**[For SUPPLEMENTARY MATERIAL]**

**Seashells and sound waves: modelling soundscapes in Chacoan great-house communities**

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**Computer modelling & analyses**

*Soundshed Analysis Tool v.0.9.3*

The Soundshed Analysis Tool is a geometric-type model which calculates sound propagation from a single point source to a single point receiver, and assumes sound is traveling through the air along straight-line paths. The development of this tool and related tools is discussed in greater detail in Primeau (2022). In short, a series of cultural and environmental data were selected to represent the sound produced by a conch trumpet being played at sunrise on the summer solstice. Environmental data used in modelling included: the air temperature (°F), the percentage of relative humidity, the ambient sound pressure level (SPL) of the study location measured in decibels (dB); an elevation raster dataset; and the resolution of the elevation raster dataset. Cultural data describing the source of the sound included: the study location saved as a GIS point feature class; the height of the sound source in feet measured between ground surface and the primary location where sound is produced (e.g. the ‘bell’ of the conch); the SPL of the source (dB); the predominant frequency (Hz) of the sound source; and the distance in feet between the sound source and the location where the SPL of the source was measured.

Modelling inputs for the conch were derived from Loose’s (2012) reproduction of a *Strombus galeatus* shell trumpet, an instrument consistent with the appropriate size range of Ancient Puebloan trumpets as reported by E. Brown (2005). Historic average air temperature and relative humidity data were used as a proxy for conditions in the Chacoan era, and background sound levels used in modelling were representative of pinyon-juniper shrubland as described in Primeau and Witt (2018). Among the four raster data modelling results produced by the Soundshed Analysis Tool are: estimated soundsheds indicating rise over ambient Sound Pressure Levels (SPL) as discussed here (see Figures 2, 4 & 6–9); and viewsheds calculated using the sound source height as an offset for each modelling location (e.g. Figure 10). For example, as seen in Figures 7 and 10, given the topography of the Padilla Wash community, most of the areas where the conch was audible aligned with areas visible to the individual playing the conch. Validation of the Soundshed Analysis Tool was performed using modern environmental data (Primeau & Witt 2018; Primeau 2022), however, estimated soundsheds produced for this research were not derived from in-situ performance with a conch trumpet.

*Statistical analyses*

We conducted a series of statistical analyses for each modelling scenario undertaken for this study to determine location randomness. The first, Fisher’s exact test, measures the probability that a non-random association exists between two categorical variables—in our case, whether habitations were located within modelled soundsheds as compared to randomly placed locations. The second, chi-square test for association, measures whether observed frequencies in categories match expected frequencies. Fisher’s exact test was used to analyse patterns *within* communities; chi-square was used to analyse patterns *between* communities. These were accomplished according to the following steps for each scenario: 1) a buffer of 2km was placed around the location of sound sources. For communities where multiple scenarios were modelled, we dissolved the 2km buffers to create a single community area. We chose a distance of 2km in order to capture the entirety of the model soundscape, as well as any outlying structures beyond that distance. 2) 250 points were randomly created within that 2km buffer. 3) Of those points, we selected all that were within 5m of any zone of audibility. The number of selected points was then compared to the habitation sites located within audibility zones for each community using Fisher’s exact test (see Table S1).

**Table S1. Statistical tests for location randomness.**

| **Site** | **Sound Source** | **Test Locations in AZ** | **Total Test Locations** | **Habs in AZ** | **Total Habs** | **Fisher's Exact p-value HAB** | **ERFs in AZ** | **Total ERFs** | **Fisher's Exact p-value ERFs** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Bis sa’ani | 17286 | 73 | 250 | 5 | 8 | 0.057 |  |  |  |
| Bis sa’ani | 17286 | 73 | 250 | 7 | 8 | 0.001 |  |  |  |
| Bis sa’ani | 17287 | 64 | 250 | 5 | 8 | 0.034 |  |  |  |
| Padilla Wash | LA40352GH | 27 | 250 | 4 | 8 | 0.009 |  |  |  |
| Padilla Wash | LA40352K | 32 | 250 | 7 | 8 | 0.000 |  |  |  |
| Kin Klizhin | GH | 46 | 250 | 16 | 23 | 0.000 | 1 | 3 | 0.462 |
| Morris 40 | 180282 | 12 | 250 | 29 | 40 | 0.000 |  |  |  |
| Morris 40 | 180197 | 9 | 250 | 29 | 40 | 0.000 |  |  |  |
| Morris 40 | 1988 | 12 | 250 | 27 | 40 | 0.000 |  |  |  |
| Pierres | 16509 | 37 | 250 | 6 | 9 | 0.001 | 7 | 8 | 0.000 |
| Pierres | 16514 | 28 | 250 | 7 | 9 | 0.000 | 7 | 8 | 0.000 |

**Table S2. Chi-Square test for association for location audibility – habitation sites – best case scenario.**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Morris 40** |  | **Padilla Wash** |  | **Pierre’s** |  | **Bis sa’ani** |  | **Kin Klizhin** |  |
|  | **Obs** | **Exp** | **Obs** | **Exp** | **Obs** | **Exp** | **Obs** | **Exp** | **Obs** | **Exp** |
| In | 33 | 30.91 | 7 | 6.18 | 7 | 6.95 | 5 | 6.18 | 16 | 17.77 |
| Out | 7 | 9.09 | 1 | 1.82 | 2 | 2.05 | 3 | 1.82 | 7 | 5.23 |
| Total | 40 |  | 8 |  | 9 |  | 8 |  | 23 |  |
|  |  |  |  |  |  |  | 𝝌2 | 2.8723 | p-value | .579426 |

**Table S3. Chi-Square test for association for location audibility - habitation sites - worst case scenario.**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Morris 40** |  | **Padilla Wash** |  | **Pierre’s** |  | **Bis sa’ani** |  | **Kin Klizhin** |  |
|  | **Obs** | **Exp** | **Obs** | **Exp** | **Obs** | **Exp** | **Obs** | **Exp** | **Obs** | **Exp** |
| In | 27 | 26.36 | 4 | 5.27 | 6 | 5.93 | 5 | 5.27 | 16 | 15.16 |
| Out | 13 | 13.64 | 4 | 2.73 | 3 | 3.07 | 3 | 2.73 | 7 | 7.84 |
| Total | 40 |  | 8 |  | 9 |  | 8 |  | 23 |  |
|  |  |  |  |  |  |  | 𝝌2 | 1.1267 | p-value | .89001 |

**Table S4. Percentage of habitations within audibility zone for each community.**

|  |  |  |
| --- | --- | --- |
|  | **Average of Percentage (Best)** | **Average of Percentage (Worst)** |
| **Ancestral** | **74.42%** | **62.36%** |
| Kin Klizhin | 78.26% | 69.57% |
| Morris 40 | 82.50% | 67.50% |
| Padilla Wash | 62.50% | 50.00% |
| **Scion** | **88.19%** | **64.58%** |
| Bis sa'ani | 87.50% | 62.50% |
| Pierre's | 88.89% | 66.67% |

**Table S5. Chi-square and z-test results for differences between habitation location in scion vs. ancestral communities according to best and worst case scenarios.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **𝝌2 Test with Yates correction** |  | **2-tailed, 2 sample Z-test** |  |
|  | **𝝌2** | **p value** | **z value** | **p value** |
| Best case | 0.2876 | 0.591772 | -0.879 | 0.37886 |
| Worst case | 0.0283 | 0.866347 | 0.1164 | 0.90448 |

**Table S6. Chi-Square test for association for location audibility - enigmatic rock features (ERFs).**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Pierre’s** |  | **Kin Klizhin** |  |
|  | **Obs** | **Exp** | **Obs** | **Exp** |
| In | 7 | 5.82 | 1 | 2.18 |
| Out | 1 | 2.18 | 2 | 0.82 |
| Total | 8 |  | 3 |  |
|  | 𝝌2 | 3.2274 | p-value | 0.072414 |

**Study locations: additional details**

In this section, we offer more detailed descriptions of the five great house communities investigated in our study.

*Bis sa’ani*

Bis sa’ani is a ‘scion’ community located 12km north-east of Chaco Canyon along the Escavada Wash—one of the primary tributary washes on the north side of the Chaco River (Figure 1). The West Great House and the East Great House Complex are situated atop a prominent, isolated, 750m long, 20m high, 20–50m wide shale ridge on the south side of Escavada Wash (Powers *et al*. 1983: 21) (Figure S1). The West Great House (LA 17287) contains 12 rooms and a kiva. Just over 100m to the east, the East Great House Complex (LA 17286) contains at least 25 rooms and four kivas with a total floor area of at least 1040m2. Small habitations and field houses form an associated community in the aeolian dunes to the south. Powers *et al*. (1983: 21–54) intensively surveyed a 2mi- (3.2km) diameter area around the great houses and mapped the great houses and community. Breternitz *et al*. (1982) conducted extensive excavations at the great houses and some of the small community sites. The viewscape at Bis sa’ani links the community with the greater Chacoan landscape. The builders of Bis sa’ani appear to have intentionally situated their great houses atop the shale ridge not for intervisibility with the immediate community of small sites, but to maintain connections with the greater Chacoan world (Van Dyke *et al*. 2021).

A close-up of a hill

Description automatically generated

*Figure S1. Bis sa’ani West Great House (LA 17287) and East Great House Complex (LA 17286) as seen from the valley floor, looking north. The two great houses are the areas of dark brown sandstone on top of the ridge, with associated rubble spilling down the slope (photograph by Van Dyke).*

*Kin Klizhin*

Kin Klizhin is an ‘ancestral’ community located within the Kin Klizhin Unit of Chaco Culture National Historical Park, along an ephemeral wash 6km south-west of West Mesa (Figure 1). The site cluster consists of a great house with a tower kiva (Figure 3), habitation sites, irrigation features and several ERFs. Archaeological investigations at Kin Klizhin have included tree-ring dating, stabilisation, examination of associated irrigation features and a survey of the surrounding community (Morrison 1876; Holsinger 1901; Hewett 1905, 1936; Judd 1954: 57; Bannister 1964; Marshall *et al*. 1979: 69–72; Powers *et al*. 1983; Powers & Van Dyke 2015). The Kin Klizhin great house (LA 4975) is a 472m2 imposing structure atop a sandy knoll. Tree-ring samples indicate the great house was constructed around 1087 (Bannister *et al*. 1970: 24). The tower kiva, described in detail by Marshall *et al*. (1979: 70), contains standing walls that reach 9m above the modern ground surface. Based on ceramics, dendrochronology and architectural features, the most intensive habitation of the surrounding community took place from AD 890 to 1130.

*Morris 40*

Morris 40 is a large ‘ancestral’ community located on Ute Mountain Ute Land west of the La Plata River in north-west New Mexico (Figure 1). It is situated on either side of a seasonal arroyo that flows to the San Juan River, with a sandstone uplift to the north-west and treeless grasslands to the south-east (Figure 5). Morris 40 has a long history of archaeological investigation (Nusbaum 1935; Morris 1939; Marshall & Stein 1978; Marshall *et al*. 1979; Robinson 2014). Throgmorton and colleagues remapped the community with handheld GPS, conducted geophysical survey with a dual-sensor magnetic gradiometer, and performed in-field pottery analysis (Throgmorton 2019). Based on uniform probability density analysis of pottery counts, the Morris 40 community was inhabited between AD 750 and 1300.

The community consists of a 450m2, two-storey masonry great house with three kivas (LA 1988), two great kivas (LA 180282), a road segment, a tower (LA 180197) and over forty domestic habitations in the surrounding 1km2. The road segment enters the community from the south and leads to the great house. The tower is indicated by a series of post holes in bedrock atop a sandstone butte located at the highest point in the community. The great house is located below the sandstone knob and is situated on a raised platform of architectural debris. It overlooks much of the surrounding community.

The configuration of the Morris 40 community changed through time. From AD 750 to 880 the community consisted of linear, multi-household structures positioned symmetrically on either side of the arroyo and a few scattered single-household dwellings. From AD 880 to the early 1000s Morris 40 decreased in size but continued to consist of both multi- and single-household dwellings and included a great kiva. In the late AD 1000s the construction of the great house coincided with a dramatic expansion of the community into surrounding terrain and a shift to smaller, single-household structures. A new great kiva was constructed in the mid- to late- AD 1100s and the scale of the community declined until it was fully depopulated in the AD 1200s.

*Padilla Wash*

Padilla Wash is an ‘ancestral’ great house community located near the western boundary of Chaco Culture National Historical Park, approximately 4km south-west of the Penasco Blanco great house (Figure 1). The community is situated on the west side of the Padilla Wash valley within rolling, treeless grasslands and occasional shale badland outcrops (Figure S2). Padilla Wash was first recorded in the 1970s by the Chaco Project and subsequently documented by Windes (2007, 2015). Throgmorton and colleagues (reported in Throgmorton 2019) remapped the community with GPS, performed geophysical survey with a dual-sensor magnetic gradiometer, and conducted in-field pottery analysis. Uniform probability density analysis of pottery counts indicate that the community was inhabited from AD 750 to 1125, with a brief reoccupation by a single household between AD 1225 and 1275 (Throgmorton 2019: tab. 6).

Padilla Wash consists of a two-storey, 315m2 great house with about 25–30 rooms and an 8m-diameter kiva (LA 40352), an earlier proto-great house (LA 41882), a great kiva (LA 40352) and about 25 smaller habitations in the surrounding 1km2. The great house and great kiva are connected by a road segment that passes through constructed mounds south of the great house. The focal point of the community was first the proto-great house (*c*. AD 850–950), then the great kiva (*c*. AD 950–1025) and finally the great house/great kiva complex (*c*. AD 1025–1125). Sites within the community tend to be located either atop or on the southern slope of sandy ridges south of the great house.

A wide view of a desert

Description automatically generated

*Figure S2. View of the Padilla Wash community, looking westward from West Mesa of Chaco Canyon (photograph by Throgmorton).*

*Pierre’s*

Pierre’s is a ‘scion’ community situated 19km north of Chaco Culture National Historical Park, on the southern edge of the break between the Chaco Slope and the mesas and badlands of the Denazin and Ah-shi-sle-pah Washes (Figure 1). The community articulates with the Great North Road, which leaves the vicinity of Chaco Canyon near Pueblo Alto and, in a series of stages, heads north for 50.5km to Kutz Canyon. Powers *et al*. (1983: 94–122) and Harper *et al*. (1988) both conducted intensive survey and recording in the Pierre’s community during the 1980s. The community was also investigated by the Chaco Roads Project (Stein 1983) and the Solstice Project (Marshall & Sofaer 1988).

The core of the Pierre’s community involves at least five central structures. Two south-facing great houses (House A and House B) are located atop a large butte near the centre of the community (Figure S3). House A contains an estimated fifteen ground-floor rooms and three enclosed kivas over an area of 255m2. House B, located 30m to the north-north-east contains an estimated thirteen ground-floor rooms and a single enclosed kiva and covers 315m2. Nearby to the north, a sandstone pinnacle called El Faro (The Lighthouse) is topped by a three-room structure with an exposed hearth. At the base of this pinnacle, House C, another massive 505m2 building, contains eighteen rooms and one enclosed kiva. A neighboring pinnacle 80m east-south-east of El Faro hosts a small room block that might be considered to represent an atalaya, or watchtower, following Marshall and Sofaer (1988).

The Pierre’s community is spatially distributed over an area of approximately 1.6km2. Over the past decades, shifting dune sands have obscured and revealed sandstone masonry and artefact scatters. Powers *et al*. (1983) documented seventeen Ancient Pueblo sites in the surrounding community; Harper *et al*. (1988) added an additional nine. Throgmorton recently conducted a site visit that clarified the existence of several ERFs (enigmatic rock features) located on mesa tops forming the topographic boundary of the community. All but one small Basketmaker III–Pueblo I artefact scatter date from the Late Pueblo II or Early Pueblo III period.

There is little doubt that Chacoans located Pierre’s in this place because of the Great North Road and because of specific visible attributes of the local topography. Pierre’s is located on the first major topographic break in the landscape moving north from Chaco Canyon. The pinnacles and butte of Pierre’s are intervisible with Pueblo Alto and may have been involved with signaling down the line of the North Road.

A landscape with a hill and blue sky

Description automatically generated

*Figure S3. Looking westward towards Pierre’s Great Houses A and B—the two rubble mounds perched atop a large butte in the center of the photo (photography by Van Dyke).*

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