



## Research Article

# Bronze Age cymbals from Dahwa: Indus musical traditions in Oman

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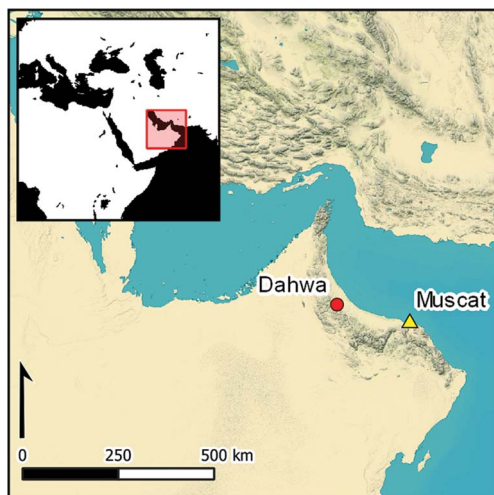
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Understanding the development and use of musical instruments in prehistory is often hampered by poor preservation of perishable materials and the relative rarity of durable examples. Here, the authors present a pair of third-millennium BC copper cymbals, excavated at Dahwa, Oman. Although they are the only well-contextualised examples from Arabia, the Dahwa cymbals are paralleled by contemporaneous examples from the Indus Valley and images in Mesopotamian iconography. Not only do the cymbals add to the body of evidence interpreted in terms of Indus migrants in Early Bronze Age Oman, they also suggest shared musical and potentially ritual practices around the Arabian Gulf at that time.

Keywords: Middle East, south-east Arabia, Umm an-Nar period, musical instruments, Indus contact, ritual activity

## Introduction

Inland settlements in south-east Arabia, such as Dahwa, Salut and Bat in what is now Oman, increasingly attest to the presence of Indus merchants and craftspeople in the third millennium BC (Frenez *et al.* 2016; Frenez 2020, 2023; Douglas *et al.* 2021). The local production

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of ceramics, including Indus-style cooking wares, is recognised alongside the import of Indus-style storage jars (Frenez *et al.* 2016), and the manufacture of other stylistically Indus artefacts at several sites indicates strong cultural links between south-east Arabia and the Indus region, arguably with considerable migration and integration of Indus people into the local Umm an-Nar culture (between 2600 and 2000 BC) (Méry *et al.* 2017). These artefacts include terracotta-toys, etched carnelian beads and, more rarely, square ivory weights, jewellery and metal objects such as seals, axes/adzes and spearheads (Frenez 2020: 19–29, 26, fig. 18; 2023).

The relationship between local (Magan) and Indus migrants is typically examined through the lens of economic interaction (Frenez 2023), but further research is needed to understand the social position of Indus migrants in Oman. The choice to settle in south-east Arabia would have related to both the socioeconomic situation at home and the opportunities perceived abroad. What does seem clear is that the Umm an-Nar society had a strong capacity to integrate migrant populations, maintaining a largely uniform culture while still allowing for diverse cultural expression (for instance, in cooking traditions). The uniformity of the Umm an-Nar culture is attested foremost in the monumental tombs that often included hundreds of individuals buried over almost a millennium (Munoz 2019). Analysis of stable isotopes from these individuals suggests that the tombs included people with migrant backgrounds (Gregoricka 2013); funerary rituals were thus likely also a means of integrating people from various backgrounds into the cultural fabric of daily life and shared ancestry.

Indus migrants may have been involved in the extraction and smelting of copper for export to the Indus Valley, particularly as lead isotope signatures indicate that Omani ores were used there (Hoffman & Miller 2009: 245, fig. 3; 2014: 705, figs. 24.3 & 24.4; Bisht & Prabhakar 2015: 10–16, fig. 7; Méry 2020). Adaptation of local craft production could suggest that mining communities included an Indus contingent who maintained strong familial ties to their places of origin. With rich evidence of copper smelting, one of the primary activities at the site of Dahwa in northern Oman seems to have been the procurement of copper for export, yet the discovery in 2018 of a pair of cymbals provides a rare window into the social lives of Indus migrants and how they became part of local Umm an-Nar settlements.

## **Dahwa 7 (DH7)**

Excavated since 2014 by the Archaeology Department at Sultan Qaboos University as part of a long-term project in the northern Al-Batinah region in northern Oman, five relatively large sites (DH1, DH5, DH6, DH7 and DH8) cluster around the Wadi Al-Sukhn at the foot of the Al-Hajar Mountains close to the modern village of Dahwa (Figure 1). Four seasons of excavations were carried out at DH7 (2017–2021), revealing surface scatters of Umm an-Nar pottery extending over an area of approximately 6.4ha (Figure 2) and three groups of settlement structures, comprising a lower, middle and upper area. Domestic structures occupy the flat lower area, while the gently sloping middle area contains a monumental structure (S3) and another small building (S2) (Figure 2, nos. S2 & S3). One small building (S1) sits at the southern edge of the topographically higher upper area, spatially separated from the buildings in the middle and lower areas and with a view over the entire settlement towards the south-east. The only Umm an-Nar tomb (T1) found so far at DH7 is located at the western edge of the settlement (Williams *et al.* 2021).

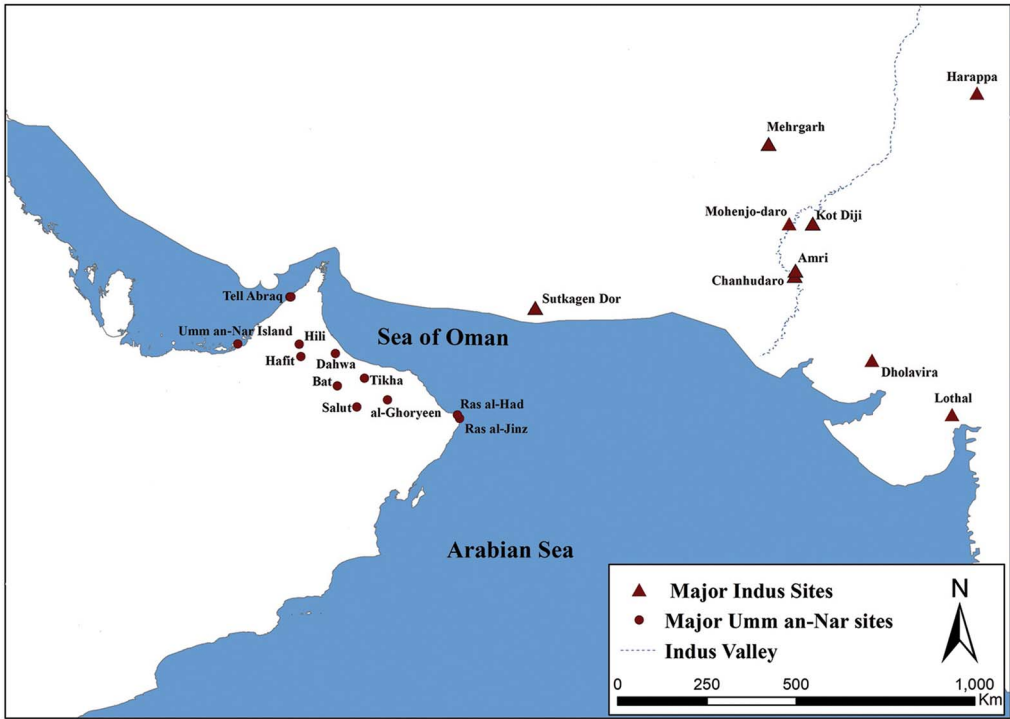


Figure 1. Location of Dahwa and other Umm an-Nar sites mentioned in the text (map by M. Hesein).

A ritual function is suggested for building S1 based on associated artefacts and architecture (Douglas *et al.* 2024). The positioning of the building in a liminal zone of the settlement landscape—on the highest area overlooking the domestic buildings and isolated from

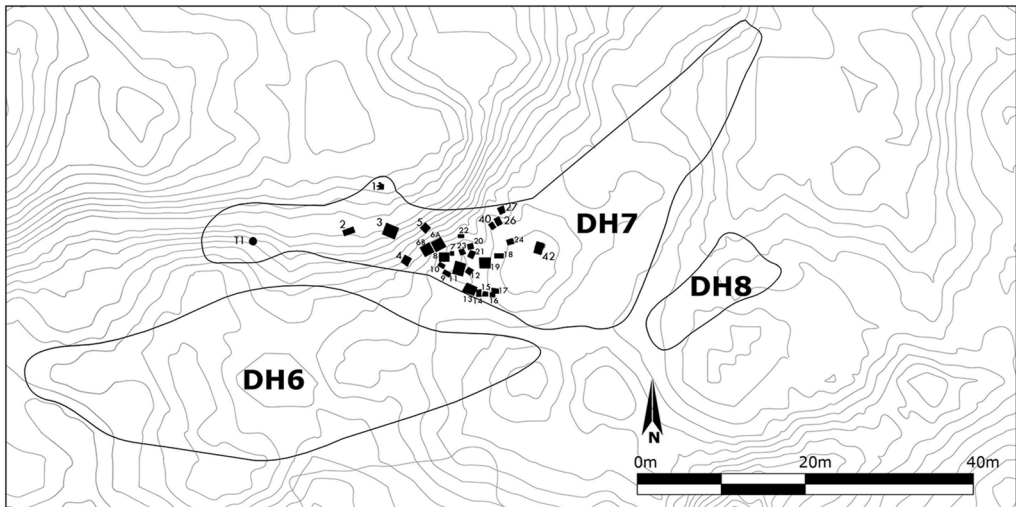


Figure 2. Plan of DH7 settlement (drawn by K. Williams & A. Akhter).

other buildings—creates a spatial distinction within the settlement. The architectural plan of the building is unique at the site but has parallels with ritual architecture in the wider region (Douglas *et al.* 2024), reinforcing the ritual element of the distinctive setting. Some artefacts associated with the building are unique at the site, including a pair of copper cymbals, and potentially also fit the interpretation as a building as used for ritual, even cultic, activity. An overview of the structure is presented here with the hope that future, targeted research will elucidate the activities undertaken in and around the building.

## **The building with the cymbals**

Building S1 was excavated over two seasons in 2018 and 2021, and shows strong similarities to S20 in DH1, excavated in 2017 (Al-Jahwari & Douglas 2021b; Douglas *et al.* 2024). Built on a natural hard soil layer, building S1 is a rectangular single-roomed building measuring 4.4 × 3.3m and orientated north–south with a slight eastward shift. A rectangular platform (L048) leads to a narrow (0.43m) entrance on the eastern side of the building (Figures 3 & 4). Up to four courses of roughly cut stones mortared with clay are preserved in some parts of the walls, with a height up to 0.45m. The large number of fallen stones removed in connection with the building suggest that it was originally fully stone built. The inside of the walls was covered with a thick plaster layer that is still well preserved on the lower course. A small step made of the same type of plaster forms the entryway and a small platform (L008), again covered with a thick plaster layer, abuts the west wall opposite the entrance.

To the left of the entrance, against the south wall, sits a semi-circular installation (L078), 1m in diameter, that is lined with one to two courses of stones (Figures 3 & 4). A small, poorly preserved installation (L080) of pure white plaster with a radius of approximately 0.4m sits in the north-east corner of the room, and a curved plaster-covered feature (L074) with a maximum length of 1.05m is located in the north-west corner. Several additional installations are found outside the building, all incorporated within an off-white plaster floor that covers the outside area in all directions. Although largely devoid of finds, these features suggest shared communal activities taking place in association with this building.

The small footprint of S1 (14.52m<sup>2</sup>) suggests that the building was not designed to accommodate a large number of people, particularly given the presence of the four internal installations. Rather, the presence of a relatively large number of installations coupled with the large outer plastered area suggests that the external area was designed to receive a larger number of people, consistent with the small rural temples of the Near East (Douglas *et al.* 2024).

Two main phases of use are recognised. The first phase represents the construction of the building and associated features, with a floor (L029) made of hard plaster material. The installations inside the building were built on top of this floor and the lack of burnt or dumped material indicates that it was cleaned prior to the next phase of construction—a paved floor (L009) of flat stones that covered the inside of the building and the outer platform (L048). Before this new floor was constructed, the area was raised with a 0.4m-thick intentional fill layer (L022) composed of hard clay mixed with different sized stones and plaster from the previous phase. This layer was relatively clean but incorporated some charcoal of





Figure 3. Drone image of building S1 taken at the end of the 2021 field season (photograph by S. Al-Mamari).

undetermined species, which produced two radiocarbon dates in the third quarter of the third millennium BC (see Table 1, Figure 5). These dates fit with radiocarbon dates from other buildings in the settlement at DH7, especially the large building/warehouse S42 (Douglas *et al.* 2024). The radiocarbon dates and ceramic evidence (see below) suggest the use of the building likely extended into the final century of the Umm an-Nar period (2100–2000 BC) (Douglas *et al.* 2024).

### The cymbals and their context

While removing the intentional fill layer (L022) from the north-west corner of the room, two cymbals were uncovered, one carefully placed on top of the other (Figure 6). This corner had previously been occupied by the curvilinear installation (L074), but it is unclear whether the

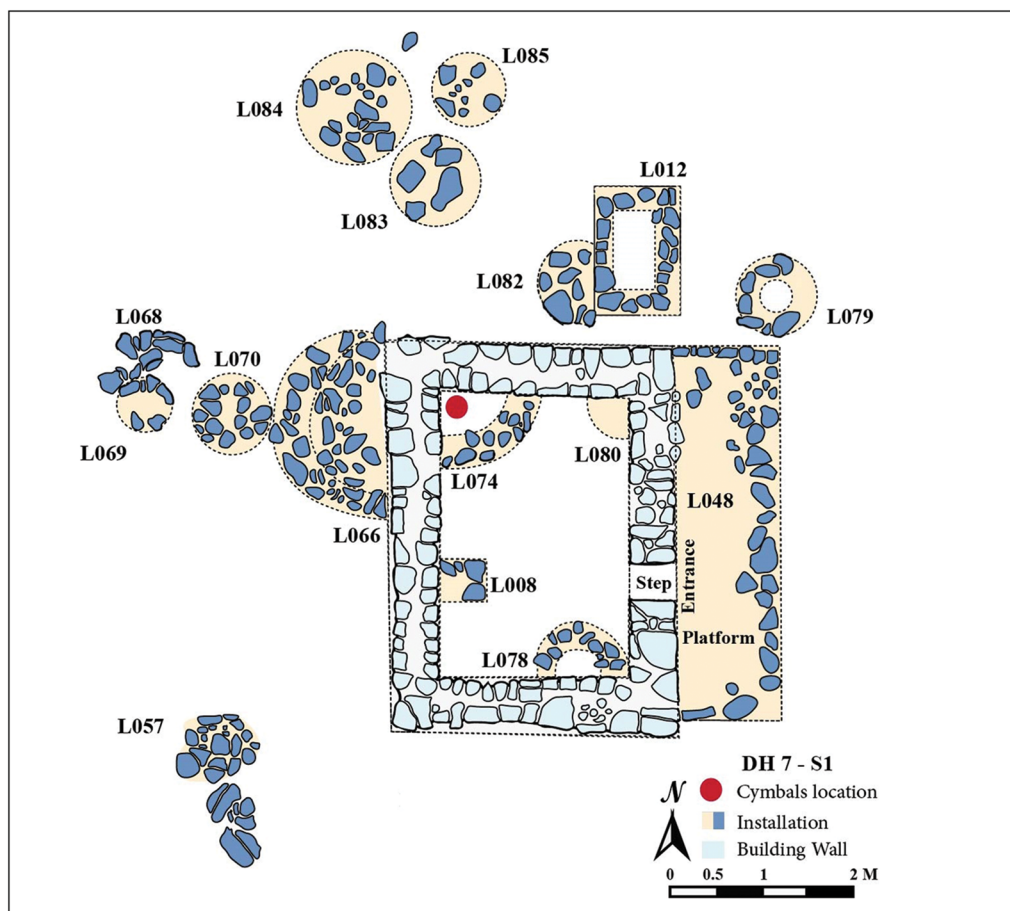


Figure 4. Plan of phase 1 of building S1 (drawn by A. Akhter).

location of the cymbals is related to the installation. The fill layer also yielded four small pieces of furnace wall lining, two small pieces of copper slag and one small Umm an-Nar ceramic sherd, and, following deposition of the fill, a new floor of flat stone slabs (L009) was laid on top. The careful placement of the cymbals in the fill layer that was subsequently covered by the stone slab floor suggests they were a votive deposit (Osborne 2004: 8; Douglas *et al.* 2024).

Fragments of a double-spouted Umm an-Nar period vessel were recovered from the stone slab floor. Spouted jars were produced from the late Umm an-Nar period onwards (Frifelt

Table 1. Radiocarbon dates from building S1 in DH7 (University of Georgia Center for Applied Isotope Studies). Calibrations calculated with OxCal v4.4.2 (Bronk Ramsey 2009) with r:5 Atmospheric data from Reimer *et al.* (2020).

UGAMS#	Sample ID	Material	Age BP	95.4% cal BC
51564	DH7:S.1-1	Charcoal	3850±25	2456–2204
51565	DH7:S.1-4	Charcoal	3790±25	2296–2138



*Bronze Age cymbals from Dahwa*

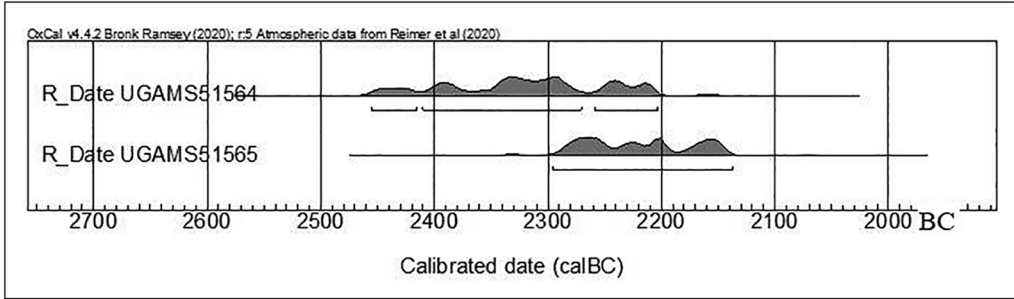


Figure 5. Probability distributions for radiocarbon dates from building S1 (OxCal v.4.4.2: Bronk Ramsey 2009), using the IntCal13 calibration curve (Reimer et al. 2020) (figure by authors).

1995: 58, figs. 80, 182, 183, 200), becoming more frequent in the following Wadi Suq period (2000–1600 BC)—when they are associated with communal consumption (de Vreeze 2016)—but double-spouted jars are not found anywhere else in south-east Arabia. This vessel was perhaps connected to libation or the communal consumption of liquids and its best parallel probably comes from the nearby settlement at DH1, where a pot with a single spout was found in building S20 (Al-Jahwari & Douglas 2021a: figs. 12 & 13).

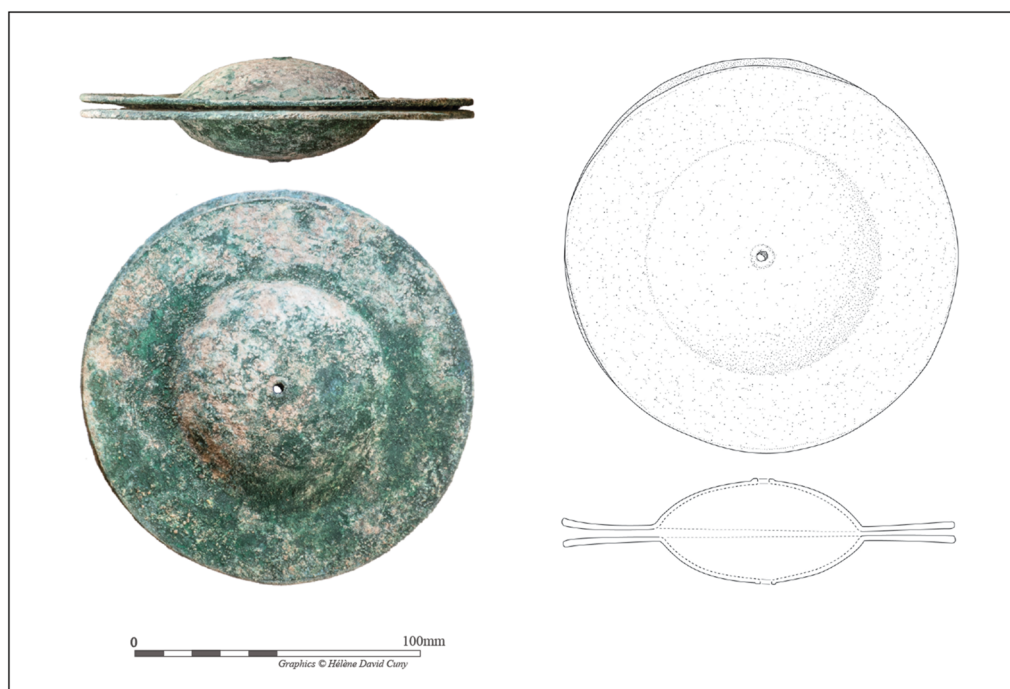


Figure 6. The cymbals after removing part of the fill layer, to the right are remains of the pavement floor (L009). Inset, the two cymbals lie on top of each other, perfectly aligned (photograph by Y. Al Rabbi).

## Description of the pair of cymbals

The cymbals are identical in shape and size. Neither show surface damage, supporting the idea of a deliberate and careful deposition. Both are circular, with an outer diameter of 138mm and an embossed middle (17mm deep and 76mm in diameter) that is perforated by a 4.2mm-diameter hole. The walls of the cymbals are thin, with a thickness of 1.5–2mm that increases slightly at the edges where it reaches 3mm (Figure 7). The combined weight of the cymbal pair is 254.3g. Over the millennia of being buried in the ground, the cymbals became corroded together. When trying to separate the pair, two small fragments detached from one of the sides; one of these was submitted for chemical analysis using portable x-ray fluorescence (see online supplementary material (OSM) for technical details).

The surface of the fragment shows a green colouration consistent with copper oxidation products typical for copper-rich materials that have been in contact with the atmosphere for an extended period. Carbonate, clay agglomerations and secondary copper minerals are also present on the surface. The fragment is predominantly composed of the red copper oxide cuprite ( $\text{Cu}_2\text{O}$ ), which is being replaced from the outside by bright green atacamite ( $\text{Cu}_2\text{Cl}(\text{OH})_3$ ). As cuprite is not stable over time when exposed to the atmosphere, this replacement is to be expected. Tellingly, however, no metallic copper ( $\text{Cu}$ ) is visible in the fragmented piece, even under the microscope, indicating that the cymbals have corroded to cuprite while other objects at the site preserve a much higher copper content (Al-Jahwari *et al.* 2021).



*Figure 7. Photograph and drawing of the cymbal pair (figure by H. David-Cuny).*

The chemical analysis of the cymbals provides two key insights. First, drawing on comparative compositional data from the region (Begemann *et al.* 2010: 146, fig. 2b), the chemical composition of the cymbals fits a Bronze Age date, with all the analysed elements falling within ranges previously reported for Umm an-Nar copper ores, ingots and artefacts (Figure 8). Particularly in terms of arsenic (As) and nickel (Ni) concentrations, the Dahwa cymbals are more compatible with Bronze Age artefacts. They also show considerable overlap with values from Wadi Suq period artefacts, although the higher value of antimony (Sb) fits the Umm an-Nar period more closely. Lower compatibility is seen with Iron Age objects from the region. It must be noted, however, that there is enough variation in the analysed assemblages from these two periods to negate the exclusion of a later date based purely on chemical composition.

The second insight concerns the origins of the copper. The presence of gossans, the oxidised decomposed rock forming the outer part of metal ores, and copper sulphide in a

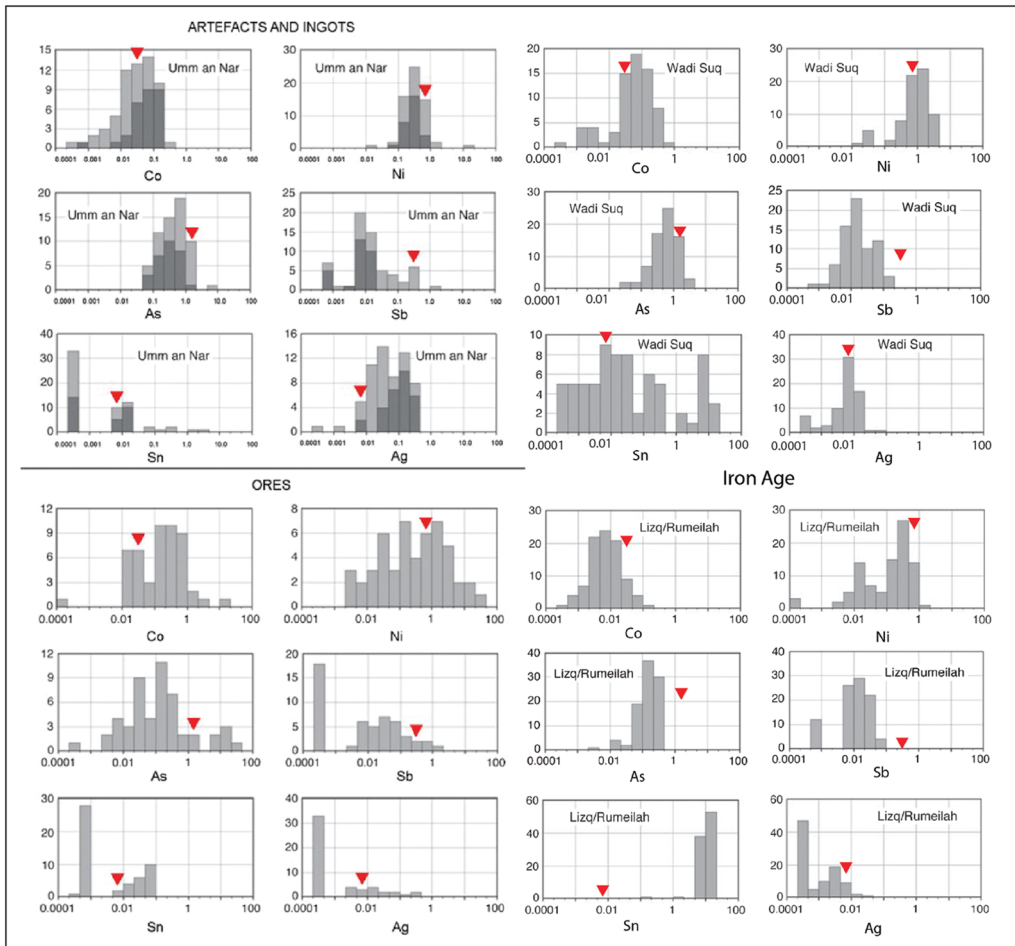


Figure 8. Concentration of specific chemical elements in the Dahwa cymbals compared with artefacts from the Umm an-Nar and Wadi Suq periods and the Iron Age (after Begemann 2010: 146, fig. 2b).

Black-Slip Indus-style storage jar at DH1, as well as slag from copper working (see Table S3) found at Dahwa, suggest a mafic rock origin of the copper mined around Dahwa. The higher As, Sb and Pb (lead) concentrations in the fragment suggest that the cymbals were not made from mafic copper sources (see Table S2) in the immediate vicinity of Dahwa, but from copper possibly originating some 170km south-west, from Nujum near Muscat (Prange 2001: tab. 36; Begemann *et al.* 2010: 166, app. 1, 167, app. 2). The cymbals thus appear to have been cast from ultramafic copper sources, which are well known in Oman. Lead isotope analysis of the cymbals seems to support their Omani provenance, with ore originating either from Nujum or from Maysar copper sources, where extensive Umm an-Nar period copper extraction is known (Figure 8; Hauptmann & Weisgerber 1981; Begemann *et al.* 2010). Ongoing analysis should help to refine this picture.

## Cymbals in the archaeological record

Issues of preservation affect our understanding of prehistoric musical traditions; musical instruments made from perishable materials, such as reeds and wood, tend not to survive in the archaeological record but bone and metal instruments can persist. Copper-alloy cymbals are among the relatively rare musical instruments recovered from Bronze Age contexts in the Near East (Braun 2002; Dumbrill 2005; Kolayda 2014; Smith 2021). These percussive instruments are found from as early as the third millennium BC in Mesopotamia and the Indus Valley, with Levantine examples appearing from the second millennium BC onwards.

The closest temporal parallels for the Dahwa cymbals are found at Mohenjo-daro in the Indus Valley, in modern-day Pakistan. These date to the mid-third millennium BC (Marshall 1931: III, pl. CXLII, nos. 1–3, 7 & 8). Sachs (1940: 151) initially drew attention to these round copper alloy objects with a central boss and “softly sloping and slightly turned up brim” as possible cymbals, or at least “precursors of the musical instrument”, although he considered their use as pot lids more likely. Yule (1985: 17, tabs. 15.123–28), proffering examples from Mohenjo Daro, Harappa and Chanhudaro (Figure 1), also suggests that some of these objects might indeed be cymbals (Figure 9). Their identification as musical instruments, however, remains unverified.

The Dahwa cymbals, found *in situ* as a pair, negate an identification as lids and, by extension, support the identification of at least some of the morphologically similar objects from Mohenjo Daro and other Harappan sites as cymbals. Such a cross-regional comparison is strengthened by the rich evidence at Dahwa for contact with the Indus Valley (Al-Jahwari *et al.* 2018; Douglas *et al.* 2021).

Archaeological examples are also known from the third-millennium BC Sumerian city-state of Ur in Mesopotamia, attesting to considerable contact with south-east Arabia and the Harappan world (Woolley 1934), while Ur III and Old Babylonian texts make mention of a wide range of metal percussive instruments including cymbals and sistrums (a form of rattle) (Shehata 2014: 108). The cemetery at Ur yielded an extensive array of musical instruments, including bull-headed lyres and a cymbal pair, the latter from the ‘death pit’ PG/1339 (Woolley 1934: 35, 126, fig. 21, 330). Similar examples found in graves at nearby Kish were initially regarded as weapons (Mackay 1929: 160–61, pl. XXXIX, 6; LXI, 2.4; 10–11) but later reinterpreted as musical instruments based on their contextual association



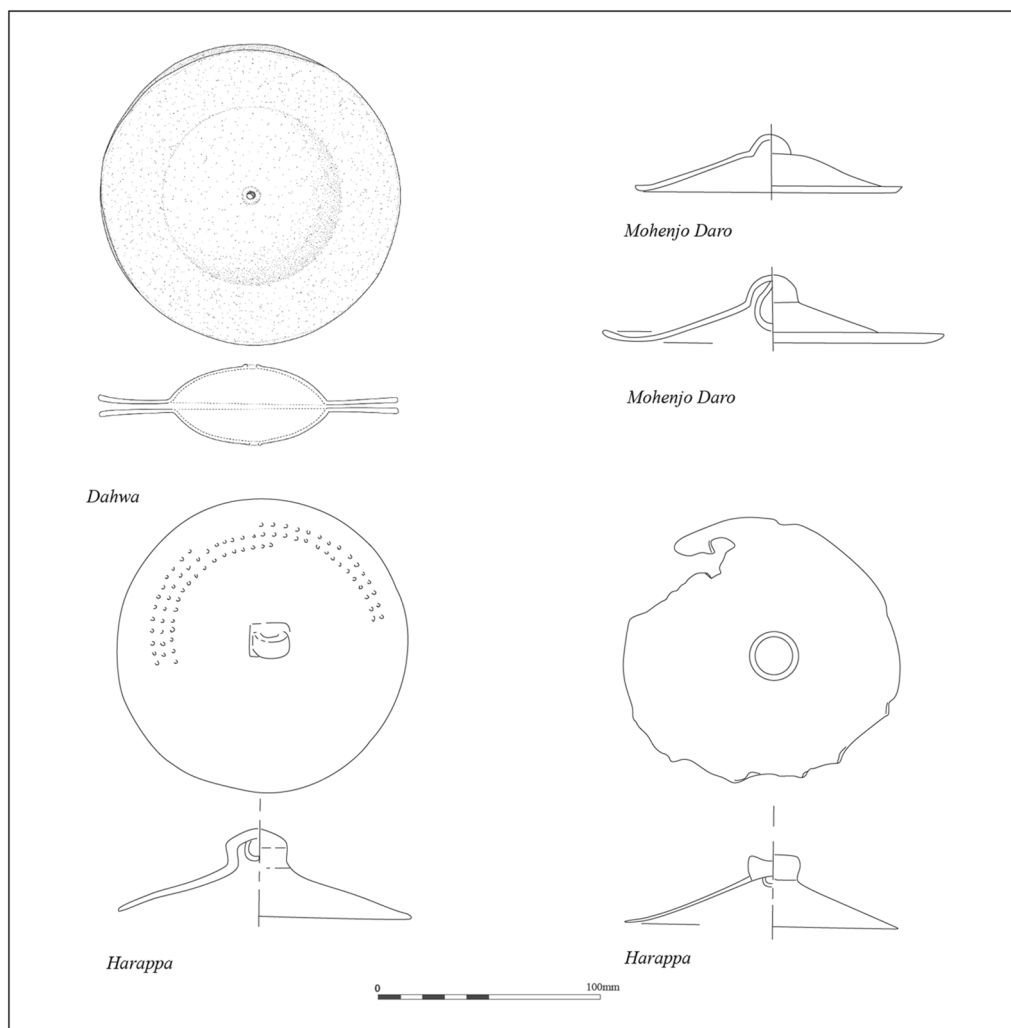


Figure 9. The Dahwa cymbals compared with Harappan examples (after Yule 1985: 17, tab. 15).

with a lyre and the depiction of both instruments on a cylinder seal (Woolley 1934: 127, fig. 23: PG/1054). However, these ‘cymbals’ consist of curved strips of copper and are morphologically closer to clappers or castanets, thus representing a distinctly different tradition from the Dahwa examples. Dumbrill (2005: pls. 81–83) identifies rounded cymbals originating from graves at Ur, but these are probably later in date and originally from the Assyrian city of Nimrud (see also Kolyada 2014: fig. 4.10).

Indirect evidence for copper-alloy cymbals in Mesopotamia comes from the late third millennium BC (c. 2200–2000BC), during the Ur III period and the rule of Gudea. A stele fragment held in the Louvre (Gudea AO4578) might have shown a musician holding cymbals, although the area where the cymbals would have been illustrated has broken off. A similar scene, possibly a fragment from the late-third millennium BC Ur-Namma stele, shows a musician playing a pair of round cymbals (Figure 10) (Barnett 1960: pl. XXVIIa) and



Figure 10. A cymbal player on a stone fragment of the Ur-Nammu stele, possibly late third millennium BC (after Barnett 1960: pl. XXVIIa).

may be reconstructed as part of a procession of drummers and cymbal players (see Suter 2000: fig. 247). Among the instruments mentioned in texts from this period, Šem/Si-im/Se-em appears to designate cymbals (Gabbay 2010: 24; Mirelman 2010: 40–41; Shehata 2014: 110; Sánchez Muñoz 2019: 44–45; Smith 2021). This instrument is mentioned 15 times in Gudean period texts (Sánchez Muñoz 2019: 45) and Gabbay (2010: 24–25) suggests it was used by both *gala* (lamentation) and *nar* (cultic) singers and was thus closely associated with ritual activities. Together with the ‘ala’ drum, also visible on the Gudea and Ur-Nammu stelae, cymbals are part of the suite of instruments depicted in ritual events such as the construction of a

temple. One of the Gudea cylinders also describes the use of these instruments to commemorate the building of the Ningirsu temple at ancient Girsu in southern Mesopotamia: “As the ruler libated in the brick making shed with propitious water, *adab*-drums, cymbals (*si-im*) and *ala*-drums were playing for him” (Cylinder A xviii 18: Electronic Text Corpus of Sumerian Royal Inscriptions, n.d.).

Parallels for the Dahwa cymbals are also found at Susa, the capital of Elam in the lower Zagros Mountains. These include similar embossed round cymbals, many of which are held at the Louvre (for example, Louvre collection: SB 12770a-b) and seem to have come from the 1902–1908 excavations of votive deposits at the Inshushinak temple, dated to c. 1500–1200 BC (Gasche 2009). The deposits likely include heirlooms from previous activity at the temple, meaning that the cymbals could substantially antedate the votive offering.

At least 28 round embossed cymbals are also found in the Levant from as early as the Late Bronze Age (1500–1300 BC) (Caubet 1987; Braun 2002: 7, 21, 29, 109). These can be grouped into two categories by size: larger cymbals with diameters from 70–120mm and smaller cymbals with diameters from 30–60mm (Braun 2002: 109). These Levantine cymbals, when well preserved and restored, still produced a bright ringing tone (Braun 2002: 109). Braun (2002: 109) suggests that the round, plated cymbals were a local Levantine Late Bronze Age invention that subsequently found its way into Mesopotamia and Egypt during the Iron Age (900–700 BC), but the Dahwa cymbals, together with the Harappan examples and the iconography from Mesopotamia, challenge this interpretation of cymbal chronology.

## An early, shared tradition of round, embossed cymbals

There is rich evidence of contact between Mesopotamia and the Indus Valley in the Ur III period (Aruz 2003; Laursen & Steinkeller 2017; Frenz 2020). The Dahwa cymbals share

similarities with possible Indus cymbals and cymbals at contemporaneous late-third-millennium sites in southern Mesopotamia, which further demonstrates inter-regional contact. Although problematic in terms of chronology, the Elamite cymbals from Susa also fit within the emerging picture of a pan-south-east-Asia use of round, embossed cymbals.

The Gudea Cylinders again offer a useful image to further this interpretation. They indicate that during the construction of the Ningirsu temple by Gudea, “Elamites came to him from Elam, and Susians came to him from Susa. Magan and Meluḥa came from their mountains in submission” (Cylinder A xv 6–9; Electronic Corpus of Sumerian Royal Inscriptions, [n.d.](#)). Dahwa, with its strong Indus affinity, suggests that cymbals could have become part of a highly connected late third millennium world where instruments and musicianship were shared between Oman, the Indus, Iran and Mesopotamia.

## **The social context of cymbals at Dahwa**

The inclusion of cymbals in ritual processions such as during the construction of the temple by Gudea is a striking reminder of the potential ritual role of these instruments and of music more generally. Yet little information is currently available concerning religion and religious practices during the third millennium BC in Oman. The use of communal burial structures during the Umm an-Nar period suggests that ancestor worship held a key role in local societies (Magee 2014: 120; Cleuziou & Tosi 2020), but religious practice outside of funerary contexts has poor archaeological visibility through the Bronze Age, with clearer cultic constructions only visible from the Iron Age onwards (Benoist 2007; Magee 2014: 237; Gernez *et al.* 2017). Dahwa potentially adds crucial evidence for non-funerary ritual activity; building S1 is only the second Bronze Age structure in south-east Arabia associated with cultic activity, the other is at the site of Umm an-Nar island, where a rectangular room was lined with several anthropomorphic statues (Al-Tikriti 2011).

It is possible that regular contact with both the Indus Valley and Mesopotamia introduced new ritual or religious concepts into south-east Arabia, such as those already illustrated for the rule of Gudea. Yet the religious framework of Harappan society is itself unclear and contested (Possehl 2003: 141–42), and interpretation of possible activities shared between the regions necessarily relies on visible similarities in material culture.

Little is known about the specific role or roles of music in Harappan society, but iconic representations of dancing—as seen in the bronze statue of the ‘dancing girl’ from Mohenjo Daro (Possehl 2003: 112–13)—suggest that dancing and by extension music were also probably important elements of daily life. Across the wider Near East, cymbals are consistently associated with ritual activity (Braun 2002: 20–21; Shehata 2014; Smith 2021). This may be seen in Mesopotamia in the earliest textual references to cymbals during the rules of Gudea and Ur-Nammu. In the Levant, cymbals are found in temple deposits, such as at Pella (Bourke 2004: 20, 21, fig. 14), and were likely a component of musical activities associated with temple rites. A similar interpretation may be proposed for the cymbals from the Elamite temple deposits at Susa and, pending further studies, it is hypothesised that the Dahwa cymbals represent a similar connection between cult, music and dancing.

## **Cymbals as cultic links in creating communities**

Our understanding of the nature of cultural relations between various groups in Bronze Age Oman is still in its infancy, but the archaeological record reflects a rich mixture of cultural traditions that found common ground in the collective practices of the time. Much ground remains to be covered in defining these complex relationships, deploying bioarchaeological methods successfully implemented in other regions (e.g. Knipper *et al.* 2017). The intermingling of communities with various backgrounds, as is likely the case at Dahwa, can expose social tensions; in such an environment, shared acts of making music, dancing and perhaps performing cultic activities could have helped to build stable communities. In this light, the dancing scenes that become a common decorative feature in south-east Arabia in the early second millennium BC with the transition to the Wadi Suq period, as visible on painted spouted jars connected with communal consumption (de Vreeze 2016), reveal more than just an appreciation of dancing. The sound of cymbals in the highest building of the settlement at Dahwa might have resonated against the sides of the hills and been heard by most inhabitants, perhaps even further along the valley. The discovery of the Dahwa cymbals encourages the view that already during the late third millennium BC, music, chanting and communal dancing set the tone for mediating contact between various communities in this region for the millennia to follow.

## **Conclusion**

The copper-alloy cymbals uncovered in building S1 at DH7 are a unique find in south-east Arabia but fit within a larger, regional distribution of similar percussive instruments around the Arabian Gulf that arose in the late third millennium BC and then spread across the wider Near East in the following millennium. The purposeful deposition of the Dahwa cymbals echoes the presence of cymbals in votive offerings in Mesopotamia and the Levant, and their morphology provides links to the Indus Valley. From their inception, cymbals appear to have been tied to ritual activity and temple settings and the discovery of the pair at Dahwa, where Umm an-Nar and Indus artefacts coexist, suggests that music and musical instruments were important cultural components of inter-regional contact and co-operation around the Arabian Gulf. The potentially multifaceted role of music in the social and ritual lives of Bronze Age communities remains a question for future research.

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## Online supplementary material (OSM)

To view supplementary material for this article, please visit <https://doi.org/10.15184/aqy.2025.23> and select the supplementary materials tab.

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