines have gradients of more than 60%. Additionally, there are notable differences in absolute heights, with the plateau at around 1000 m and the canyon at altitudes below 400 m above sea level. These differences are a result of the challenging terrain and difficult transit conditions observed during the fieldwork (Fig. 4). The categorisation of

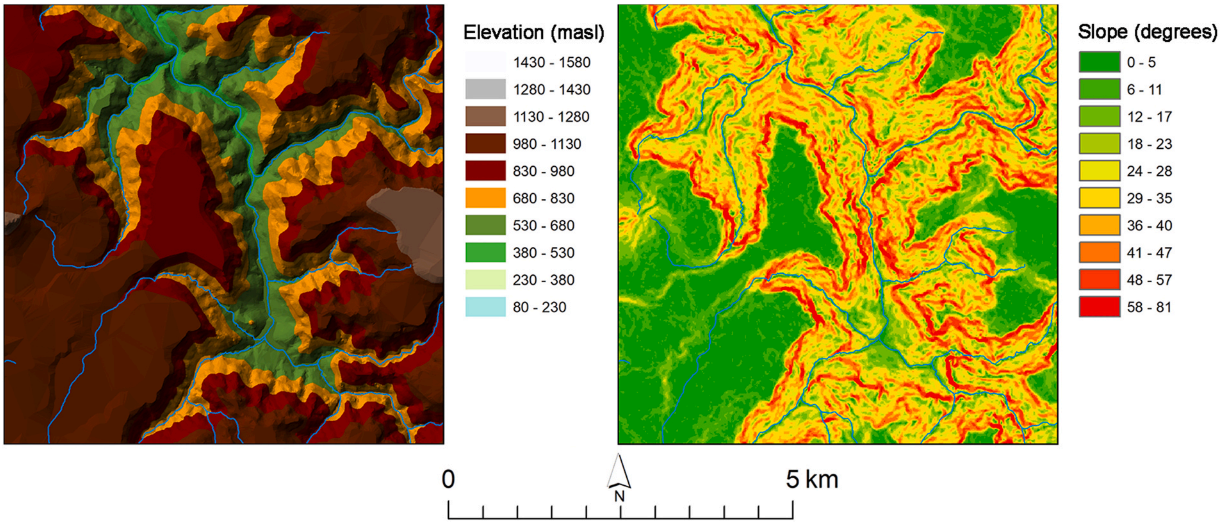

Fig. 4. Digital elevation and slope models of the study area.

all the sites in our study area, according to their importance and location, is summarized in Table 1.

4. Viewshed

As explained in the introduction, interest in the connection between visibility and rock art emerged mainly in the 1980s. Richard Bradley, for example, analyzed the relationship between natural routes and locations with high visibility overlooking larger areas and rock art sites in England and Scotland (Bradley, 1991) and Galicia, Spain (Bradley et al., 1994). His work and that of other researchers (Wienhold and Robinson, 2019) was the basis for significant advances in the last decades of the 20th century thanks to the use of GIS, a tool that allowed the systematic assessment of rock art and its relationship with its natural and archaeological environment. The earliest studies were undertaken in Scotland and the United States (Gaffney et al., 1995). In the latter country, Hartley and Vawser (1998) analyzed the relationship between the location of rock art and visibility on the Colorado plains using GIS. In our study area, the proposals of Gutiérrez Martínez (2019b) should be highlighted. She used GIS to analyze the visual relationship between rock art sites and the catchment areas of different natural resources, such as those located in the Tres Vírgenes volcanic zone where obsidian and pigments were obtained, and that between emblematic and secondary sites (Gutiérrez Martínez, 2013). In this article we will use GIS in a different way to examine both viewshed and soundshed from the rock art shelters following the methodology developed in García Atiénzar et al. (2022).

4.1. Methodology

The study of visibility undertaken in this article assesses viewsheds by paying attention to visibility ranges, viewshed amplitude and site prominence. In each of these analyses the principal and secondary site results will be compared. In addition, the location in the canyon – i.e. whether the site is situated in the lower, middle or upper sector – is examined to ascertain whether it bears any relationship to the three elements mentioned above.

For the viewshed range, the categories defined by Fábrega-Álvarez and Parcero-Oubiña (2019) will be followed. These authors went beyond Higuchi's (1983) and Ogburn's (2006) suggestions regarding the detected size and the effect of distance from an observation point on visibility. They also developed an Individual Distance Viewshed (IDV) tool for the ESRI ArcMap to apply their proposals (Table 2). This toolbox calculates the fuzzy viewshed (Fisher, 1994; Ogburn, 2006), allowing the change of parameters such as the observable element height, set at 1.6 m (the average height of a human being) and the height for each observation point (Fábrega-Álvarez and Parcero-Oubiña, 2019). For the second parameter, we took into consideration the height of the murals, since the Great Mural style is known for sometimes having elevated, high murals that influence the visibility of the paintings. Finally, the IDV tool takes into account the vegetation of the surrounding environment, as it is considered that a landscape with certain kinds of vegetation could be a limiting factor on long-distance visibility. However, in our specific case, the vegetation largely consists of a xerophytic shrubland, with plants like agaves, barrel and cardon cacti. Thus we configure the IDV tool using the 'bare earth landscape' option.

For the GIS analysis, the QGIS 3.30 and ESRI ArcMap 10.7 software will be used with a digital elevation model (DEM) and 5m resolution as a cartographic base (https://www.inegi.org.mx/). The GIS analysis with the IDV tool produces a fuzzy viewshed raster in which, as customary in 'regular' (i.e. binary) viewshed rasters, 0 indicates cells that are not visible, 1 indicates cells that are visible and values in-between correspond to a drop in visibility as function of the target distance and size. Values between 0 and 0.1 imply that, despite being within a theoretical line of sight, an individual would not be perceptible from the observer point due to the distance. Values between 0.1 and 1 imply that an individual would be differently perceptible from the observer point, according to the following thresholds (Fábrega-Álvarez and Parcero-Oubiña, 2019, Table 2):

In addition to visibility ranges, our analysis will focus on the amplitude of the visual field, which we will combine with prominence. To compare sites, the viewshed can be categorized in terms of how it is perceived from and towards the surrounding area. This is especially relevant when exploring the possibility that some shelters were interpreted as territorial and landscape landmarks. Four categories are distinguished for the medium distance range:

- Panoramic: the visible areas have an amplitude equal to or greater than 180° and the horizon can be observed from the shelter, with hardly any interruptions, towards two or more cardinal points.
- Wide: the visible areas are between 90° and 180° wide, with one or two cardinal points visible from the shelter with little interruption.
- Sectoral: the visible areas offer an amplitude of between 45° and 90° and are oriented without interruptions towards one cardinal point or, with interruptions, towards two.
- Partial: the visible areas are restricted to isolated areas in the vicinity of the shelter and have amplitudes of less than 45°.

Table 1
Sites with Great Mural style art in Santa Teresa Canyon.

No.	Name(s)	No. of motifs (approx.)	Anthropomorphs	Zoomorphs	Geometric	Superimpositions	Adjacent large area	Location in valley	Hierarchy
Emblematic and principal sites									
1	Cueva Pintada	1000–1500	●	●	●	●	●	Lower	Emblematic
2	Boca de San Julio	50–100	●	●	●	●	●	Lower	Principal
3	El Cacarizo I	20–50	●	●	●	●	●	Higher	Principal
4	Cueva de las Flechas	50–100	●	●	●	●	●	Lower	Principal
5	C. La Soledad	20–50	●	●	●	●	●	Middle	Principal
6	La Palma de Santa Teresa	20–50	●	●	●	●	●	Higher	Principal
Secondary sites									
7	C. de la Música	5–20	●	●	●	●	●	Middle	Secondary
8	La Venada	0–5		●			●	Middle	Secondary
9	El Cacarizo II	0–5	●	●			●	Higher	Secondary
10	B. de Santa Teresa	0–5		●	●		●	Higher	Secondary
11	C. de la Rata	0–5		●			●	Middle	Secondary
12	El Torote	0–5	●				●	Middle	Secondary
13	Zopilote y Pez	0–5		●			●	Lower	Secondary

Table 2
Visibility ranges and definition of the parameters considered according to Fábrega-Álvarez and Parcero-Oubiña (2019).

Range	Fuzzy membership	Type of identification	Distances and degree of recognition
Immediate range	0.99–1	Identification of specific individuals	(0–60m) Specific details can be determined, i.e. the person can be recognized.
	0.75–0.99	Detailed individual recognition	(60–225m) It is possible to distinguish parts of the human body and even clothing.
Medium range	0.5–0.75	Basic individual recognition	(225–600m) Basic characteristics are recognized. For example, if the moving object is a person.
	0.25–0.5	Human recognition	(600–1250m) Basic movements of distinct parts of the human body can be distinguished. This would be the limit of visibility for objects approximately 1 m high.
Long range	0.1–0.25	First detection	(1250–2500m) it is only possible to distinguish someone/something in the field of vision.
Out of range	0–0.1	Beyond detection	(>2500m)

The evaluation of prominence, i.e. the potential perception of sites with regard to the viewshed (Gaffney et al., 1995, p. 60), is influenced by the observer's height in relation to the surrounding environment. It can be calculated in several ways, as described by Llobera (2001). In this study, we decided to compare the absolute height (Z) of each site with the median, maximum and minimum values of the surrounding area within a 1000 m radius. We used the 'Area statistics' tool in QGIS to perform this analysis.

4.2. Results

The comparison of the visibility ranges – immediate range (0–225 m), medium range (225–1250 m) and long range (1250–2500 m) – of the analyzed sites in Santa Teresa Canyon shows some small differences between emblematic, principal and secondary sites (Table 3).

Comparing the surface area visible from the sites, it is observed that the emblematic site, Cueva Pintada, does not stand out in comparison to the principal sites. However, if we compare the emblematic and principal sites to the secondary sites, the former present larger visual fields than the latter in the immediate surroundings, although the differences are not statistically significant. However, when comparing the results at medium and long distances, this trend is reversed (Figs. 5 and 6). This first inference reveals that the emblematic and principal rock art sites would not have been selected for their broader visibility at medium and long distances. Likewise, they are not easily recognizable landscape elements when the observer moves away from their immediate surroundings.

Table 3
Area in hectares of the Fuzzy Distance distinctive visibility ranges of the study area. A) Individual identification; B) Detailed individual recognition; C) Basic recognition of the individual; D) Human recognition; E) First detection.

No.	Name	Immediate range			Medium range			Long range	Total (Acc.)
		A	B	Acc.	C	D	Acc.	E	
Emblematic and Principal sites									
1	C. Pintada	0.81	5.68	6.50	16.71	37.58	60.79	10.43	71.22
2	B. San Julio	0.87	2.20	3.08	8.86	15.86	27.81	13.58	41.39
3	El Cacarizo	0.88	7.48	8.37	50.53	86.01	144.92	54.57	199.48
4	C. Flechas	1.14	5.76	6.91	13.46	10.14	30.52	1.968	32.48
5	La Soledad	0.76	6.97	7.73	15.33	33.92	56.99	23.05	80.04
6	La Palma de Sta Teresa	1.22	8.06	9.29	13.73	77.43	100.45	176.64	277.09
Secondary sites									
7	C. Música	0.76	5.23	6.00	35.25	61.39	102.64	82.95	185.58
8	La Venada	0.56	4.90	5.47	26.78	37.93	70.19	70.365	140.55
9	El Cacarizo II	1.04	3.63	4.68	35.82	140.83	181.33	93.80	275.13
10	B. de Sta Teresa	0.98	5.52	6.51	41.55	142.15	190.21	215.17	405.37
11	C. Rata	1.25	7.96	9.22	31.24	35.21	75.67	92.71	168.38
12	El Torote	0.84	5.27	4.43	12.67	53.11	18.14	13.35	85.27
13	Zopilote y Pez	0.68	7.49	8.19	25.86	26.44	60.49	26.26	86.74

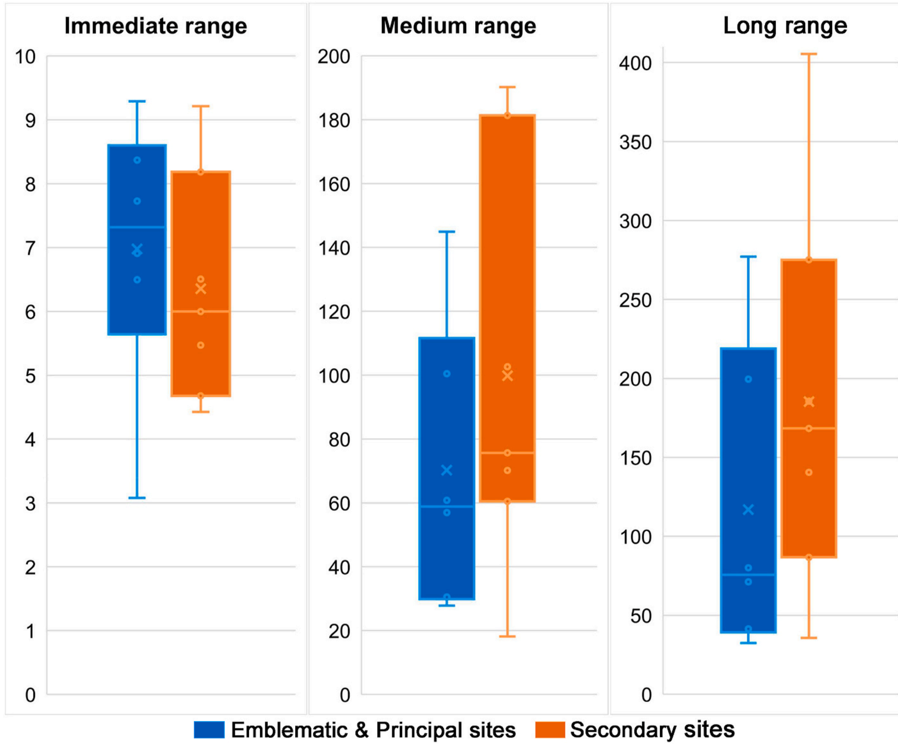

Fig. 5. Values in hectares of visible area represented by box plots. Dots: absolute values; Horizontal line: median; Boxes: quartiles; Whiskers: maximum and minimum values of each series. Prepared by the authors.

The amplitude of the visual field of the Santa Teresa Canyon rock art sites always points towards the interior of the main canyon or its minor tributary canyons. Most sites, whether emblematic, principal or secondary, offer wide, panoramic views when considering the immediate surroundings. However, when analysing medium-range ranges, where a human being can be identified in some detail, or long range, where it is difficult to see a person moving, visibility is notably restricted. In these ranges, there is a predominance of sectorial or partial visibilities with major interruptions caused by the complex topography (Fig. 6). There is no relationship between the hierarchy category and the amplitude, given that, for example, the three sites with the greatest amplitudes, Cueva Pintada (1), Cueva de la Música (7) and Zapilote y Pez (13), are located in low and medium sectors.

Taking all the viewsheds together, it is interesting to note that practically the whole canyon is covered by the accumulated viewsheds from each site. This is not the case when the viewsheds of, on the one hand, the emblematic and principal sites, or on the other, the secondary sites, are analyzed independently (see Fig. 7). For instance, the principal site of La Palma de Santa Teresa has a visual connection with several secondary sites situated in the southern zone of the longitudinal axis traced by Santa Teresa Canyon. These sites are also visible to each other. In the central section of the canyon, there is intervisibility between the principal sites of Cueva Pintada and Cueva de las Flechas, on either side of the canyon about a hundred meters from each other. However, neither of these two sites has a visual connection with the secondary sites or the principal site of La Soledad, the latter placed in the interior of one of the tributary ravines. In the northern sector, there is also a visual connection between the principal sites of Boca de San Julio and Cueva de la Música, as well as with other secondary sites in the main canyon. However, there is no such connection with those located in the transversal ravines.

The prominence analysis (Table 4; Fig. 8) indicates that the rock art sites are mainly located below the average values for each analyzed area (radius = 1000 m). This lack of altitude at many sites is related to the characteristics of the physical space, defined by abrupt changes in elevation and steep slopes, and therefore the difficulty of movement between the lower canyon and the plateaus. The use of shelters as a medium for rock art was not intended to monumentalize them over long distances, but rather only in the immediate surroundings. This suggests that the choice of shelters was not based on their long-distance perception, but on other factors. In the case of the emblematic and principal sites with a large number of motifs, perhaps it was the availability of extensive surfaces to paint, usually tending towards verticality, that allowed the large figures painted on them to be seen clearly from at least the immediate vicinity. Given that all were located in the lower part of the canyon this means the riverbed also served as the main routeway through the valley. Considering the size of many of the paintings, and their wide development, it was feasible for passers-by or people approaching them to capture the visual messages.

The results obtained by the analysis of visibility from the Santa Teresa Canyon rock art sites have provided some differences between the emblematic, principal and secondary sites, although these are not highly significant (Fig. 9). It seems that the prominence of each site in the canyon – lower, medium or higher – is the most influential factor in the range of vision that sites experience: with those situated in the higher section of the canyon enjoying the best views. The two sites that stand out, El Cacarizo II (9) and Banco de Santa Teresa (10), are both considered to have a high location in the canyon and high prominence. In contrast, Cueva Pintada (1), Boca de San Julio (2), and Cueva de las Flechas (4), located in the lower section of the canyon, have smaller viewshed areas and less prominence.

5. Soundshed

The first archaeological analyses of sound, or archaeoacoustics, focused on the evidence of musical instruments found at archaeological sites, including some with rock art; for example, the location of natural lithophones with rock art in Nigeria (Fagg, 1956) and Palaeolithic caves in Europe (Glory, 1964). From the 1980s there emerged an interest in the role of acoustics at rock art sites (Reznikoff, 1987; Dauvois and

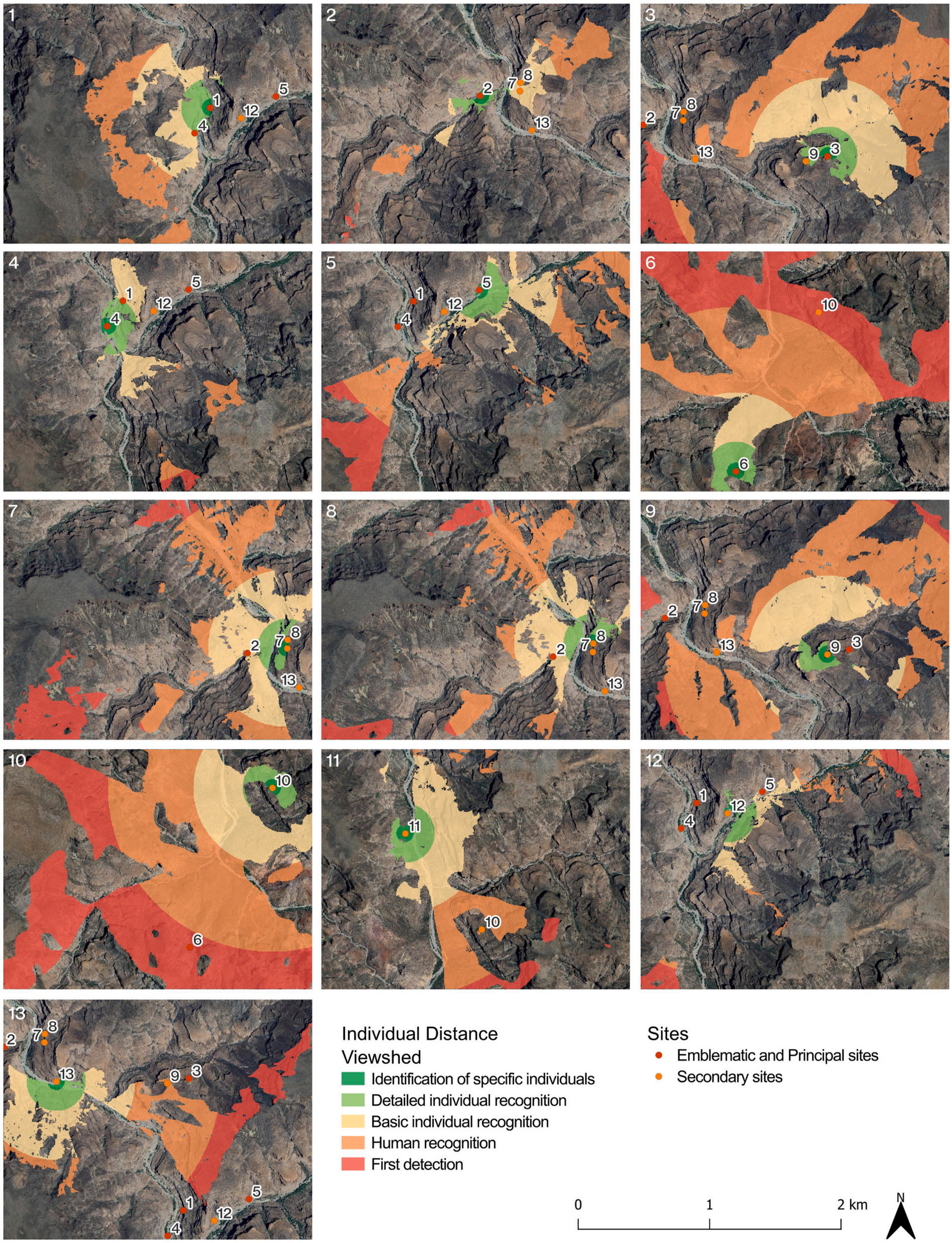

Fig. 6. Modelling of visual basins with representation of the attenuated visibility categories. The information on the numbers is found in Fig. 3.

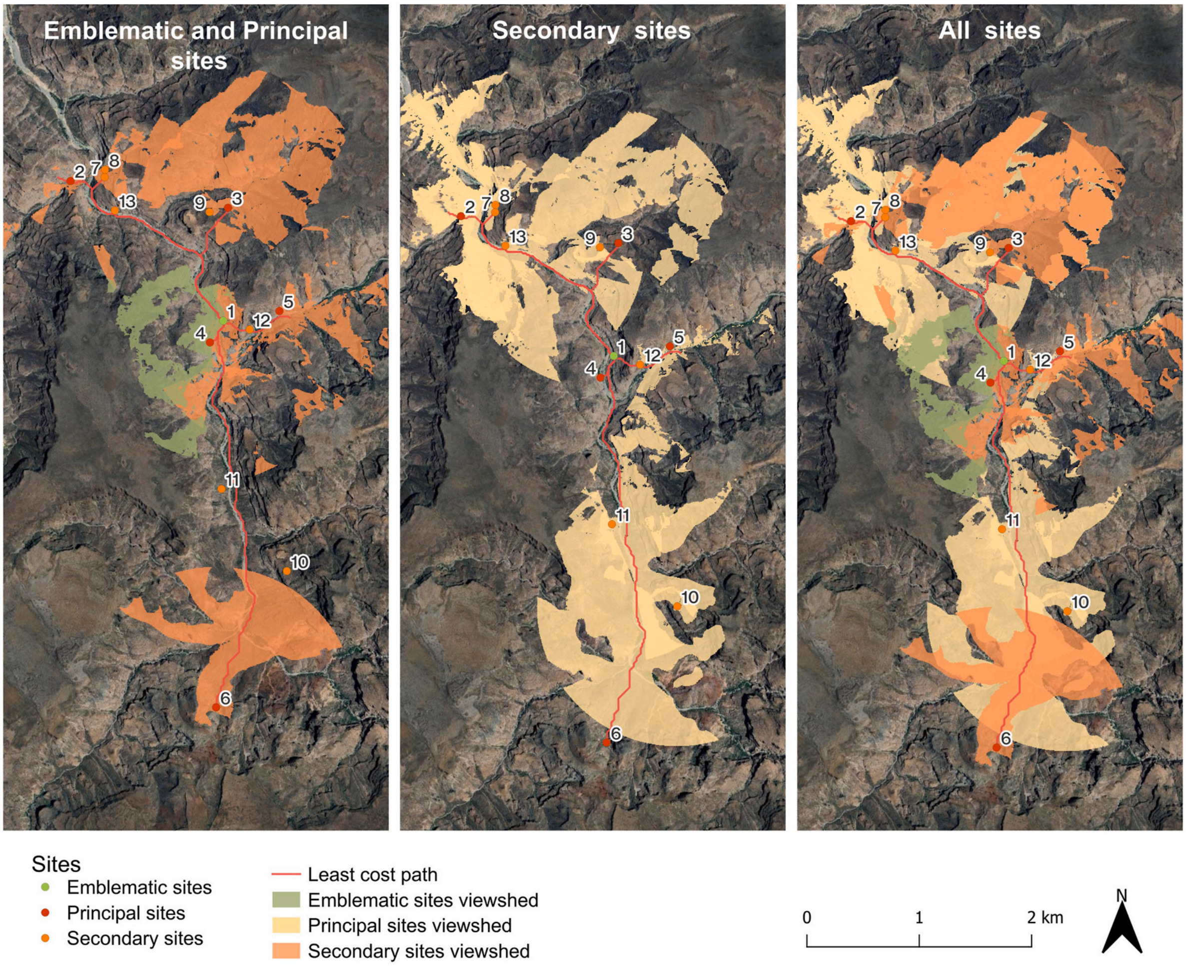

Fig. 7. Cumulative visibility and its relationship to the lowest cost path that would have connected them. The information on the numbers is found in Fig. 3.

Table 4
Prominence. Values, expressed in meters above sea level (a.s.l.), of the absolute height of each site, as well as that of its immediate surroundings.

NO.	Name	Loc.	Prominence	a.s.l.	Median	Average	Minimum	Maximum
Emblematic and principal sites								
1	C. Pintada	L	−175	514	689	694	469	989
2	B. San Julio	L	−137	473	610	622	431	973
3	El Cacarizo	H	−23	687	710	715	459	1035
4	C. Flechas	L	−199	505	704	713	473	991
5	C. Soledad	M	−131	590	721	720	476	1041
6	La Palma de Santa Teresa	H	−4	813	817	836	564	1140
Secondary sites								
7	C. Música	M	−80	532	612	623	433	968
8	La Venada	M	−102	510	612	621	432	958
9	El Cacarizo II	H	−3	686	689	690	455	1006
10	B. de Sta Teresa	H	64	773	709	741	539	1129
11	C. Rata	M	−157	600	757	768	504	1035
12	El Torote	M	−119	588	707	711	477	1035
13	Zopilote y Pez	L	−127	497	624	646	435	981

Boutillon, 1990; Hedges, 1993; Steinbring, 1992), a trend that has continued into the 21st century (Waller, 2006; Díaz-Andreu and García Benito, 2012; Fazenda et al., 2017; Till, 2019; Díaz-Andreu et al., 2021[3]). In parallel, there were studies in sound and communication (Zahorik, 2002; Constantidinis, 2004) and an interest in exploring sound propagation from archaeological sites through GIS modelling (Mlekuz, 2004; Díaz-Andreu et al., 2017; Primeau and Witt, 2018; García Atiénzar et al., 2022; Van Dyke et al., 2024), two perspectives that are especially useful to the analysis undertaken in this article. This article contributes to all these studies by looking at sound propagation in the rock art landscape of Santa Teresa Canyon using GIS as a method of analysis.

5.1. Methodology

The soundshed analysis modelling was performed using Sound Mapping Tools v. 4.4 on ESRI ArcGis 10.7 (Reed et al., 2010, 2012),

[3] See also other articles on https://www.ub.edu/artsoundscapes/publications/.

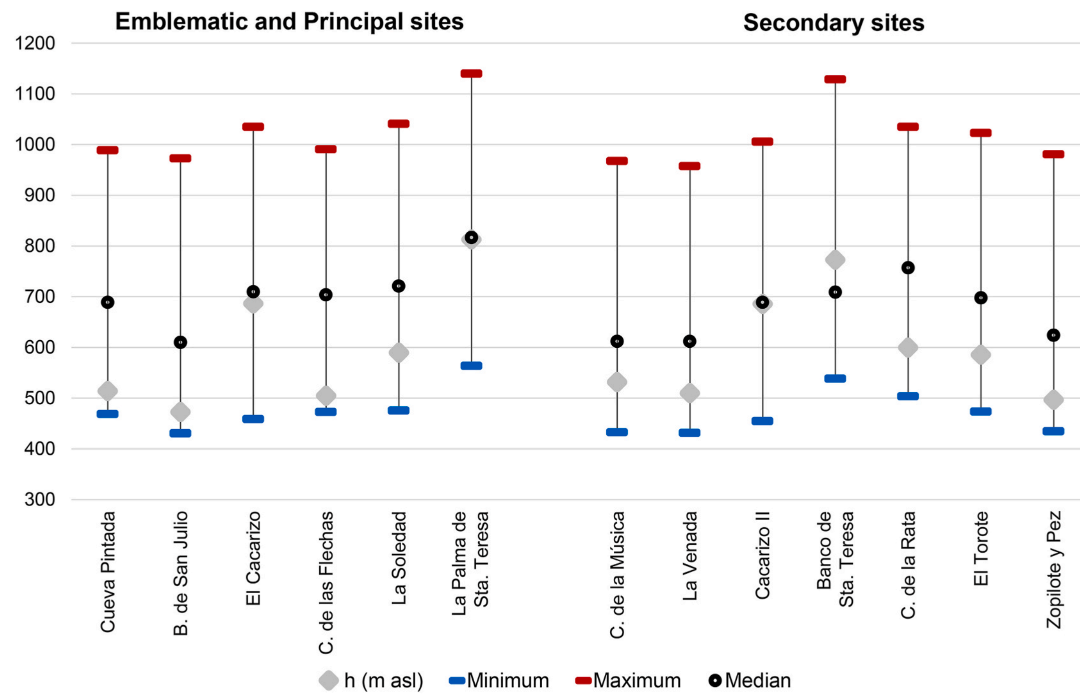

Fig. 8. Graphical representation of the values, expressed in meters a.s.l., of the absolute height of each site, as well as that of its immediate surroundings.

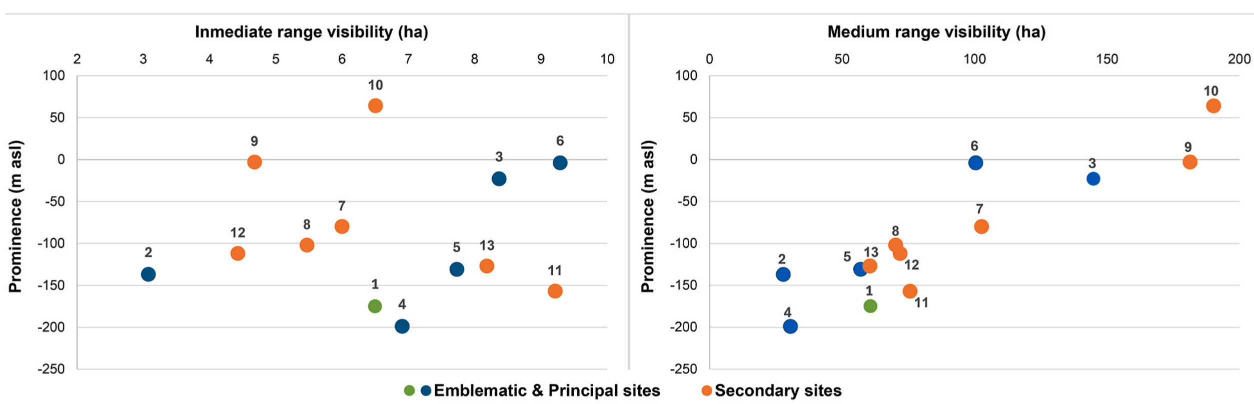

Fig. 9. Relationship between viewshed and prominence (Green dot: Emblematic site; Blue dots: Principal sites; Orange dots: Secondary sites). The information on the numbers is found in Fig. 3.

specifically the SPreAD-GIS script. This tool is based on the System for the Prediction of Acoustic Detectability (SPreAD) developed by the US Forest Service to manage noise from outdoor recreation (Harrison et al., 1980) that uses the physics of sound propagation to predict sound levels across the landscape. It is enormously versatile as it takes into account both the characteristics of the sound source and most of the variables that affect its spherical propagation: distance to the source; air absorption, which is dependent on temperature, relative humidity and altitude; vegetation and ground cover; wind speed and directionality; and topography (Reed et al., 2012: 2–3). This allows the calculation of sound propagation patterns and sound level above ambient conditions. The Sound Mapping Tools program has been developed for one-third octave frequency bands (125–2000 Hz) considering single or multiple sound sources. Its application in archaeology also requires accurate data for Sound Pressure Levels (SPL) and the frequency components of the sound source, the two most relevant acoustic variables in sound modelling. With regard to SPL, the higher it is, the greater the area in which the sound is likely to be heard before it falls below the ambient noise level (Rossing, 2007: 115). In terms of frequency, the attenuation of sound waves is a dependent variable. In this context, air absorption is very significant in the propagation of sound over long distances in the open air, assuming attenuation of higher frequencies (Rossing, 2007: 116). Thus, for the loudness calculation we have established as the most suitable sound source emission values 90 dB SPL at 1 m and a frequency between 500 and 1500 Hz, values suitable for modelling the sound emitted by prehistoric percussion instruments, as well as a large number of wind instruments and human voices (Pearsons et al., 1977; Olsen, 1998; Aiano, 2006; Reznikoff, 2014; Ibáñez et al., 2015).

In addition to decisions about level and frequency values, another decision to be taken relates to how to resolve the decrease in SPL from the point of origin due to, among other factors, absorption from terrain and vegetation. To solve this, as mentioned above, we used the SPreAD-GIS tool that allows us to calculate sound decay as a function of topography, predominant land cover and distance from the sound source. For topography, the same DEM was used as for the visibility analyses, while for vegetation cover Corine Land Cover (CLC[4]) was used.

[4] https://www.esa.int/ESA_Multimedia/Images/2018/10/Mapping_Mexico_s_land_cover.

To adapt the CLC data to SPreAD-GIS, the layer was reclassified into different categories (Díaz-Andreu et al., 2017: Table 1). On the other hand, the decrease in sound level can also be affected by atmospheric absorption variables directly related to the time of year in which the analysis takes place. In this case, it was decided to assign the values corresponding to a typical summer day with no prevailing wind, an air temperature of 25 °C and a humidity of 50%.

For comparison and analysis, the results obtained are divided into two soundshed ranges: 20–50 dB, related to soft and moderate noises, and 50–90 dB, corresponding to high sound levels caused, for example, by groups of people talking loudly, and even shouting at the highest number of decibels.

5.2. Results

Noise propagation analyses in our study area reveal that acoustical messages emitted from the emblematic and principal sites would have been heard more clearly over a wider geographical area than those emitted from secondary sites, when analysing sound propagation between 50 and 90 dB. In comparison to the principal sites, Cueva Pintada has one of the highest amplitudes regarding moderate/high sound levels, but it is worse than any of them in terms of the amplitude of soft sounds. The comparison between emblematic and principal sites and secondary sites shows a similar pattern; their amplitude of high sound levels is higher than of secondary sites. However, when considering the entire audibility zones, which includes sound levels between 20 and 90 dB, there are no noticeable differences between the principal and secondary sites (Table 5; Fig. 10).

The analysis of sound propagation (Fig. 11), especially in the case of the highest range, i.e. 90-50 dB, the sound frequency heard with greater clarity, makes it clear that sound is projected from the sites towards their surroundings in a semi-spherical manner, with the ravine slopes acting as a limiting element. When considering the lowest frequencies between the lowest human hearing threshold 20 dB and 50 dB, it is observed that the sound uses the ravines as the main propagation channels.

Interestingly, the combination of the noise propagation of all sites reveals that, with the exception of a few sound-blind spots, it is possible to hear sounds produced from the different rock art sites in most areas of the canyon (Fig. 12). Thus, the cumulative soundscapes demonstrate that anyone in the canyon could hear sounds from one or more rock art sites and, at the same time, that the territory could be acoustically controlled from the rock art sites.

Concerning the soundshed from the rock art sites in Santa Teresa Canyon (Fig. 13), the tendency in the relationship with the prominence and the sound propagation is similar to that of the viewshed. The sites located in a higher area with greater prominence also have a wider sound propagation. There is no clear distinction between principal and secondary sites considering them as a whole, but it is worth noting that the two sites with highest values in relation to the prominence and both sound and visual areas are the same secondary sites: Banco de Santa Teresa and El Cacarizo II. However, if one considers the higher sound frequencies - 90-50 dB - associated with messages that would have been transmitted more clearly, the emblematic site of Cueva Pintada offers significantly high values despite being located very close to the base of the canyon. This fact can also be extrapolated to other principal sites such as Cueva de las Flechas (4).

Table 5
Area (in hectares) audible from sites with Great Mural style rock art.

NO.	Rock art sites	Location	90-50 dB	50-20 dB	90-20 dB (accum.)
Principal sites					
1	C. Pintada	L	1.67	40.94	42.61
2	B. San Julio	L	1.07	43.64	44.71
3	El Cacarizo	H	1.27	153.94	155.21
4	C. Flechas	L	1.61	149.72	151.33
5	C. Soledad	M	1.17	78.46	79.63
6	La P. de Santa Teresa	H	2.03	156.04	158.07
Secondary sites					
7	C. Música	M	0.95	121.30	122.25
8	La Venada	M	0.80	101.02	101.82
9	El Cacarizo II	H	1.61	248.92	250.53
10	B. de Sta Teresa	H	0.74	285.73	286.48
11	Cueva de la Rata	M	1.17	64.79	65.96
12	El Torote	M	0.72	47.79	48.51
13	Zopilote y Pez	L	1.54	92.73	94.27

6. Discussion

In this article we used the GIS analytical tools to assess the viewshed and soundshed of a selection of 13 rock art sites in Santa Teresa Canyon. These are sites with paintings about which sufficient information has been published and whose location has been confirmed. The study took into account two criteria to characterize the sites: hierarchy (emblematic, principal and secondary) and location in the canyon (lower, middle or higher sector). In the viewshed analysis we distinguished between range (immediate, medium, long and out of range) and amplitude of the visual field (panoramic, wide, sectorial and partial). Using the Sound Mapping Tools, two soundshed ranges were calculated, one for soft noises between 20 and 50 dB and another one for moderate/high noises between 50 and 90 dB. In this section we discuss whether the results for viewsheds and soundsheds are comparable in terms of the two established site categories. The objective of this comparison is to unravel the potential role of rock art sites, taking into account the differences between them. To articulate the discussion, we raise successive questions related to the choice of shelters as a medium for rock art.

Was hierarchy, i.e. the first criterion used to characterize a site, influenced by the visibility or the sound dispersion from it? The question could be rephrased as: were rock art shelters chosen for the purpose of converting them into emblematic, principal or secondary due to the circumstances mentioned above? Some authors, however, would suggest an alternative way of rephrasing the questions, taking into account the probable worldview shared by the communities living in the area. The right question would then be: did the sites with particular characteristics in terms of what could be seen or communicated from them have the agency to attract people to let them be painted and repainted in particular ways? Looking at the results of the viewshed analysis, it can be said that, compared to the principal sites, the emblematic site of Cueva Pintada does not stand out either in the visibility ranges or the amplitude, as it is similar to them. It is located in the lower section of the valley, which also appears to be the preferred location for the two principal sites with the most figures (from 50 to 100).[5] In terms of the soundshed, there is a clear difference; despite the fact that the principal sites generally have a high amplitude regarding the moderate/high sound levels, the emblematic site of Cueva Pintada has one of the highest.

What happens when we compare the emblematic and principal sites with the secondary sites? In this case, there are some disparities in visibility: despite the fact that there are no differences as regards the immediate area (with a usually wide amplitude), in the medium and long-range the secondary sites are those that are clearly able to visually perceive wider areas. The pattern is reversed in sound transmission, as emblematic and principal sites have better values, especially of

[5] In the lower section of the canyon, in addition to these sites with a high number of figures, there is also a secondary site, "Zopilote y Pez". This site was found by chance in an unexpected location during the 2018 campaign. It is exceptional not only because of its low number of motifs in a location usually reserved for sites with much higher numbers, but also because, in contrast to all the other sites, it is not in a shelter and is closer than any other to the canyon bed. It is only because it is high up on a rock face that it has not disappeared, as the lower part of the surface is likely to be covered during floods.

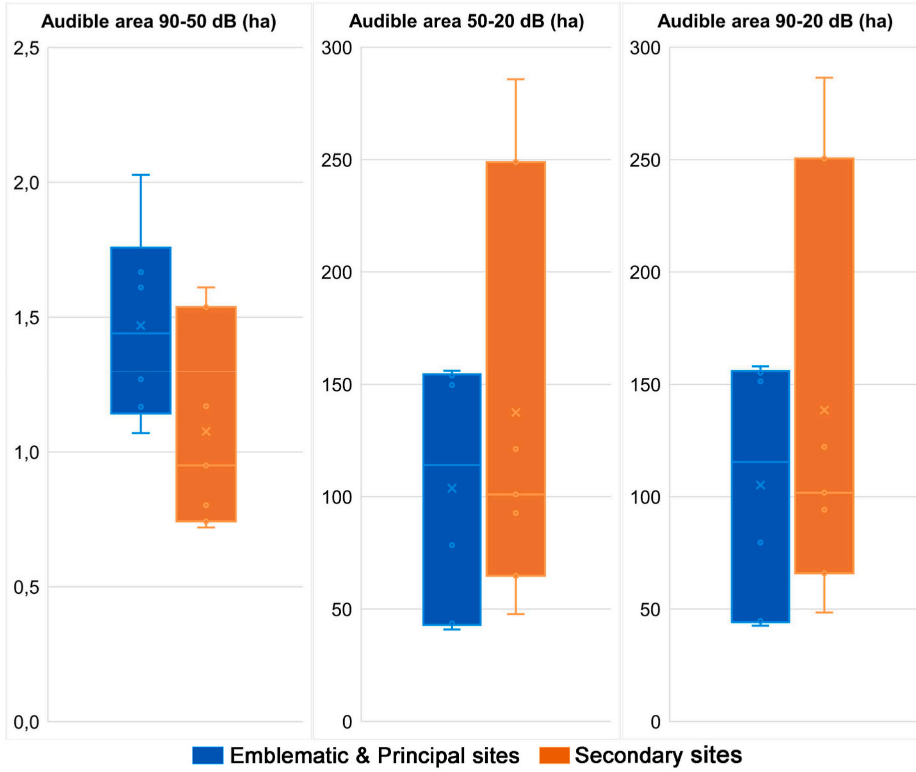

Fig. 10. Values in hectares of audible area represented by box plots. Dots: absolute values; Horizontal line: median; Boxes: quartiles; Whiskers: maximum and minimum values of each series.

moderate/high sounds. However, this clear difference between the two groups disappears when the whole audibility range from 20 to 90 dB is considered.

In addition to hierarchy, a second category was location in the canyon. We have already commented firstly that the sites with the greatest number of motifs – the emblematic Cueva Pintada and the principal sites of Boca de San Julio and Cueva de las Flechas – are in the lower section of the canyon and, secondly that the secondary sites are in the middle and upper sectors of the canyon. The combination of the viewshed and soundshed analyses with the location in the canyon has revealed some differences. The sites with more prominence had more extensive views, especially those in the higher part of the canyon. A similar pattern is found with regard to sound. It is worth noting that the two sites with the highest values in the relation of prominence and both sound and visual areas are the same secondary sites: Banco de Santa Teresa and El Cacarizo II. The principal sites with the highest number of motifs that are located in the lower part of the canyon show similar values to the other principal sites, the highest values related to La Palma de Santa Teresa that has less than 50 figures painted in it. However, Cueva Pintada and nearby site of Cueva de las Flechas show high values.

The comparison between the cumulative maps both for viewsheds and soundsheds presents a remarkably interesting pattern. In both cases the accumulation of the areas of emblematic and principal sites, on the one hand, and secondary sites, on the other, show that about half of the terrain remained inaccessible to the eye or ear. Revealingly, however, if these two cumulative maps are joined, both in the case of visibility and sound propagation, in both cases practically the whole canyon is sensorially accessible. It is also to be noted that the main routeway throughout the valley is also included in these cumulative maps.

7. Conclusions

Sight, hearing and other senses are crucial in how we perceive the world; they form a physical connection to our environment. The value placed on what we see or hear varies by culture and evokes specific emotional responses. This phenomenological perception of the world is not only cultural but may also have a practical side: the senses provide practical information about several aspects including navigating through a territory. In this article we have explored the senses of sight and hearing using GIS, an alternative method to that used to analyze acoustics in a previous study. The results obtained here complement our earlier findings, as the place with more interesting sound characteristics continues to be the area next to the only emblematic site in the area: Cueva Pintada. However, we have gone beyond our prior work, as we have also considered sight and established a series of categories according to site hierarchy and the location of the site in the canyon. Our results show that there is a complementarity in the role of the three types of sites depending on their place in the hierarchy. The only emblematic site, Cueva Pintada, enjoyed easy access and presented the best conditions for sound propagation, making it ideal to serve as an aggregation site at particular times of the year, functionality previously proposed by Viñas (2013). It was also one of the rock art sites in the area with the greatest visual amplitude. The principal sites were either located in the lower part of the valley – those with the most motifs – or dispersed in other areas. They were interspersed with secondary sites that usually had higher visibility ranges, although the sound propagation was not as good in the moderate/high frequencies, those needed for group gatherings.

We could consider that all the painted sites served a social function, which varied according to their hierarchy and, consequently, had different social meanings and symbolic uses. As various authors have pointed out (Crosby, 1997; Viñas, 2013; Gutiérrez Martínez and Hyland, 2002; Gutiérrez Martínez, 2013; Laylander, 2005), these caves may have been associated with ancestor veneration and clan identity rituals, particularly those featuring characteristic anthropomorphic figures (principal and emblematic).

Due to its steep elevation and slope, the Santa Teresa Canyon lacks the physical characteristics ideal for creating elevated murals, suggesting that the criteria for selecting this location were based on ideological rather than material or physical considerations. Moreover, as we have

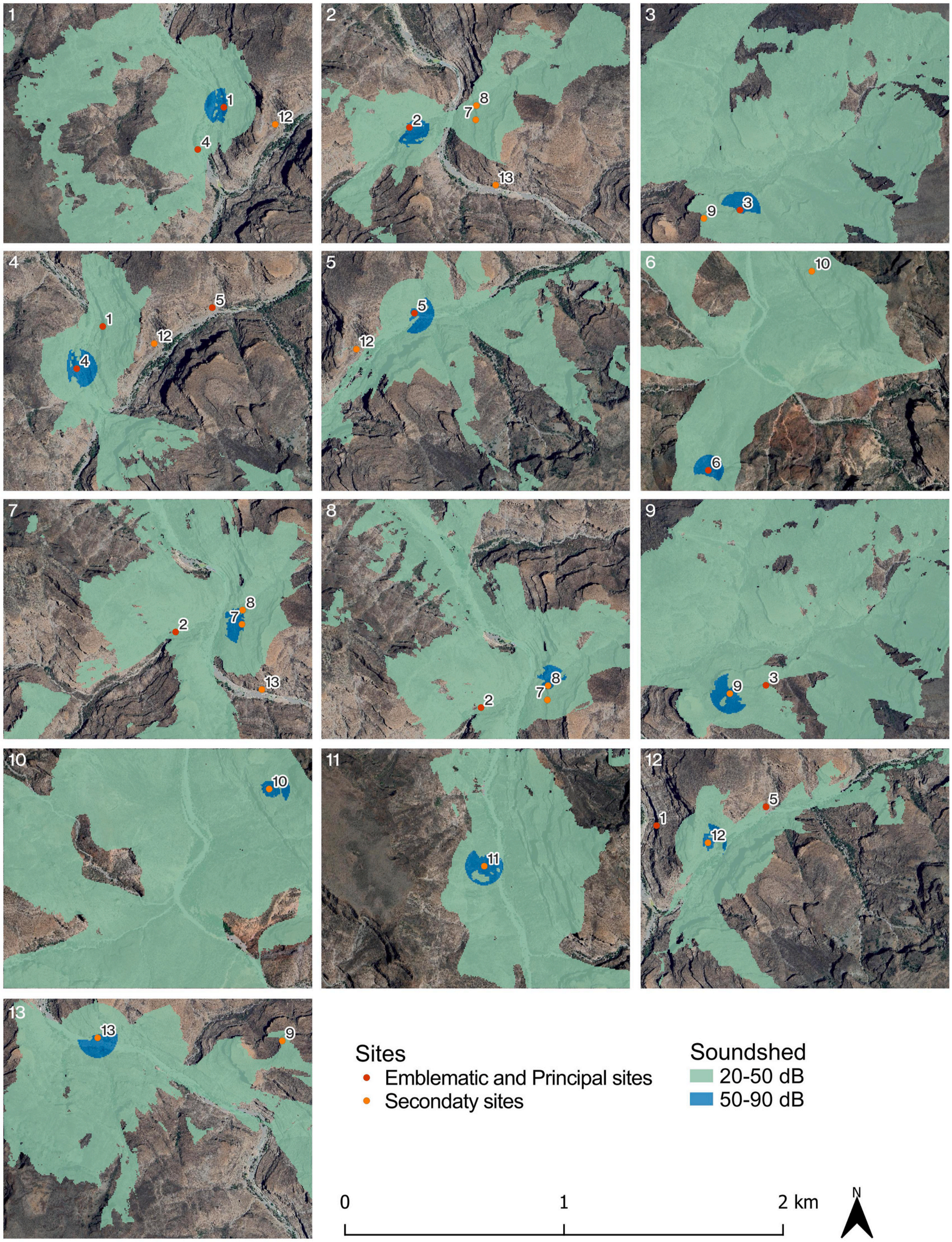

Fig. 11. Modelling sound propagation from sites with Great Mural style art. The information on the numbers is found in Fig. 3.

explained throughout this paper, the sites were designed to be seen or heard by individuals moving through the area. Collectively, the sites visually and sonically covered the canyon, ensuring that anyone could be seen or heard from at least one rock art site. Simultaneously, everyone in the canyon could hear or be heard by someone at one of these sites. The Santa Teresa Canyon, therefore, functioned as a composite sensory landscape where each site complemented the others. The painted images and the sounds of people—whether making noise, telling stories, or playing music—would have enriched the phenomenological experience of the place. However, precisely how this interplay occurred is a type of information that has been lost over time.

We can consider that the ability to recognize rock art shelters, either

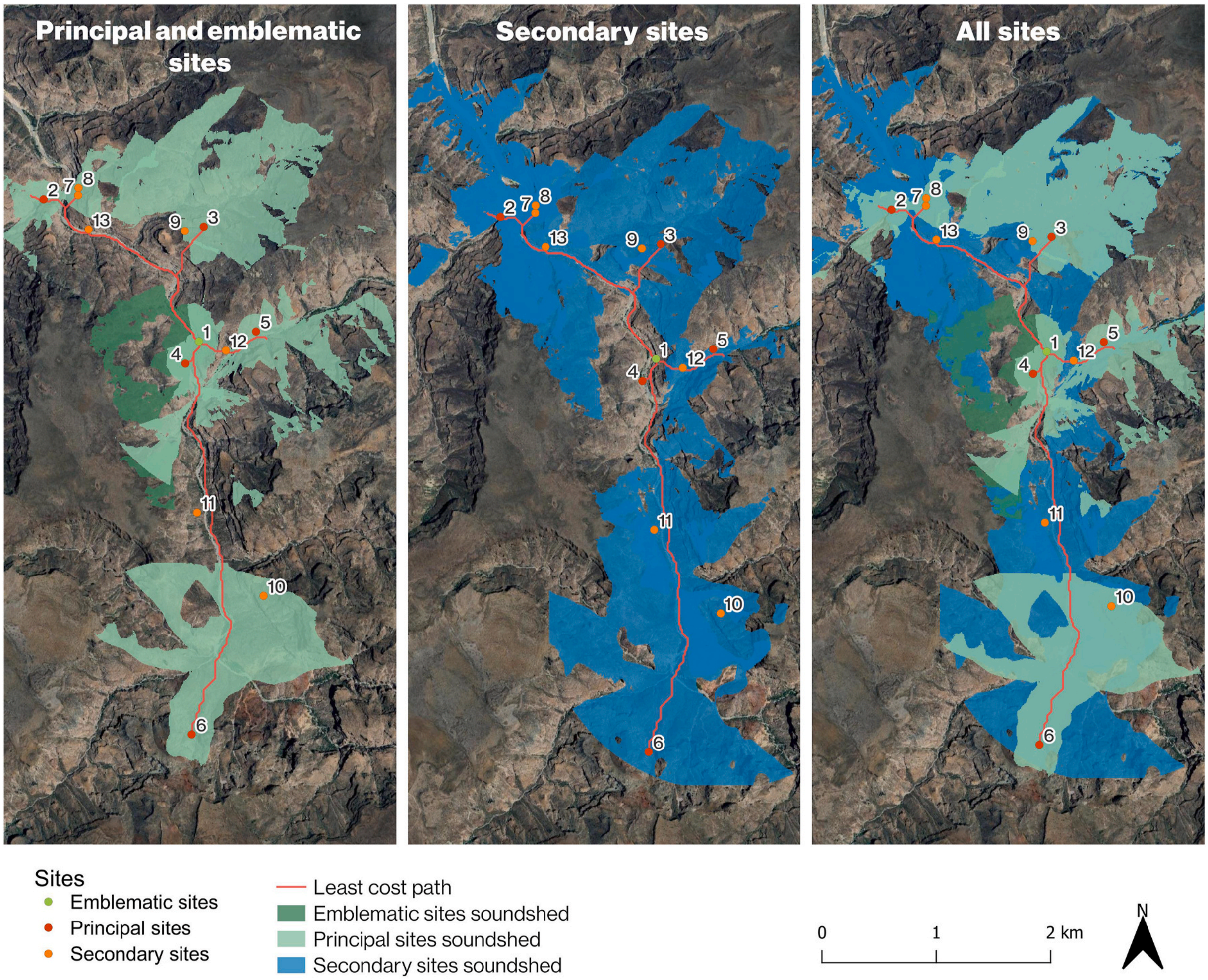

Fig. 12. Cumulative soundscapes and their relationship to the least cost route that would have connected them. The information on the numbers is found in Fig. 3.

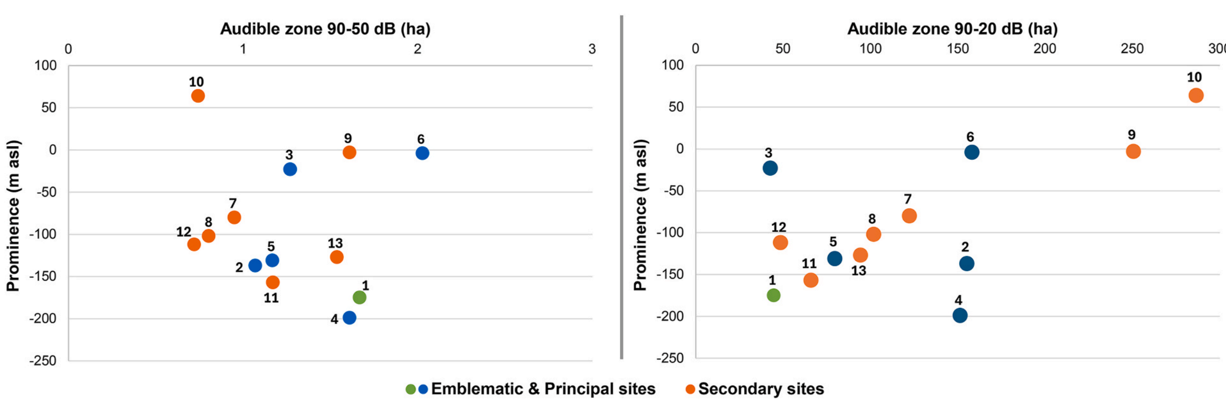

Fig. 13. Relationship between sound propagation and prominence (Green dot: Emblematic site; Blue dots: Principal sites; Orange dots: Secondary sites). The information about the numbers is found in Fig. 3.

by sound or sight, played a role in organizing the landscape and imbuing the area with cultural significance. The intention to be seen or heard aligns with social strategies for creating a culturally meaningful landscape. In this context, emblematic, principal, and secondary sites were not positioned randomly. In archaeology, deciphering the specific meaning behind landscape organization and understanding how societies appropriated and used the landscape remain significant challenges. Some authors have suggested that this organization could have been related to clan territories (Gutiérrez Martínez, 2013; Gutiérrez Martínez and Hyland, 2002). Furthermore, we propose that there may have been symbolic or mythical reasons behind the creation of paintings that were recognizable across the landscape.

CRediT authorship contribution statement

Natalia González Vázquez: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Gabriel García Atiénzar:** Writing – review

& editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Neemias Santos da Rosa:** Writing – review & editing, Supervision, Conceptualization. **María de la Luz Gutiérrez Martínez:** Writing – review & editing, Resources, Investigation. **César Villalobos:** Writing – review & editing, Investigation. **Margarita Díaz-Andreu:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they not have competing interest as a result of the research published in this article.

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