Radiocarbon, Vol 66, Nr 1, 2024, p 205–248 DOI:10.1017/RDC.2024.24

HORIZONTAL WATERMILL CHRONOLOGIES BASED ON ^{14}C DATING OF ORGANICS IN MORTARS: A CASE STUDY FROM JARASH, JORDAN

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ABSTRACT. Horizontal watermills in the southern Levant have proved difficult to date. This study investigates the use of radiocarbon (^{14}C) dating of various organic carbon fractions in structural mortars and carbonate deposits to identify *terminus post quem* (TPQ) construction dates for seven arubah watermills and two chute watermills in northern Jordan. Dating results from the various organic fractions are discussed in the contexts of carbon fraction integrity and mortar type. The arubah watermill construction dates fall into two chronological groups. Four arubah watermills have Middle Islamic (late 12th to early 14th century AD) construction dates based on macrocharcoal and bulk organic fraction ages, whereas the bulk organic fraction ages of two earlier arubah watermills straddle the Byzantine-Early Islamic transition. Their possible fifth to seventh-century construction dates are among the earliest in the southern Levant. Limited ^{14}C data from the chute water mills suggests that the earliest may date to the sixth–seventh century period, concurrent with the older arubah watermills. The study supports the viability of the AMS ^{14}C method to provide estimated TPQ construction dates for watermills, providing caution is exercised. Short-lived macrocharcoals have the highest integrity but are subject to severe sample loss during pretreatment. ^{14}C ages from humic and humin fractions in earthen mortars are influenced by "old carbon" contamination, possibly a soil reservoir effect, and are centuries older than the probable construction date. Attention is drawn to the potential use of arubah carbonate deposits as proxy records of water flow, watermill use, and hydroclimate.

KEYWORDS: arubah, chute watermill, horizontal watermill, Middle Islamic, mortar, carbonate deposits, radiocarbon dating, macrocharcoal.

INTRODUCTION

Watermill ruins are relatively common in parts of the southern Levant;[1] however, the dating of their construction has often proved difficult or inconclusive because of poor preservation, the absence of archaeological excavation, or the lack of material that can be reliably dated. Interpretational complexities include difficulty distinguishing original constructions from later modifications or the erroneous early attribution of the construction date due to the reuse of pre-existing water supply infrastructure. The accurate dating of watermills is fundamental to understanding the chronology of the technology's introduction and spatial diffusion. This paper is a case study into the absolute dating of watermill construction and use by radiocarbon analysis (^{14}C) of organic fractions in construction mortars and secondary calcium carbonate deposits in nine horizontal watermills in the Jarash district in northern Jordan.

The case study stems from the author's doctoral research that included the ^{14}C dating of macrocharcoal inclusions in mortars from various aqueducts in the Jarash district in northern Jordan (Boyer 2022:190–192) and similar research by others (Lichtenberger et al. 2015; Philippsen and Olsen 2020; Daugbjerg et al. 2021; Passchier et al. 2021). Under the auspices of the Jarash Water Project (JWP), the author's doctoral research identified likely 12th–13th century AD construction dates for two horizontal watermills—the so-called "Germanus" (WED-01) and the "North Gate" (WJ-02) watermills (Boyer 2022:352), highlighting the potential for the broader application of ^{14}C dating to watermills in the district.

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[1]The term *southern Levant* includes Lebanon, southern Syria and the countries and territories bordering the Jordan River.

The two watermills in the JWP doctoral study (WED-01, WJ-02), a watermill at Ein Gedi beside the Dead Sea (Hadas 2001) and a watermill in Iraq (Usta and Tonghini 2023) are the only published examples known to the author of ^{14}C dating of organic materials (*OM*) in horizontal watermills in the Middle East. Several European watermill studies have obtained ^{14}C dates from wooden mill components, especially mill-wheels (Rynne 2015; Jessen 2017); however, these components are rarely preserved in the southern Levant. There have been no published ^{14}C dates of OM from watermill carbonate deposits. ^{14}C dating has been previously used to date lime binders in mortars and plasters in the study area, a technique often known as "mortar dating" (Lichtenberger et al. 2015; Boyer 2019; Philippsen and Olsen 2020). The preparation and analysis of these samples are more complex than the ^{14}C dating of OM: sample materials often prove unsuitable due to contamination by carbon from unburnt limestone, groundwater, or recrystallized carbonate. Hydraulic *cocciopesto* mortars have also been found to be unsuitable for mortar dating (Daugbjerg et al. 2021:16). The current study adopted the ^{14}C dating of OM because of the near-ubiquitous presence of macrocharcoals in the watermill mortars, the relative simplicity of the analytical approach compared to lime binder dating, and the limestone contamination problem often encountered when dating lime binder in local mortars.

The two horizontal watermills previously dated by the JWP were included in an expanded case study involving samples taken from a total of nine horizontal watermills with the aim of obtaining absolute dates for their construction and use in the context of the known archaeology of horizontal watermills in the southern Levant (Figure 1). These watermills were selected on the basis that they were representative of the extant horizontal watermills in the study area and the availability of sample material for dating. The case study area is identical to the one adopted in the author's doctoral research. The studied watermills were supplied from surface and underground (spring) sources within the watersheds of the Jarash Valley and the Majarr-Tannur Valley, and the outer limits of these watersheds form the study area boundary (Figure 2). The case study included six isolated watermills plus three watermills in a cluster adjacent to the ancient city's southern Watergate that were investigated in more detail. The ^{14}C dating results are considered in the context of the sample type, organic fraction, watermill type and architecture. ^{14}C dates were mainly obtained from hydraulic and non-hydraulic (i.e. aerial) mortars; however, carbonate deposits from several mill-races and penstocks were also dated. Comparisons are made between ^{14}C dates obtained from different organic fractions of the same sample at several sites.

BACKGROUND

Historical Context

The Jarash study area lies in the uplands of northwestern Jordan. A benign physical environment that combines a Mediterranean climate, moderate annual rainfall, natural springs, and rich soils attracted settlement to the area from Neolithic times. A small Hellenistic colony (Gerasa) was established beside the wadi on the site of modern Jarash by the second century BC, one of the founding settlements of the Decapolis. A substantial town was established under Roman rule in the early centuries of the Christian era. Gerasa persisted as an urban centre until at least the 10th century (Walmsley 2011:142), although gradually diminished by repeated earthquake damage, climate change, and socioeconomic factors. Strong spring flows in the Hellenistic and Roman periods sustained extensive aqueduct networks and perennial flow in the Jarash and lower Majarr-Tannur valleys. Much of the Roman aqueduct network had failed by the Early Islamic period, probably due to frequent

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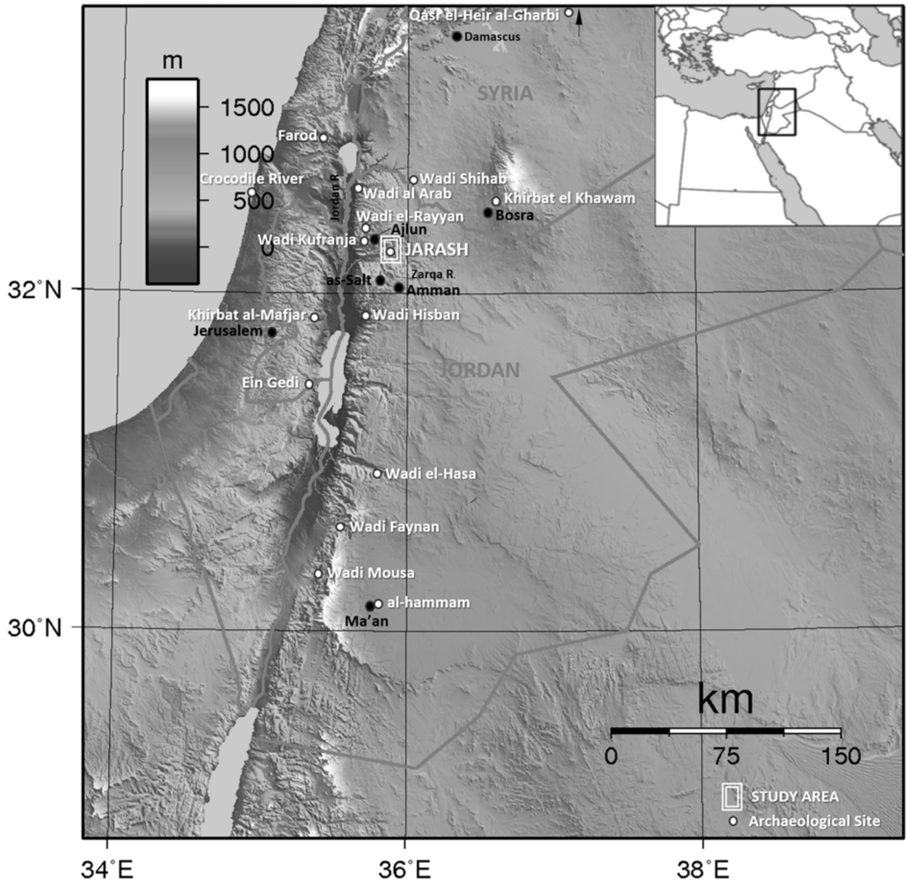

Figure 1 Location of the study area and other sites mentioned in the text. (Base plan, Wikipedia Commons).

earthquake damage and a lack of maintenance (Boyer 2022). A village-sized community is attested in Jarash ("Jaraš") in the Mamluk–early Ottoman period by archaeological excavation and Ottoman tax records (Hütteroth and Abdulfattah 1977:164; Peterson 2018); however, permanent settlement ceased sometime after the late 16th century until revived by the arrival of Circassian colonists in 1878 (Al-Soub et al. 2015).

The earliest archaeological evidence of water power in the study area is the late sixth-century vertical-wheeled water-powered sawmill for cutting stone blocks constructed in the abandoned second-century Temple of Artemis in the ancient city (Seigne 2002; Seigne and Morin 2007, 2008). Before the case study, archaeological evidence of the timing of the introduction of the horizontal watermills in the study area was limited to the dating of the two watermills in the JWP study to the 12th–13th centuries (Boyer 2022). Sparse historical records assist in partially filling the knowledge gap between the sixth-century sawmill in the city and the expansion of watermill activities in the Jarash Valley following the establishment of the Circassian colony in the late 19th century. Yaqut (1179–1229), a Muslim geographer writing in 1225, noted a river that operated several watermills in Jarash (Le Strange 1890:462). Another piece of written historical evidence comes from the Early Ottoman taxation returns for 1596–1597, which record the taxing of watermills (Hütteroth and Abdulfattah 1977:164; Peterson 2018).

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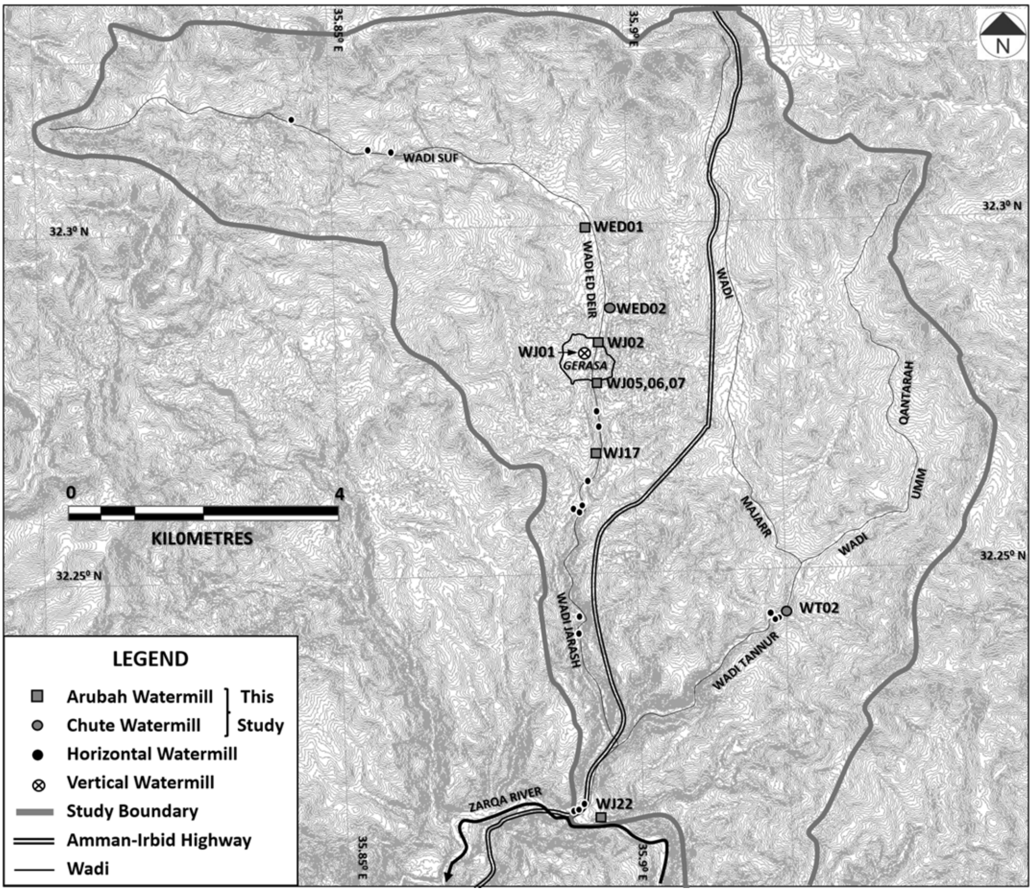

Figure 2 Location of watermill sites included in the current study. Watermill site numbers are prefixed according to the wadi in which they are located: Wadi ed Deir (WED-), Wadi Jarash (WJ-), and Wadi Tannur (WT-).

The dating of the two JWP watermills also demonstrates the partial restoration of the spring-fed aqueduct network and the use of the wadi streams to supply the watermills by the Middle Islamic period. Seven centuries later, the Circassians expanded this restoration to the limits of available water resources (Schumacher 1902:119; Huntington 1911:280), with the majority supplied via wadi stream diversion canals. Photographic evidence suggests that some of these watermills remained in use until at least 1918.

Physiographic Context

The study area is subject to a biseasonal Mediterranean-type climate, with rainfall confined to a season from October to April. The average annual rainfall at the Jarash bridge (Zarqa River) between 1980 and 2013 was 372.4 mm (Shammout and Abualhaija 2020:3044, table 1). The rainfall is sufficient for dry farming; however, there is strong interannual variability due to changes in the track and duration of eastern Mediterranean cyclones, exacerbated by a steep hydroclimatic gradient east of the Jordanian highlands (Shehadeh 1985; Boyer 2022:35–36). The rainfall recharges the predominantly karstic aquifers that supply many springs in the study area. Surplus surface runoff discharges into the wadis, but the bulk of wadi stream flows are derived from the surplus spring discharges that are not otherwise diverted for agricultural use (Boyer 2022:57–70). There is currently a small perennial flow in Wadi Jarash south of the city; however, wetter climatic regimes would have ensured more significant perennial stream flows in the Jarash Valley and Wadi Tannur historically.

Palaeoclimate proxy data from a Roman aqueduct to Jarash confirms that a biseasonal climate also prevailed in the first to third centuries AD (Passchier et al. 2021). Flow rate estimates from spring-fed aqueducts in the same period show that spring flows were substantially higher than today, reflecting a wetter climatic regime (Boyer 2022:163–165). These strong flow rates are consistent with regional hydroclimate proxies that indicate that, apart from periodic drought phases, a wet climatic regime persisted in the southern Levant from the second century BC to the sixth–seventh centuries AD (Rambeau and Black 2011; Izdebski et al. 2016). The Medieval Climate Anomaly period (AD 1000–1200) was marked by cool, dry conditions in the southern Levant (Lüning et al. 2019; Kushnir and Stein 2019) and was followed by a return to humid conditions in the 13th to early 14th centuries in the early Mamluk period (Xoplaki et al. 2018:371–372). Regional hydroclimate proxies point to a return to drier conditions after the mid-14th century (Xoplaki et al. 2018:372).

Water supply in the city area became increasingly impacted by climatic change and seismic events in the sixth to eighth centuries, and these factors would also have impacted water supply and agriculture across the study area (Boyer 2022:106–109). Earthquake impacts would have exacerbated periodic water supply problems for watermill operators resulting from climatic factors and competing demands from irrigators who shared the water sources. The study found evidence of direct structural damage to most watermill head races and concomitant damage to supply canals. All major aqueduct networks in the study area dating to the Classical period suffered catastrophic damage, and it is unlikely that they survived the mid-eighth-century earthquakes intact (Boyer 2022). The mid-eighth-century earthquakes that devastated the region are among the best-documented major seismic events with a moment magnitude (M_w) ≥ 7 (Tsafrir and Foerster 1992; Ambraseys 2009:234–238; Grigoratos et al. 2020:821–822). These events caused much damage and social upheaval in the city area (Jørgensen 2018; Lichtenberger and Raja 2019; Boyer 2022:71–77). However, later earthquakes with an Mw ≥ 7, including AD 1033, 1202, and 1458, would have probably impacted the watermills dating to the Middle Islamic period identified in this study.

Watermill Technology

Watermills harness water flow energy to turn a mill-wheel that, in turn, drives one or more pairs of millstones. Fundamentally, they can be divided into horizontally- and vertically-wheeled types.[2] The wheel in a horizontally-wheeled watermill (*horizontal watermill)* rotates in a horizontal plane and has a vertical shaft directly connected to the upper (runner) stone in a pair of millstones above the mill-wheel chamber. In a vertically-wheeled mill (*vertical watermill*), the mill-wheel has a horizontal shaft and turns in a vertical plane. Since millstones rotate about a vertical axis, vertical watermills must be geared to convert the energy from the horizontal shaft to the vertical shaft connected to the millstones. Texts from Antiquity demonstrate the existence of both vertical and horizontal waterwheels by the third century BC (Lewis 1997:26–36; Brun 2016:24; Wilson 2020:149).

[2]See Moog (2019: 3–5) for a summary of designations.

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Regardless of watermill type, each mill-wheel is driven by water flow delivered by a penstock in the form of a pipe, chute, or shaft. Further typological subdivision is possible based on the penstock's placement, declination, or design. The mill-wheel rotation could directly or indirectly drive mechanical devices in diverse industrial roles (Smith 1977:228; Brun 2016:40–44; Wilson 2020:167–184). Most watermills in the southern Levant were probably employed to grind grain, but the sixth-century Jarash mill is a sawmill for cutting stone and many in the Jordan Valley were used for crushing sugar cane (Abu-Dalo 2010).

Vertical watermills can be divided into overshot, breast-shot and undershot types, depending on the elevation of the head race relative to the mill-wheel. Many vertical watermill sites from Antiquity, especially the first four centuries of the Christian era, have been archaeologically attested in Europe (Wilson 2020). However, few are attested in the Levant (Brun 2016; Wilson 2020). The sixth-century watermill-powered stone saw in Jarash, already described, is the only example of an overshot mill in the southern Levant, and an installation at Qasr al-Hayr al-Gharbi in Syria may be the only example of a breast-shot watermill (Genequand 2016:517). Examples of undershot mills include installations built into the outflow of two dams on the Crocodile River near Caesarea Maritima (Ad et al. 2005; Porath et al. 2007:86).

The current case study focused on horizontal watermills. These installations are common in the study area and the southern Levant. A vigorous debate has ensued on how they should best be categorized, which has generally focused on variations in mill-wheel blade design (Wilson 1960; Cresswell 1993; Kreiner 2000). A concise compendium of the critical points under debate is provided by Moog (2019:23–24, table 5). A horizontal watermill typology based on the type of water conduit delivery, the nature of the mill-wheel construction, and the blade form in the mill-wheel has been suggested by Moog (2019:25, table 6); however, reliable evidence of mill-wheel construction and blade morphology in the southern Levant is absent before the late Ottoman period. Consequently, the horizontal watermills described in the current study are differentiated into two fundamental types based on the design of the penstock that delivers water to the mill-wheel:

- The penstock is an open chute inclined down a slope and not contained in a tower (hereafter, *chute watermill*), and
- The penstock is an enclosed vertical cylindrical chamber or arubah (Avitsur 1960) within a stone tower that is typically 4–10 m high (hereafter, *arubah watermill)*.

Gardiner and McQuitty (1987) and Schriwer (2015:8–9) recognized similar basic typologies and suggested several architecturally based sub-types. The arrangement of the horizontal mill-wheel, the mill-wheel chamber and the paired millstones are the same for chute and arubah watermills.

The earliest attested horizontal watermills are from the western Mediterranean. They include two chute watermills from the Côte d'Azur region of France: a watermill at Saint-Martin (Taradeau), which operated between the second and fifth centuries (Bérato 2004:76–78), and a watermill at Le Cannet-des-Maures dated from coins and ceramics to the fourth century (Martos 2001:157). From the latest research, the remarkable turbine mills at Chemtou in Tunisia may have a fifth-century TPQ (Wilson 1995; Hess et al. 2017:63–97). In contrast, the earliest attested chute watermill (Ein Gedi) in the southern Levant is from the sixth–seventh century and the earliest attested arubah watermill (Khirbat al Khawam) is from the eighth–ninth century (Table 1).

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Table 1 Published dates of early horizontal watermill sites in the southern Levant/Middle East (dating reliability is variable).

Watermill type	Site name	Location	Date	Dating method	Reference
Arubah	Kanatha	Syria	"Late-Hellenistic-Imperial Roman"?	Relies on the dating of supply conduits	Ertel 2013:51–52; Ertel and Schnitzer 2015.
Arubah	Crocodile River	Israel	"AD 345–380"?	^{14}C	Schiøler 1989: 138.
Arubah	Farod	Israel	5th–6th?	Not stated	Avitsur 1971:402.
Arubah	Mosul ('BU1')	Iraq	cal AD 611–759 (1σ)	^{14}C	Usta and Tonghini 202:113.
Arubah	Khirbat al-Khawam	Syria	8th–9th	Artifacts	Genequand 2016:525
Chute	Ein Gedi	Dead Sea	AD 530–680	^{14}C	Hadas 2001:77.
Chute	Qasr el-Heir el-Gharbi (2nd phase)	Syria	8th	Archaeological context	Schlumberger 1939; 1986; Genequand 2006; 2016:514–517.
Chute	Khirbat al-Mafjar	Jordan Valley	8th	Archaeological context	Genequand 2016:520.
Chute	Ma'an	Jordan	8th	Archaeological context	Genequand 2003:28; 2016:517–521.
Chute	Khirbat al-Khawam	Syria	8th	Coins & ceramics	Blanc and Genequand 2007; Genequand 2016.

A detailed study of watermill ruins in Qanawat (Kanatha) identified evidence of early horizontal watermills supplied via conduits that were dated to the "late Hellenistic-early Imperial Roman" period (Ertel 2013:51–52; Ertel and Schnitzer 2015); however, the watermills themselves have not been dated definitively. Mortar from the Wadi Shihab watermill cluster in southern Syria is claimed to have been dated to the first century AD, but the supporting evidence has not been published (Schnitzer 2002; Ertel 2013:51, n. 24; Ertel and Schnitzer 2015:296). Schiøler's fourth-century AD radiocarbon date of a mortar sample taken from an Arubah watermill on the Crocodile River lacks supporting detail and has been questioned by Wilson (1995:506). A series of three arubah watermills at Farod (Israel) have been dated to the fifth-sixth century (Avitsur 1971:402) but without supporting evidence.

Watermill Studies in Jordan

Several regionally based watermill-focused studies have been conducted in the southern Levant (Avitzur 1960, 1971; Frankel 2007: Schriwer 2015). Watermill-focused research in the study area, however, is limited to a study of the already mentioned mid-sixth century water-powered stone saw (WJ-01) installed in the abandoned Temple of Artemis in Gerasa (Seigne 2002; Seigne and Morin 2008). Most horizontal mill studies in Jordan have focused on arubah watermills in the wadis draining the Ajlun Highlands, northwest of Jarash. A pioneering analysis of six watermills in Wadi al Arab (Gardiner and McQuitty 1987) was followed by studies of watermills and their technology in Wadi Kufranja (Malkawi 1994; Greene 1995) and considerations of mill typology by McQuitty (1995). The recovery of Mamluk-Ottoman pottery from five mill-houses in Wadi Kafranja is a rare example of the date of watermill installations being attested by excavation (Malkawi cited in MacKenzie 2002:619). McQuitty (2004) subsequently considered the dating evidence of watermills in the regional context. Historical studies of mills from the Ayyubid-Mamluk period were conducted by MacKenzie (2000, 2002, 2003) in the Ajlun district and the as-Salt district in the late Ottoman period by Rogan (1991, 1995). Al-Batayneh (2006) provided details of a restored tower mill in Wadi el-Rayyan.

Watermills have been recorded in several studies elsewhere in Jordan. The most detailed commentary concerns nine Islamic arubah watermills in Wadi Mousa near Petra (Al-Salameen 2019:296–303). MacDonald (1988:284–88) described 14 watermills located during a survey of the Wadi el Hasa district, but none was securely dated. Ibach (1987) mentioned 10 arubah watermills in Wadi Hesban that were tentatively attributed to the Ayyubid-Mamluk period on ceramic evidence. An arubah watermill in Wadi Faynan was supplied from a Roman reservoir; however, the period of watermill use has not been securely dated (Barker et al. 1999:278–281; McQuitty 2004:263).

Site Description and Sampling

Seven arubah and two chute watermill sites were included in the case study (Figure 2). Their locations and architectural details are summarized in Table 2.

The nine case study sites form part of a larger group of watermill sites identified during archaeological field surveys by the JWP (Boyer 2017:399–402, 2018:362–363, 2022:282–283) and the Jerash Hinterland Survey (JHS) (Kennedy and Baker 2008, 2009; Baker and Kennedy 2010, 2011). The availability of sample material determined the selection of watermill sites in the case study; however, they also represent a reasonable cross-section of watermill sites in the study area. Watermill sites in the Jarash district are rapidly disappearing due to modern

Table 2 Summary of watermill architectural details.

Watermill site		Latitude/longitude			Head race substruction		Head race		Tower dimensions (m)			
This study	JWP	Northing	Easting	Water source	Construction	Condition	Length (m)	Slope (%)	Arubah	Base	Height	Tower condition
Arubah Watermills												
WED-01	145	32.300920	35.892590	Spring?	1.6 m wide masonry walls with cemented rubble fill	Largely destroyed	38	?	0.68	—	5–6 m ?	Watermill built into pre-existing two-storey mausoleum, with the mausoleum substituting for the arubah tower and millhouse. Lower storey buried beneath masonry tumble
WJ-02	135	32.284269	35.894715	Wadi	1.0 m wide; Layers of mortared rubble faced with spolia masonry.	Largely intact	15	Not measured	≥ 0.8	3.2 x 3.1	>9.0	Intact
WJ-05	148	32.276187	35.893588	Spring?	0.8 m wide masonry wall	Destroyed	?	?	0.62	2.3 x 2.3 (est.)	>4.1	Tower stub only
WJ-06	148	32.276303	35.893419	Spring?	Short, 3 m wide; Cemented rubble fill faced with masonry-similar to tower	Intact	3	10 (est.)	?	3.5 x 3.2	>6.4	Largely intact
WJ-07	148	32.276190	35.893400	Wadi?	C. 1.0 m wide masonry wall	Partially destroyed	>10	?	0.38	3.0 x 3.0?	?	Lower part of arubah only; tower destroyed

(Continued)

Table 2 (*Continued*)

Watermill site		Latitude/longitude			Head race substruction		Head race		Tower dimensions (m)			
This study	JWP	Northing	Easting	Water source	Construction	Condition	Length (m)	Slope (%)	Arubah	Base	Height	Tower condition
WJ-17	140	32.267570	35.894323	Wadi	C. 1.0 m wide; Cemented rubble faced with spolia masonry; two arches	Largely intact. Evidence of earlier narrow masonry substruct-ion	20	Not measured	?	2.05 x 2.05	>6.0	Largely intact
WJ-22	149	32.214485	35.890963	Wadi?	Two bedrock canals 0.5 m wide	Largely destroyed	?	?	0.7	3.1 x 2.5 (est.)	>4.5	Tower stub only
Chute Watermills												
WED-02	184a	32.288061	35.896136	Wadi	1.0 m wide masonry wall	Largely destroyed	20	25-35				No Tower
WT-02	136	32.243721	35.924530	Wadi	1.0 m wide masonry wall	Partially intact	15	20				No Tower

farming and building developments, and the case study relied on archaeological evidence identified from a careful analysis of remote sensing imagery (satellite imagery and modern and historical aerial photographs) and ground photography in addition to ground surveys.

Wadi ed Deir

WED-01

This unique installation is a structural adaptation of a late second-century Roman mausoleum, the so-called Tomb of Germanus (Welles 1938:451–452, no. 219). The mausoleum floor plans were first sketched by William Bankes circa 1818 and redrawn by Charles Barry in 1819 (Seigne 2006:142; Boyer 2016:290). The site was first recognized as a watermill ("Tahunet es-samuri") at the end of the 19th century (Schumacher 1902:162–164) (Figure 3a). The watermill adaptation involved the construction of an arubah into the western end of the two-storey mausoleum, with the original Roman structure conveniently substituting for the conventional arubah tower and mill-house. The arubah height is estimated to have been 5–6 m (Figure 3b). The head race was supported on a masonry substruction supplied by a canal from Shawahid spring to the north. The disposition of the mill-wheel and milling floor is uncertain; however, they may have all been accommodated in the lower storey. A diagram showing an interpreted reconstruction of the watermill based on Charles Barry's drawing (Bankes Archive: Item D-BKL/H/J/7/3/13: 1819) is presented in Figure 3c.

WED-02

This installation was identified as a likely chute watermill from preserved masonry sections of the chute substruction, carbonate encrustations on the masonry, and a walled structure that may have formed part of a mill-house (Figures 4a, 4b). The head race was supplied from a small rectangular bedrock reservoir constructed in the bed of a canal supplied from the Wadi ed Deir stream. The site may be the watermill ("Tahunet dar'jusef") identified at the end of the 19th century (Schumacher 1918; Steuernagel 1925:271).

Intramural City Area

WJ-02 and the WJ-05/WJ-06/WJ-07 cluster lie at opposite ends of the section of Wadi Jarash that passes through the ancient walled city (Figure 5).

Watermill WJ-02 lies adjacent to the city's ancient North Gate and is complete apart from the original mill-house. Early 20th-century aerial photographs show it was supplied via an earthen diversion canal from Wadi ed Deir. The watermill was named "el-'adebije" by Schumacher (1902:119). It was not operating when William Bankes and Charles Barry visited Jarash 80 years earlier (Boyer 2017:402 Figure 20a) but was restored to use by the Circassians in the late 19th century. The tall arubah tower is well executed with mortared joints and incorporates ashlars robbed from the adjacent North Gate (Figure 6). Masonry *spolia* was also used to buttress both elevations of the head race substruction. Several repairs to the substruction are evident, and a section through it reveals a crudely layered and porous rubble core faced with *spolia* masonry.

Watergate Cluster

Arubah watermills WJ-05 to WJ-07, together with a section of a significant diversion canal, are clustered within a 650 square metre area on the eastern wadi bank close to the city's ancient Watergate (collectively referred to as the Watergate cluster). The principal archaeological features and ^{14}C sample sites are shown in Figure 7a). The disposition of the extant structures in the cluster determined from the JWP total station site survey is shown in Figure 7b.

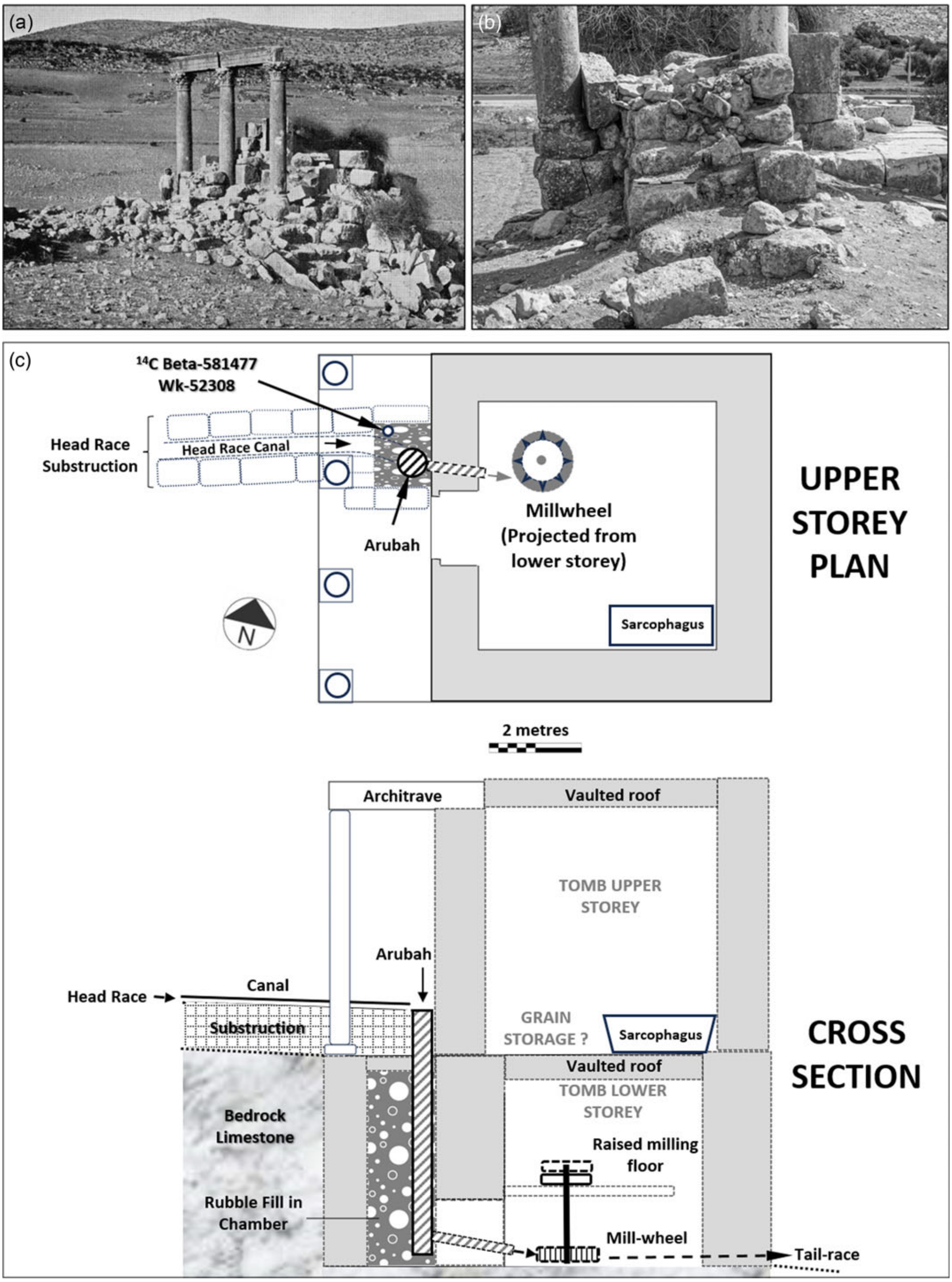

Figure 3 Arubah watermill WED-01: (a) Tomb of Germanus and the site of *Tahunet es samuri* in the 1930s (Kraeling 1938: pl. 7b); (b) WED-01 head race substruction in 2014; (c) Cross-section of the reconstructed arubah watermill installation showing the arubah and the hypothetical placement of mill-wheel and milling chamber in the lower storey (view looking north).

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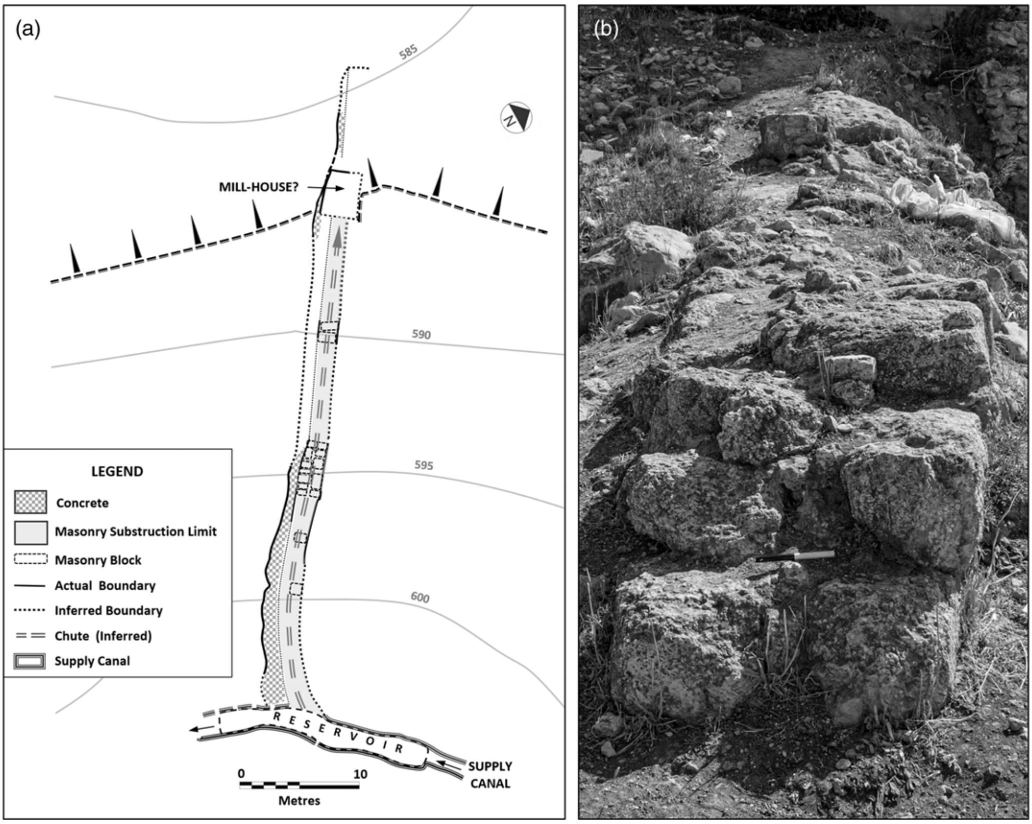

Figure 4 Chute watermill WED-02: (a) Plan of the extant archaeological features; (b) View along the head race masonry substruction (scale 20 cm).

The watermills are clustered on a limestone promontory that stood circa 15 m above the level of the stream flowing from the adjacent Watergate waterfall in Antiquity and provided the topography necessary for the construction of the Arubah tower.

A close study of the watermills in this cluster revealed an archaeologically-based relative chronology for their construction. The WJ-06 head race post-dates the WJ-05 head race, and the WJ-06 tail-race post-dates the WJ-07 head race substruction. The WJ-07 arubah tower, built directly in front of the diversion canal outfall, was constructed after the canal had been decommissioned. The chronological relationship between WJ-05 and WJ-07 could not be firmly determined archaeologically; however, WJ-05 was probably built over the diversion canal and post-dates it.

WJ-05

Although poorly preserved, there is sufficient evidence to show that the footprint of the WJ-05 tower was around 50% smaller than the WJ-06 tower and similar to the footprint of the WJ-17. In contrast to the robust head race substruction of WJ-06, the WJ-05 head race (now missing) was carried on a masonry wall only 0.8 m wide, the width being deduced from the disposition of carbonate deposits on the tower (Figure 8a). The head race alignment can be traced by the thick carbonate encrustations along the top of the wadi bank to the north of the watermill. The

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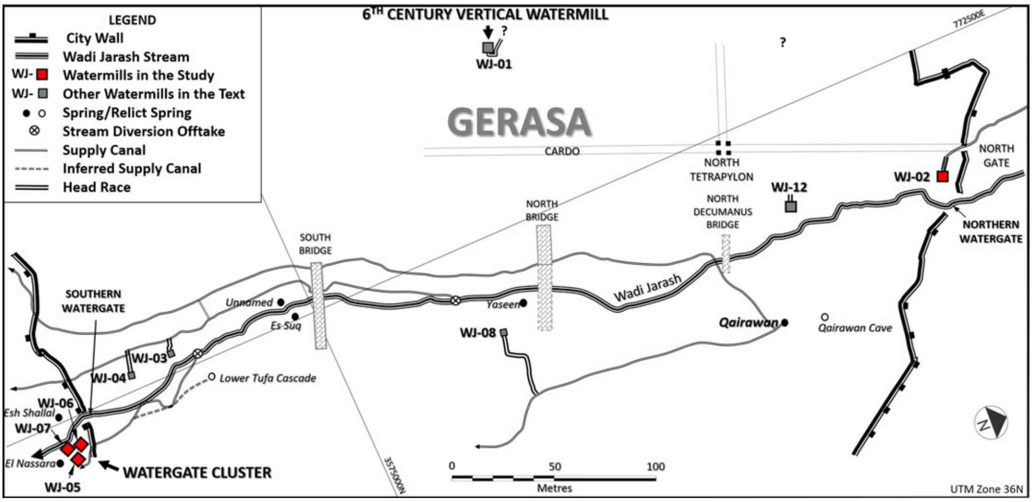

Figure 5 Plan showing the spatial context of arubah watermills WJ-02, WJ05, WJ-06 and WJ-07 in the city area.

Figure 6 Arubah watermill WJ-02: Southern elevation and sample locations (2 m pole).

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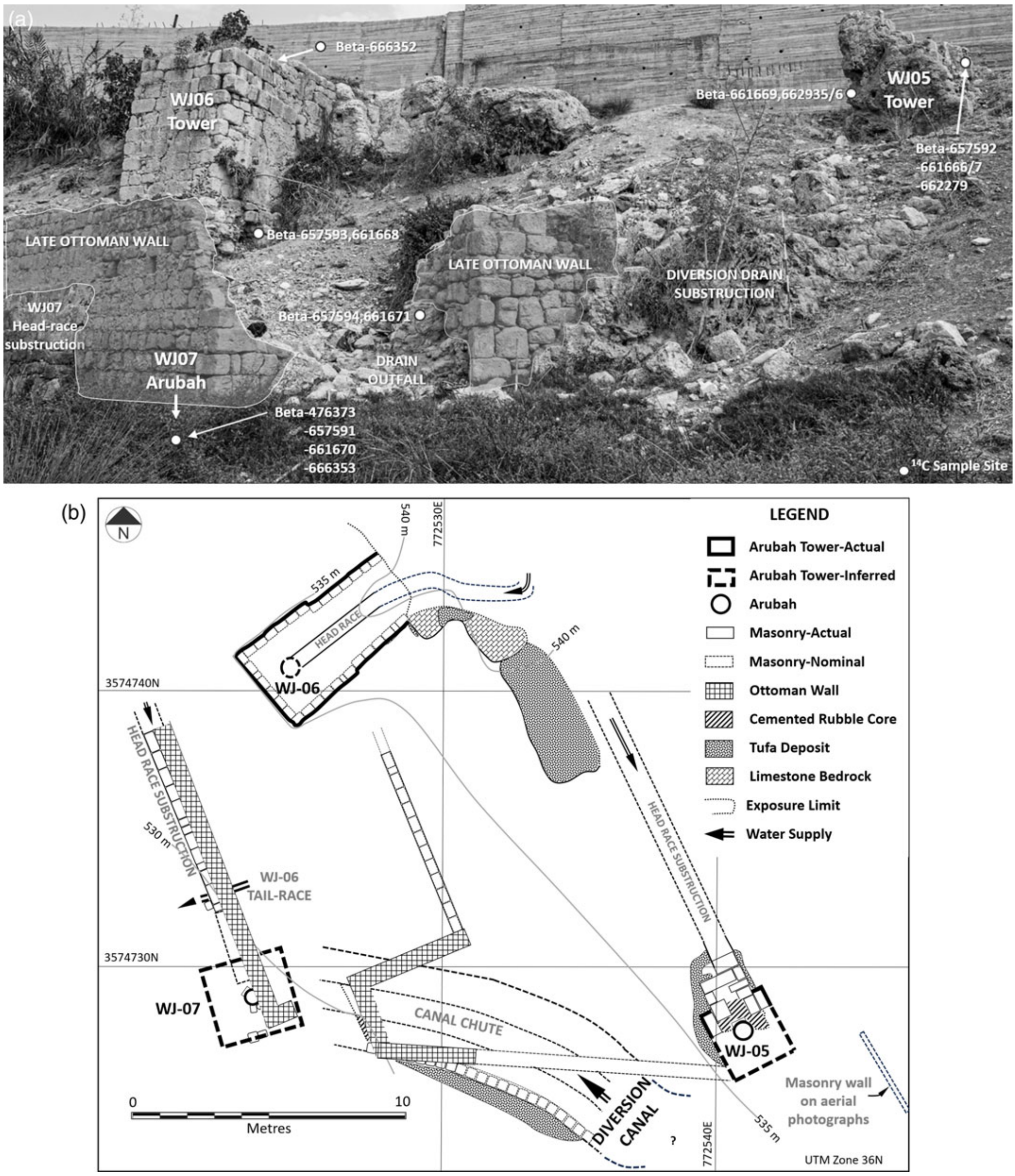

Figure 7 Arubah watermills of the Watergate cluster: (a) View of the watermill ruins and sample locations from the southwest; (b) Plan of the installations compiled from the total station survey.

remnant stub of the WJ-05 tower reveals a roughly square, well-built, stepped masonry structure with a core of mortared cobbles surrounding the arubah.

The arubah shaft is lined with ashlar blocks cut to shape, sealed with *cocciopesto* mortar, and lined with an accumulation of hard, finely laminated crystalline carbonate 10 cm thick. This carbonate accumulation reduced the arubah's effective internal diameter from 62 cm to 42 cm and its water-holding capacity by around 50%. Pick marks on the lining of the arubah and carbonate accumulation are evidence of an abandoned attempt to remove the carbonate

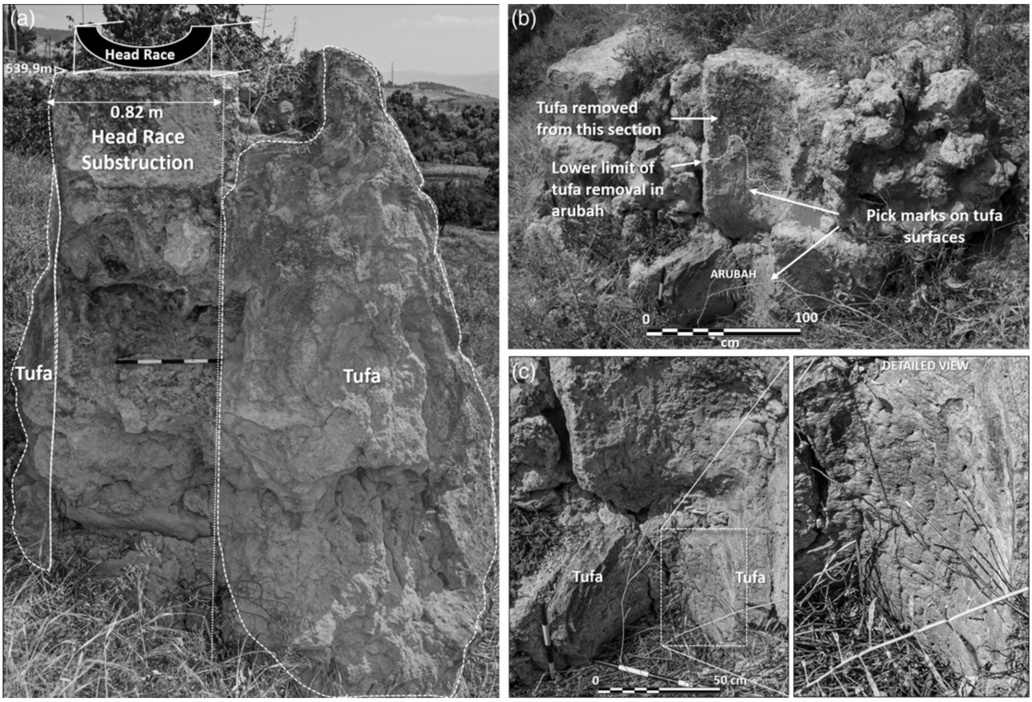

Figure 8 Arubah watermill WJ-05: (a) Northern elevation of the tower, showing the junction with the head race substruction; (b) Cross-sectional view of the arubah and evidence of carbonate deposits removal; (c) Detailed views of carbonate deposits removal evidence.

deposits and restore the arubah's water storage capacity (Figures 8b, 8c). The abandonment of carbonate removal around 1.6 m below the top of the tower marked the end of the watermill's use.

WJ-06

The mortared masonry of the arubah tower of WJ-06 has suffered earthquake damage but is almost intact, as is the short mill-race substruction that connected the tower to the wadi bank. A partially exposed masonry wall south of the tower may have formed part of the mill-house for WJ-06 or WJ-07. WJ-06 is the watermill referred to as "tahunet abu'arak" by Schumacher (1902:119, Figure 6). A detailed plan drawn in the 1930s suggests that WJ-06 was supplied via a diversion canal from Wadi Jarash circa 70 m upstream of the Watergate (Dura-Europos and Gerasa Collection, 1928–1937: Plan SE B1, Negative number:1938.5999.5004.24). The late Ottoman mill-house is visible in early 20th-century aerial photographs and plans from the 1930s (Kraeling 1938:Plan 1), and the remnants of the late Ottoman walls shown in Figure 7b relate to this building.

WJ-07

WJ-07 is the least well-preserved watermill in the Watergate cluster. An *in situ* section of the arubah and several masonry blocks are the only surviving evidence of the arubah tower constructed directly in front of the diversion canal outfall. A well-constructed, carbonate-encrusted masonry wall preserved in a later (Ottoman) wall a few metres north of the arubah is probably a section of the WJ-07's original head race substruction. Based on the height of

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carbonate deposits on this wall, the top of the arubah tower is estimated to have been close to 531.2 m above Mean Sea Level (MSL), 2.3 m above the presently preserved arubah section and circa 9 m below the top of WJ-05 and WJ-06. Assuming an original tower height of 6 m, the elevation of the base of the WJ-07 tower would have been circa 525 m MSL. The lower part of the tower is buried beneath colluvium.

Diversion Canal

The 1 m wide diversion canal was built on a massive 3.5 m wide substruction of mortared rubble faced with masonry up to 2 m high. The canal is inclined 10 degrees down the wadi bank. The canal sidewalls are lined with laminated carbonate 25 cm thick at the outfall. Carbonate samples from the canal were included in the study to provide chronological context for the adjacent watermill installations.

Southern Jarash valley

WJ-17 is a well-preserved watermill showing evidence of several construction phases. The tower has the smallest footprint of any arubah watermill in the case study. The earliest tower phase extends 3.5 m above the modern land surface (Figure 9a). It was supplied via a head race on a solid masonry substruction circa 1 m wide, a fragment of which is preserved against the northeastern corner of the tower. The tower height was subsequently raised by 2.4 m, and an arched head race substruction was added. The samples from WJ-17 were taken from two levels within this later substruction, which comprises a core of weak mortared rubble faced with crudely coursed spolia blocks (Figure 9b).

WJ-22 lies on the north bank of the Zarqa River, six km downstream of WJ-17 and 20 m from the active stream. A 20 m gap separates the tower from an adjacent promontory. The extant arubah tower ruins comprise the arubah, mortared rubble core, and remnants of the masonry cladding on the eastern and northern elevations. The exposed tower had a height of circa 3.5 m in 2014 (Figure 10a). The tower's base and mill-house are buried beneath colluvial sediments. Short sections of the original head race channels are preserved in sandstone bedrock on the promontory. These channels were large, remnants on the tower being 0.5 m by 0.5 m in section (Figure 10b). Each may have had a separate source, but these have not been identified with certainty. The ends of the head race channels on the tower were filled with mortared rubble similar to that used in the tower construction and replaced by a head race from a different water source to the north. A complete profile of the arubah lined with hydraulic mortar and carbonate deposits is exposed in the tower's southern elevation (Figure 10c), revealing three phases of laminated carbonate deposition that reflect successive changes in the water supply arrangements to the watermill.

Wadi Tannur

Chute watermill WT-02 was identified from the head race substruction and a short section of the chute canal. There is no firm evidence of the original mill-house. The installation lies on the slope immediately below the main outlet of the perennial Tannur spring. The chute canal substruction is only visible at ground level (Figure 11a). The downslope end of the chute canal is 10 cm wide (Figure 11b), similar to the chute canals described from Umayyad watermills in southern Syria (Genequand 2016). As in the case of the WED-02 chute watermill, the outer walls of the WT-02 head race substruction were reinforced with concrete. The chute canal became partially filled with rubble after the watermill ceased operation, and the rubble was cemented in place with hard crystalline carbonate. Carbonate-encrusted masonry foundations a few metres south of the WT-02 chute substruction may have been a mill building associated with WT-02 or a separate watermill installation tentatively identified as part of chute watermill WT-03.

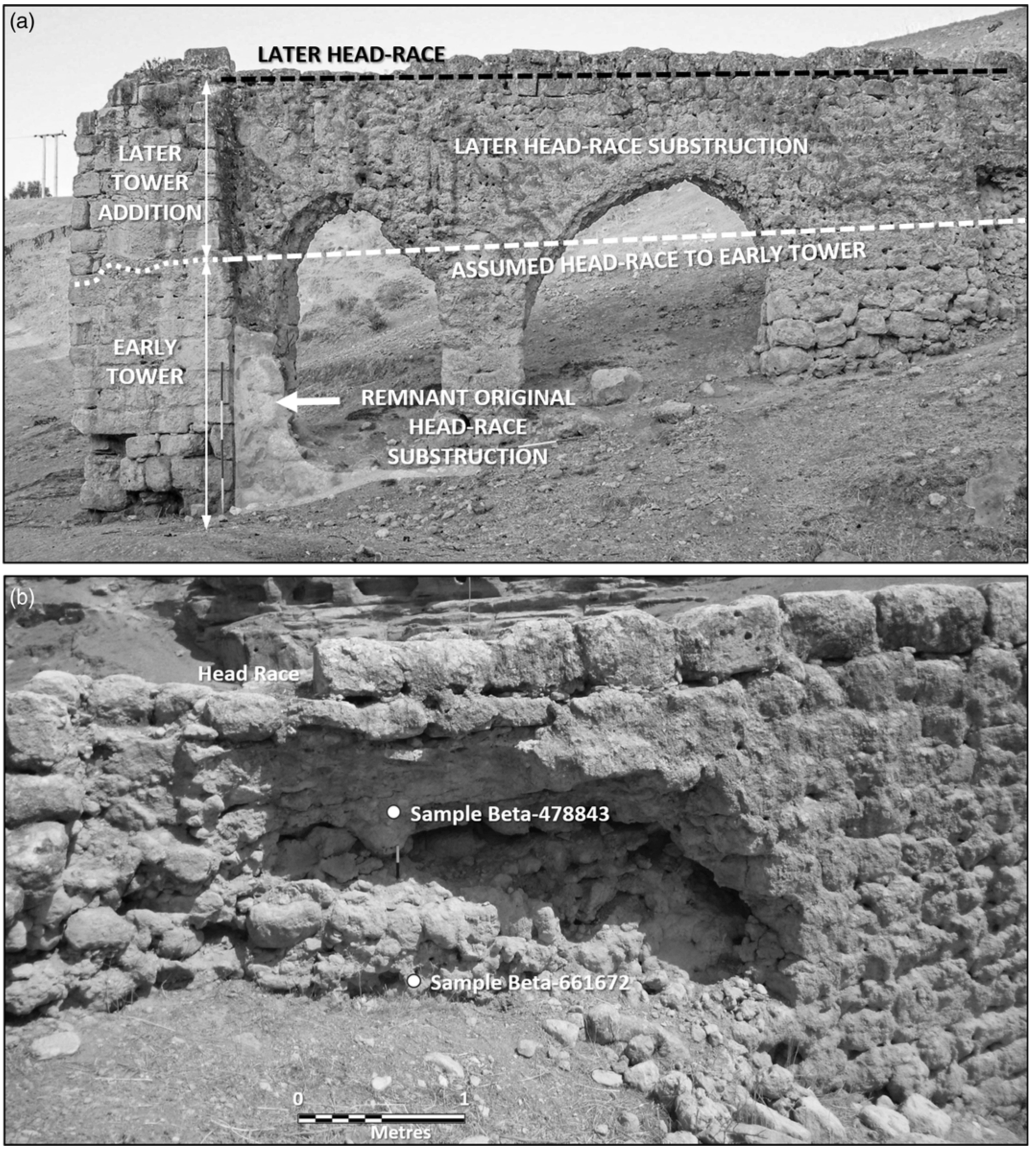

Figure 9 Arubah watermill WJ-17: (a) The northern elevation of the arubah tower and head race substruction; (b) The southern elevation of the head race substruction showing sample locations.

MATERIALS AND METHODS

Sampling Methodology and Mortar Characterization

All sample materials used in the case study were collected from in situ upstanding structures. Sampling initially involved the collection of 20 bulk reference samples from mortars and carbonate deposits in representative structural contexts, each up to 200 g, using a hammer and chisel. The targeted structural contexts were the watermill tower, arubah, head race, and head race substruction. The guiding principles for sample selection were for the samples to be original construction materials, representative of the targeted structural context, and free of

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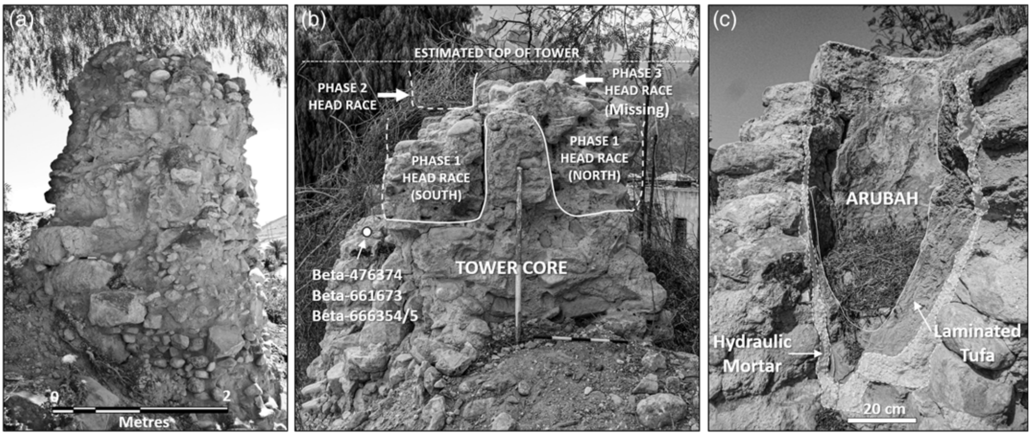

Figure 10 Arubah watermill WJ-22: (a) The northern elevation of the tower; (b) The eastern elevation, showing sample locations and the evidence of the two original head races backfilled with mortared rubble (vertical pole 1 m); (c) The southern elevation showing a cross-section through the arubah.

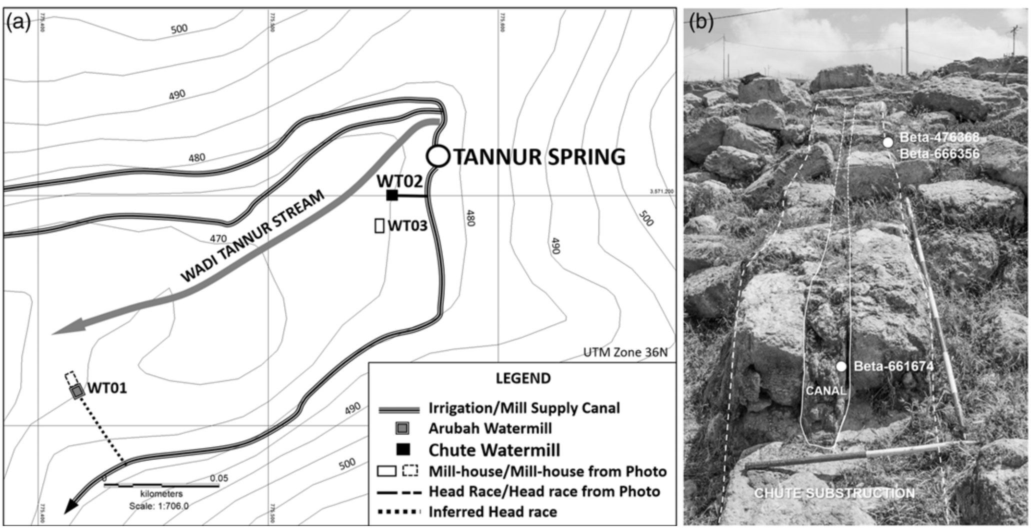

Figure 11 Chute watermill WT-02: (a) Location plan; (b) View upslope showing the WT-02 chute canal, masonry substruction and sample locations.

contamination, with a preference for materials containing macrocharcoals. After manually removing any obvious surface contamination, the cleaned bulk samples were placed in sealed plastic bags. Subsequently, 32 samples, including 10 replicate samples and 10 sample fractions (suffixed A, B, and C in Table 3), ranging in size from 0.08 g to 80 g, of representative materials were selected from the original bulk reference materials and submitted for ^{14}C analysis. In the case of four samples, separated macrocharcoals were submitted for analysis. The remaining submitted samples were raw materials (see Table 3 for details).

Most of the arubah watermills showed evidence of architectural modification over their lifetime, which was noted when sampling and interpreting the ^{14}C results. The range of

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Table 3 Radiocarbon dates from the case study.

Sample					Organic fraction analyzed	Submitted sample (g)	Post-treatment sample yield (%)	^{14}C age ± 1σ (BP)	Calibrated age (OxCal v4.4.4; IntCal20)		IRMS $\delta^{13}C$ (‰)
Mortar type	Architectural context	Laboratory number	Sample reference	Sample fraction					68.3% probability	95.4% probability	
Mill WED-01											
Aerial	Substruction mortar	Beta-581477*#	WED-01/1/Replic.1		Charred olive pits	0.08	<0.01	920 ± 30	1045–1166	1035–1210	–22.4
Aerial	Substruction mortar	Wk-52308*#	WED-01/1/Replic.2		Carbonized twigs	0.2	ND	831 ± 19	1213–1260	1176–1266	—
Mill WED-02											
Aerial (gray)	Substruction mortar	Beta-476376	WED-02/1/Replic.1		Charred (unknown)	42.9	ND	—	Insufficient material		—
Aerial (gray)	Substruction mortar	Beta-661664	WED-02/1/Replic.2		Bulk organic	38.0	0.07	990 ± 30	998–1148	993–1155	–28.2
Mill WJ-02											
Aerial (gray)	Substruction mortar-possible repair	Beta-476369	WJ-02/1		Charred (unknown)	9.9	ND	—	Insufficient material		—
Aerial (gray)	Substruction mortar-possible repair	Beta-478844*	WJ-02/2		Charred (unknown)	22.3	0.00	820 ± 30	1216–1265	1175–1273	–22.3
Aerial (gray)	Substruction mortar-possible repair	Beta-661665	WJ-02/3		Bulk organic	63.8	0.18	660 ± 30	1287–1387	1279–1394	–27.0
Mill WJ-05											
Hydraulic (earthen)	Arubah mortar	Beta-657592	WJ-05/1	A	Bulk organic	24.1	5.26	1500 ± 30	555–601	484–644	–23.7
Hydraulic (earthen)	Arubah mortar	Beta-661666	WJ-05/1	B	Alkali insoluble	18.3	6.70	1220 ± 30	784–878	687–888	–24.5

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Table 3 (*Continued*)

Sample					Organic fraction analyzed	Submitted sample (g)	Post-treatment sample yield (%)	^{14}C age ± 1σ (BP)	Calibrated age (OxCal v4.4.4; IntCal20)		IRMS $\delta^{13}C$ (‰)
Mortar type	Architectural context	Laboratory number	Sample reference	Sample fraction					68.3% probability	95.4% probability	
Hydraulic (earthen)	Arubah mortar	Beta-662279	WJ-05/1	C	Alkali soluble	—	0.02	1810 ± 30	212–319	131–336	–25.8
Hydraulic (earthen)	Arubah mortar	Beta-661667	WJ-05/2		Bulk organic	36.8	0.30	1370 ± 30	642–673	605–772	–26.8
Aerial (earthen)	Tower core	Beta-661669	WJ-05/3	A	Bulk organic	80.1	1.30	1530 ± 30	482–595	434–603	–23.8
Aerial (earthen)	Tower core	Beta-662935	WJ-05/3	B	Alkali soluble	—	0.00	1880 ± 30	130–205	81–236	–25.9
Aerial (earthen)	Tower core	Beta-662936	WJ-05/3	C	Alkali insoluble	—	0.52	1730 ± 30	255–379	248–406	–23.9
Mill WJ-06											
Aerial (gray)	Mortared masonry	Beta-657593	WJ-06/1/ Replic.1		Bulk organic	64.2	0.81	520 ± 30	1405–1432	1327–1444	–24.3
Aerial (gray)	Mortared masonry	Beta-661668	WJ-06/1/ Replic.2		Bulk organic	15.3	1.98	500 ± 30	1412–1439	1399–1450	–24.4
Hydraulic & carbona-te	Head race	Beta-666352	WJ-06/2		Bulk organic	54.1	0.35	580 ± 30	1322–1406	1305–1419	–26.1
Mill WJ-07											
Hydraulic (gray)	Arubah mortar	Beta-476373	WJ-07/1		Charred (unknown)	27.9	ND	—	Insufficient material		—
Hydraulic	Arubah mortar	Beta-657591	WJ-07/2/ Replic. 1		Bulk organic	50.6	0.72	1280 ± 30	677–771	662–821	–24.0
Hydraulic	Arubah mortar	Beta-661670	WJ-07/2/ Replic. 2		Bulk organic	7.9	2.60	1240 ± 30	690–867	679–880	–24.3
Carbonate	Arubah wall	Beta-666353	WJ-07/3		Bulk organic	31.2	0.33	1440 ± 30	603–644	576–654	–26.5

(*Continued*)

Table 3 (*Continued*)

Sample					Organic fraction analyzed	Submitted sample (g)	Post-treatment sample yield (%)	^{14}C age ± 1σ (BP)	Calibrated age (OxCal v4.4.4; IntCal20)		IRMS $\delta^{13}C$ (‰)
Mortar type	Architectural context	Laboratory number	Sample reference	Sample fraction					68.3% probability	95.4% probability	
Diversion canal											
Carbonate (middle)	Canal wall	Beta-657594	Canal/1/Replic.1		Bulk organic	39.1	1.17	1930 ± 30	28–154	22–206	–24.7
Carbonate (middle)	Canal wall	Beta-661671	Canal/1/Replic.2		Bulk organic	54.4	0.47	1760 ± 30	246–339	234–381	–24.7
Mill WJ-17											
Aerial (gray)	Substruction mortar-possible repair	Beta-478843	WJ-17/1		Wood charcoal	11.4	0.01	340 ± 30	1494–1631	1474–1638	–24.7
Aerial (earthen)	Substruction core	Beta-661672	WJ-17/2		Bulk organic	36.2	0.39	790 ± 30	1227–1269	1215–1280	–25.3
Mill WJ-22											
Aerial (earthen)	Tower core	Beta-476374#	WJ-22/1/Replic.1		Wood charcoal	0.6	0.37	910 ± 30	1047–1204	1040–1214	–26.1
Aerial (earthen)	Tower core	Beta-661673#	WJ-22/1/Replic.2		Carbonized twigs	1.5	0.19	710 ± 30	1273–1299	1262–1387	–25.3
Aerial (earthen)	Tower core	Beta-666354	WJ-22/2	A	Alkali soluble	77.0	0.00	1170 ± 30	776–945	772–974	–27.8
Aerial (earthen)	Tower core	Beta-666355	WJ-22/2	B	Alakli insoluble	—	0.29	1030 ± 30	994–1026	899–1147	–26.3
Mill WT-02											
Hydraulic (gray)	Head race	Beta-476368	WT-02/1		Charred (unknown)	10.0	0.01	180 ± 30	Date out of range		–23.1
Hydraulic (pink)	Head race	Beta-661674	WT-02/2		Bulk organic	10.9	0.90	1480 ± 30	568–636	550–644	–26.9
Hydraulic (gray)	Head race	Beta-666356	WT-02/3		Fibrous charcoal	82.8	<0.01	—	Graphitization failed		—

*Published in Boyer 2022: 352. ND = No Data
#Sample includes selected organic material

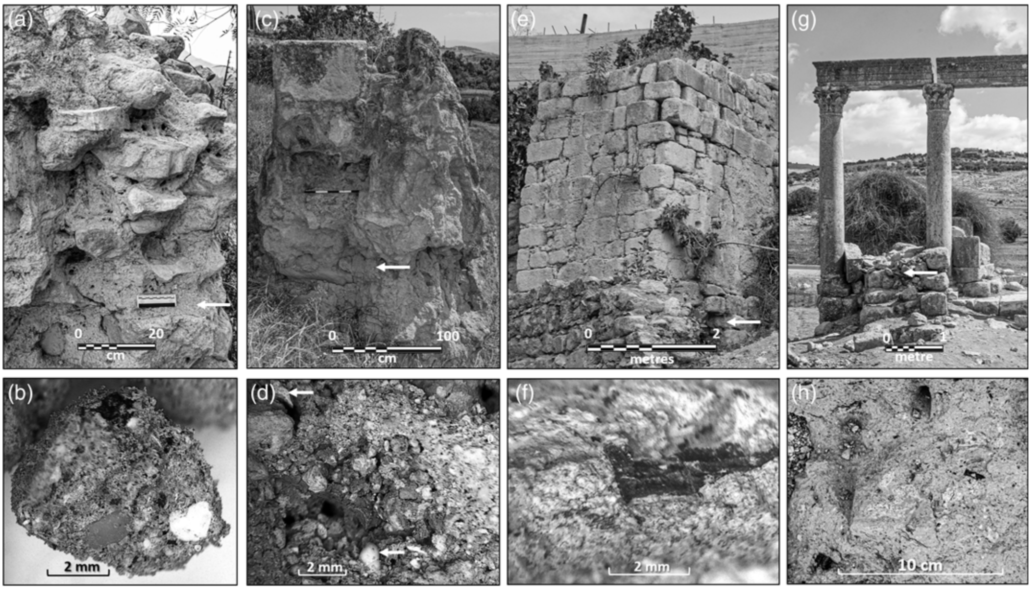

Figure 12 Aerial mortars: (a) WJ-22 arubah tower core sample site; (b) WJ-22 photomicrograph; (c) WJ-05 arubah tower core sample site; (d) WJ-05 photomicrograph (gastropod shells arrowed); (e) WJ-06 masonry mortar sample site; (f) WJ-06 photomicrograph; (g) WED-01 head race sample site; (h) WED-01 macro photograph.

significant modifications includes raising the height of the arubah tower, raising the height of the head race substruction, relocating the head race substruction following a change in water source, and repairing the head race and substruction. Minor modifications include repeated applications of hydraulic mortar to the head race canal and arubah. Many repairs rectified earthquake-induced damage, although the placement of watermills near wadi beds exposed them to damaging flood events. The narrow profile and generally inferior construction quality of head race substructions made them particularly prone to damage. The tower is the most substantial part of arubah watermill architecture, but is not immune to damage.

Non-hydraulic (i.e., aerial) mortar samples were collected from structural contexts, including masonry and the rubble core of arubah towers and head race substructions. The aggregates in these heterogeneous mortars are invariably polymictic and ill-sorted. This mortar type includes brown earthen mortars, distinguished by their overall brownish color, and non-earthen cream-gray lime-rich mortars. Earthen mortar was used in the rubble core of the WJ-17 head race substruction and the rubble cores of all arubah towers in the study. Earthen aerial mortars are porous and friable with minor lime lumps in the aggregate and a matrix containing carbonized inclusions to 1 mm. Their overall brownish hue is due to the clay soil binder in the mortar mix. The earthen mortar from WJ-22 contains distinctive lime lumps up to 2 mm (Figures 12a, 12b). In contrast, earthen mortar from WJ-05 includes shell fragments from freshwater gastropods and crabs incorporated when the mortar was mixed (Figures 12c, 12d). The gray, non-earthen aerial mortars have a higher lime binder, lime lump and macrocharcoal content (Figures 12e–12h).

Hydraulic *cocciopesto* mortars were used to seal head race canals and the inner walls of arubah. The sampled mortars form a heterogeneous group with a lime binder and polymictic aggregate

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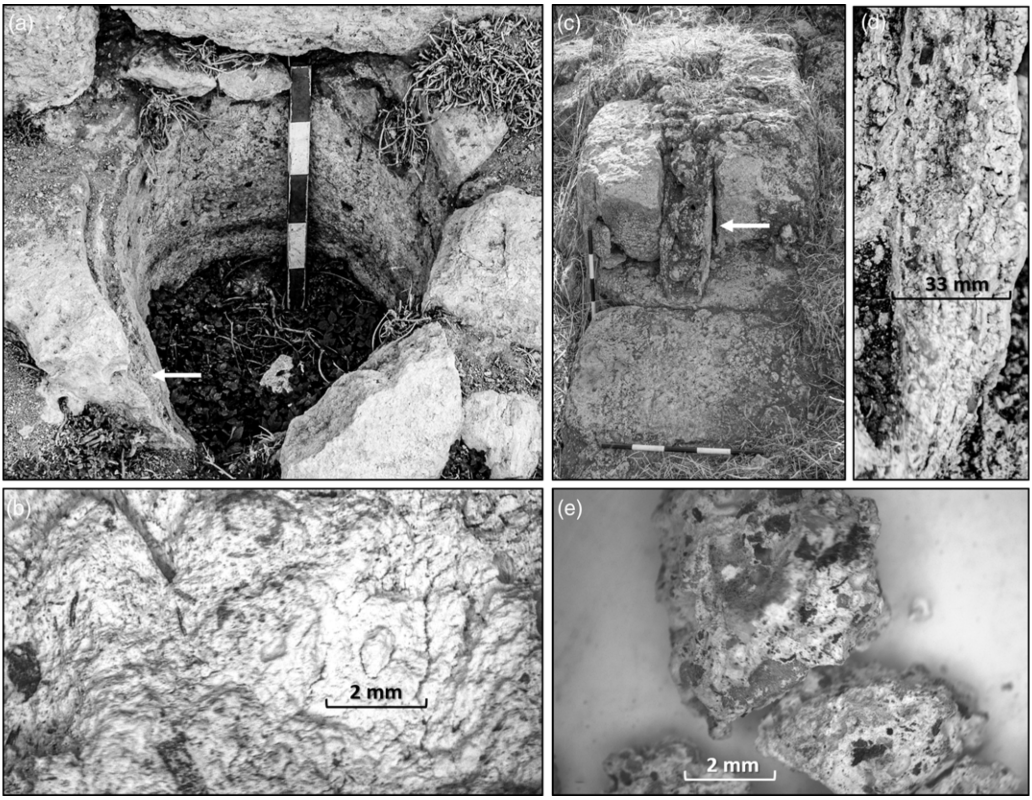

Figure 13 Hydraulic mortars: (a) WJ-07 sample location (pole 50 cm); (b) WJ-07 photomicrograph; (c) WT-02 sample location (pole 50 cm); (d) WT-02 macro photograph; (e) WT-02 photomicrograph.

(Figures 13a–13e). Except for sample Beta-661674 from WT-02, fired ceramics form a subordinate aggregate component of the hydraulic mortars. Evidence of several applications of hydraulic mortar was observed at WJ-05 and WJ-06. While most hydraulic mortars in the study are gray non-earthen types, the pale brown hydraulic mortar from the WJ-05 arubah appears to have an earthen component.

Calcium carbonate-saturated water from karstic water sources precipitated as laminated carbonate on the inside walls of head races and penstocks of arubah and chute watermills. (Figures 14a–14f). The thickness of these deposits in watermills varied from 1–3.5 cm (WED-01, WJ-06, WT-02) to 10–17 cm (WJ-05 and WJ-22). Carbonate deposit laminae include hard and soft porous types, with individual laminae ranging from 1 to >10 mm in thickness. Similar carbonate deposits lining a Roman aqueduct supplying water to Gerasa/Jarash have been studied in detail (Passchier et al. 2021), and there have been detailed studies of other aqueducts across the Roman Empire (Sürmelihindi et al. 2013; Passchier et al. 2016a; Passchier et al. 2016b; Sürmelihindi and Passchier 2023). Studies of carbonate deposits lining parts of the vertical watermill installations at Barbegal (Sürmelihindi et al. 2018) and Ephesos (Passchier and Surmelihindi 2015) have shown that these materials can also provide chemical and isotopic evidence that can be used to evaluate water flow conditions and as proxies in palaeoclimatic reconstructions.

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Figure 14 Carbonate deposits lining hydraulic structures: (a) WJ-07 arubah sample location; (b) WJ-07 photomicrograph; (c) Watergate diversion canal sample location (pole 50 cm); (d) Watergate diversion canal macro photograph; (e) WJ-06 head race sample location; (f) WJ-06 photomicrograph.

^{14}C Analysis

Background

Several potential options are available for the absolute dating of construction materials in the absence of conventional dateable stratigraphic contexts and have been used previously in Jarash. They include conventional ^{14}C, AMS ^{14}C, and optically stimulated luminescence (OSL), but each has limitations. Due to small sample sizes, AMS ^{14}C dating of OM and lime binder are the most commonly employed ^{14}C research methods for the absolute dating of historical construction materials. Plausible dates have recently been obtained from the OSL dating of plasters and mortars in buildings from the Roman and later periods (Moropoulou et al. 2018; Sanjurjo-Sánchez 2022); however, incomplete optical bleaching during the mixing of the mortar leads to an overestimation of the age (Urbanová and Guibert 2017; Urbanová et al. 2018), and this problem was also encountered in a recent study in Jarash (Phillipsen and Olsen 2020). AMS ^{14}C dating of lime binders in mortars and plasters has been previously attempted in the study area (Lichtenberger et al. 2015; Philippsen and Olsen 2020). The preparation and analysis of these samples are more complex than the AMS ^{14}C dating of OM. Sample materials often prove unsuitable due to contamination by carbon from unburnt

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limestone, groundwater, or recrystallized carbonate, or the results have proved inconclusive. Hydraulic *cocciopesto* mortars have also been found to be unsuitable for mortar dating (Daugbjerg et al. 2021:16).

Given the challenges of using the alternative age determination methods described above, it was decided to use the AMS ^{14}C method to date OM fractions in mortars in the case study. This method has been successfully applied to the dating of lime mortars and plasters with macrocharcoal inclusions from the study area (Lichtenberger et al. 2015; Philippsen and Olsen 2020; Daugbjerg et al. 2021, 2022; Passchier et al. 2021; Boyer 2022). The method has also been employed in dating construction materials from other Jordanian archaeological sites (Al-Bashaireh 2013; 2017) and globally (Berger 1992; Van Strydonck et al. 1992; Vega et al. 2013; Ponce-Antón et al. 2020; Regev et al. 2020; Daugbjerg et al. 2022; Brabcová et al. 2023). The effectiveness of ^{14}C dating and the correct interpretation of the results is influenced by OM particle size, the number of OM fractions present and their sources. There is frequently a substantial loss of OM material during ^{14}C sample pretreatment. Macrocharcoals offer the best chance of identifying a selective carbon source, whereas the bulk organic fraction (BOF) has a lower integrity as it can represent a variety of carbon sources. Various factors influence sample integrity by producing dates that are too old or too young. ^{14}C dating results from wood macrocharcoal can be influenced by the "old wood" effect, derived from older heartwood or delayed use or reuse of the material. The study sought to minimize this risk by preferentially selecting short-lived materials such as twigs for analysis to provide a reliable TPQ date as close as possible to the construction date; however, such taxa were found to be poorly preserved and rarely survived laboratory pretreatment. The risk of samples being contaminated with younger OM was minimized by manually removing the contaminants with tweezers under a binocular microscope before shipment to the laboratory. Given the upstanding in situ nature of the contexts sampled, the samples were not subject to bioturbation influences.

The difficulty in recovering sufficient macrocharcoals for standard AMS ^{14}C dating led to the dating of the BOF fraction and paired alkali-soluble (humic) and alkali-insoluble (humin) OM fractions in the current study. Limited research has previously been published on dating paired humin and humic fractions in construction mortars (Rech et al. 2003). Contamination from younger humic acids derived from percolating groundwater was not an issue in the case study because all samples were collected from upstanding structures; however, materials such as earthen mortars may be contaminated by old carbon due to a soil reservoir effect resulting from the capacity of soil clay fractions to fix and store carbon for extended periods (Becker-Heidmann and Scharpenseel 1992:308; Jull et al. 2013:68). Several studies have previously investigated AMS ^{14}C dating of the BOF fraction in carbonate deposits lining water installations (Caran et al. 1995; Winsborough et al. 1996; Blyth et al. 2017; Neely et al. 2022), and this technique was applied to three samples in the current study. Studies have found that organic carbon in carbonate deposits in hydraulic structures is derived from biofilms and algae growing on the surface of the crystalizing carbonate during sedimentation (Caran et al. 1995; Winsborough et al. 1996; Sürmelihindi et al. 2013; Neely et al. 2022; Sürmelihindi et al. 2023). Detrital charcoal grains trapped in carbonate crystals were observed in some carbonate deposit samples in the study and will be older than OM derived from biofilms and algae.

AMS ^{14}C Dating in the Case Study

Apart from one sample shipped to the Waikato Radiocarbon Dating Laboratory, Hamilton, New Zealand (Wk-prefix), samples were shipped to the Beta Analytic laboratory, Miami (Beta-prefix) for AMS ^{14}C determination. The AMS protocol was selected because of the small

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OM content of the samples. Where possible, macrocharcoal inclusions were manually selected using a binocular microscope prior to shipment to the laboratory for standard AMS ^{14}C determination; however, for most samples, the OM content was too fragile for manual selection. It was found that this fragile material generally did not survive standard AMS acid-base-acid (ABA) pretreatment, and the AMS ^{14}C determination was made using bulk organic sediment, alkali-soluble organic or alkali-insoluble organic pretreatment protocols. The amount of selected macrocharcoals or carbonized material available for ^{14}C analysis after ABA pretreatment ranged from <0.01% to 0.37% of the pretreated sample weight (details in Table 3).

Each standard AMS determination followed conventional ABA pretreatment. At the Beta Analytic Laboratory, CO_2 from the combustion of the sample in an oxygen airstream is graphitized by hydrogen reduction over a cobalt catalyst and $^{14}C/^{13}C$ ratio of the sample is measured relative to the $^{14}C/^{13}C$ ratio in Oxalic acid II in an in-house particle accelerator. The result is corrected for the total fractionation of machine graphite $\delta^{13}C$ and is reported as the Conventional Radiocarbon Age in years BP (Beta Analytic 2023). In the Waikato Radiocarbon Dating Laboratory, CO_2 from the combustion of the sample with CuO and silver wire is graphitized by hydrogen reduction over an iron catalyst. The graphite sample is analysed at Keck Radiocarbon Dating Laboratory, University of California, using an in-house accelerator. The $^{14}C/^{12}C$ ratio of the sample is measured relative to the $^{14}C/^{12}$ ratio in Oxalic Acid II. The result is fractionation-corrected using measured online AMS $\delta^{13}C$ values and is reported as the Conventional Radiocarbon Age in years BP. Laboratory quality assurance included the analysis of known-value reference materials.

AMS ^{14}C analyses of the bulk organic sediment (BOF) and humic and humin fractions were all conducted at the Beta Analytic Laboratory using conventional pretreatment protocols (Beta Analytic 2023). These protocols involve sieving to <180 microns to remove roots or macrofossils; however, it should be noted that this process also introduces a bias as it removes macrocharcoals.

AMS ^{14}C determinations were attempted on at least two samples from each watermill. Macrocharcoals represent a selective carbon source and were the preferred OM fraction for dating. All samples encountered a significant loss of OM during pretreatment, and macrocharcoal dates were obtained from only four arubah watermills. The BOF fraction was analysed in 15 samples and was often selected where the total macrocharcoal fraction was too small for separate analysis. The number of humic and humin analyses conducted was constrained by the need for samples to be large enough to contain sufficient OM and the quantity of sample material available for study. AMS ^{14}C analysis was conducted on BOF and paired humic and humin fractions in earthen aerial mortar (fractions WJ-05/1A-1C) and earthen hydraulic mortar (fractions WJ-05/3A–3C) from watermill WJ-05 and on paired humic and humin fractions in earthen aerial mortar from watermill WJ-22 (fractions WJ-22/2A-2B) in order to compare dating results from different OM fractions in the same sample. Replicate samples were submitted from watermills WED-01, WED-02, WJ-06, WJ-22 and the Watergate diversion canal to check on the analytical precision and homogeneity of the carbon source.

RESULTS AND DISCUSSION

The reported $\delta^{13}C$ values are derived from an isotope ratio mass spectrometer (IRMS). The $\delta^{13}C$ values for all samples in the study are very low, in the range of –22.4 to –27.8‰ (Table 3),

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consistent with a carbon source primarily derived from C3 plant material (Boutton 1991). The $\delta^{13}C$ values from the BOF fraction in carbonate deposit samples in the study are in the range of –24.7 to –26.5‰, which contrasts with $\delta^{13}C$ in the range of –8.0 to –11.4‰ obtained from carbonate deposits in a Roman aqueduct to Gerasa supplied from karstic springs sourced from aquifers in Upper Cretaceous limestones (Passchier et al. 2021). The very low $\delta^{13}C$ from the dated OM implies there has been little input of "dead" carbon from karstic bedrock that could result in ^{14}C dates that are too old, a conclusion also reached in several other studies (Nishikawa et al. 2012; Neely et al. 2022).

^{14}C Dating

Introduction

Twenty-eight AMS ^{14}C analyses were obtained from the 32 samples submitted for analysis. Calibrated dates in years BC/AD were obtained using the IntCal 2020 calibration curve (Reimer et al. 2020) and OxCal version 4.4.4 (Bronk Ramsay 2021). The results from the dated organic fractions for each watermill are presented in Table 3, along with details of mortar type and structural context. The results are discussed in the ensuing sections in the context of individual watermills.

WED-01

^{14}C determinations were obtained from olive pit fragments and twigs recovered from replicate samples of gray non-earthen aerial mortar. Both types of OM are typically regarded as short-lived, yet their uncalibrated ages are not within 2σ. There is some overlap in calibrated ages in the 2σ range, which falls in the 11th–13th century (Middle Islamic) period, with the olive pit age influenced by a plateau in the atmospheric calibration curve (Figure 15). The olive pits have greater durability than the twigs and their older age is attributed to an old wood effect—plausibly, the delayed use of old olive pits already on the ground when the mortar was mixed. An analogous situation is described below regarding the inclusion of freshwater shell fragments in the mortar mix from watermill WJ-05. Alternatively, old olive pits may have formed part of the fuel used to burn the lime used as a binder. The calibrated AD 1176–1266 (2σ) age of the short-lived twigs is considered to be close to the watermill construction date, which falls in the Mamluk period.

WED-02

Heavy sample loss during sample pretreatment resulted in a single BOF age from a sample of gray aerial mortar submitted from this chute watermill. The cal AD 993–1155 (2σ) date range falls in the Fatimid-Seljuq (Middle Islamic) period and predates the nearby arubah watermills WED-01 and WJ-02 from the Mamluk period.

WJ-02

Separate ^{14}C analyses were obtained from BOF OM and charred fragments in a gray aerial head race mortar, possibly a repair. There is no overlap in the 2σ range in the uncalibrated or calibrated ages. The charred material's age of cal AD 1175–1273 (2σ) is the same as the age of the twigs from WED-01. An old wood effect may influence the charred material age, and a younger carbon source may influence the BOF age; however, the calibrated ages of both samples fall in the Mamluk (Middle Islamic) period.

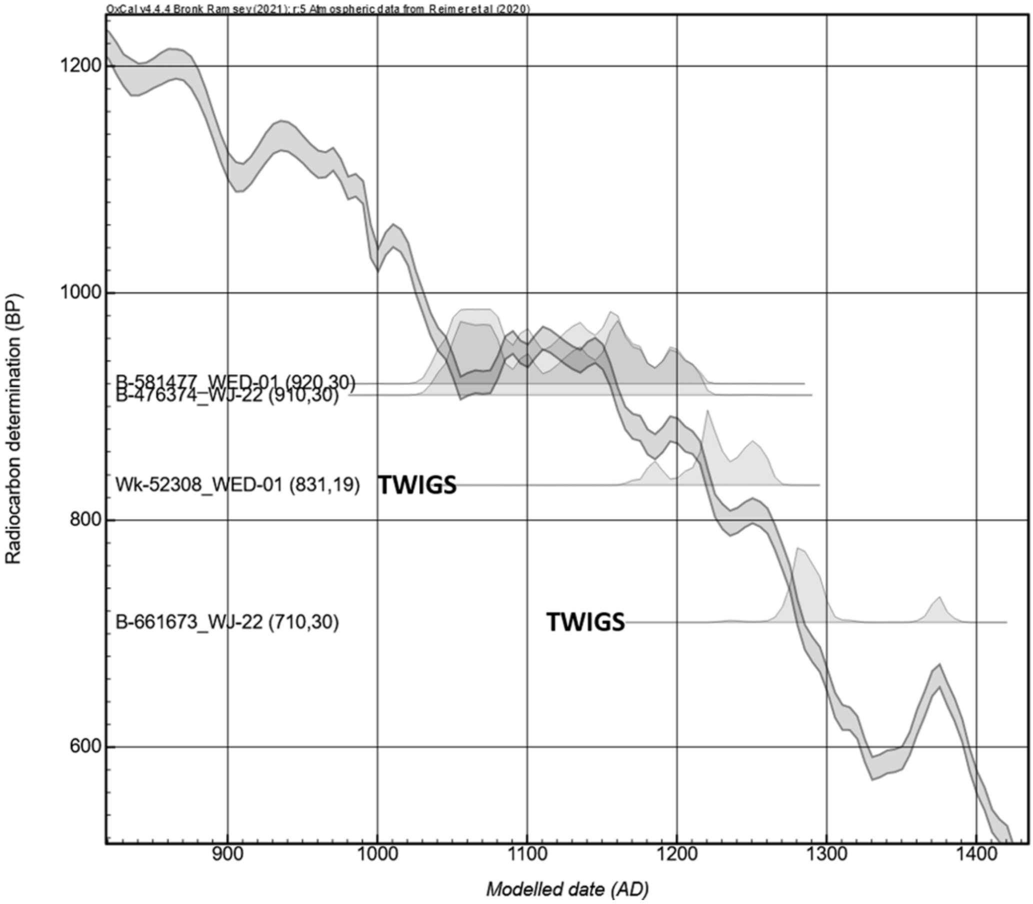

Figure 15 Calibrated ^{14}C dating results (2σ) of twigs and other macrocharcoals from arubah watermills WED-01 and WJ-22 overlain on the IntCal 2020 atmospheric calibration curve.

WJ-05

The aerial and hydraulic samples from this watermill are unusual because they are both earthen types. Determinations were obtained from seven samples; however, the dating of macrocharcoals was impossible due to their friable nature. There is a slight overlap in the 2σ calibrated ages from the two BOF samples from the arubah hydraulic mortar (Beta-657592 and 661667), which straddle the Byzantine-Early Islamic transition in the late fifth to late eighth centuries. The BOF age of cal AD 434–603 (2σ) from the earthen aerial mortar from the tower core (Beta-661669) supports a probable fifth–eighth-century construction date. An unusual aspect of the tower core mortar was the inclusion of shell fragments from gastropods and crabs when the mortar was mixed—presumably on the wadi bank.

Very different ages were obtained from the humic and humin fractions. There is an overlap in the 2σ range of uncalibrated humic ages from hydraulic and aerial mortars, which are circa three centuries older than the uncalibrated BOF ages. The uncalibrated age of humin from the aerial mortar (1730 ± 30 BP) is reasonably close to the uncalibrated age of humic material (1880 ± 30 BP) in this mortar. However, the uncalibrated age of humin material in the

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hydraulic mortar (1220 ± 30 BP) is circa six centuries younger than the hydraulic mortar humic date (1810 ± 30 BP) and is considered an outlier. The early age results from the humic and humin fractions in the earthen aerial mortar appear to relate to a soil reservoir carbon response from the soil clay binder added to the mortar and are much older than the watermill's construction date.

WJ-06

Two replicate samples of gray non-earthen aerial mortar from the tower masonry produced almost identical uncalibrated BOF ages, and a BOF sample from the head race yielded a similar uncalibrated age. The non-specific nature of carbon sources in BOF means that BOF ages have lower integrity than short-lived macrocharcoals; however, the clustering of 2σ calibrated BOF ages from non-earthen mortars from two different architectural contexts supports a Mamluk (Middle Islamic) construction date in the early 14th–mid 15th century period for WJ-06.

WJ-07

Little remains of the original architecture of this watermill; however, separate BOF ages were obtained from hydraulic mortar and carbonate deposits in the arubah. The replicate samples of hydraulic mortar (Beta-657591 and 661670) produced almost identical uncalibrated BOF ages (1240–1280 ± 30 BP), confirming the analytical precision and homogeneity of the OM in this fraction. The uncalibrated BOF age from the arubah carbonate deposit is two centuries older (1440 ± 30 BP), which may be influenced by older charcoal particles trapped in porous carbonate. Field relationships show that watermill WJ-07 post-dates an adjacent diversion canal. The 2σ calibrated dates for replicate BOF samples from carbonate samples in this canal fall within the Roman (first–fourth century) period but do not overlap. The 2σ calibrated BOF ages from WJ-07 fall in the Early Islamic (seventh–late ninth century) period and provide a possible date range for watermill construction. These ages are later than BOF ages from the adjacent watermill WJ-05, implying a hiatus of several centuries between the diversion canal's closure and the construction of WJ-07.

WJ-17

Separate ^{14}C determinations were obtained from wood charcoal and BOF in different mortar types from the watermill's head race substruction. There is a 450 ^{14}C yr offset in the ages of these samples. The wood charcoal from a gray aerial mortar (Beta-478843) provided the study's youngest date of cal AD 1474–1638 (2σ). The sample was taken towards the top of the head race substruction and stratigraphically above the BOF sample site (Beta-661672) in the substruction's core, and maybe a repair. If correct, the BOF age of cal AD 1215–1280 (2σ) could be close to the build date of this substruction; however, as already noted, this was probably not the watermill's original head race substruction.

WJ-22

^{14}C determinations were conducted on separate samples of charred material and twigs from replicate earthen mortar samples taken from the core of the watermill tower. As was the case from replicate macrocharcoal dates from watermill WED-01, there is a significant offset in uncalibrated ages between the macrocharcoals in WJ-22; however, the age offset in the WJ-22 samples is greater. Due to a plateau in the atmospheric calibration curve, the calibrated 2σ ages of the two macrocharcoal fractions from WJ-22 range from the early 11th century to the late 14th century (see Figure 15). The older date from the charred material is attributed to an old wood effect, and the cal AD 1262–1387 (2σ) date range from the short-lived twigs places the watermill's probable construction date in the Middle Islamic Mamluk period.

The uncalibrated ages of the humin and humic fractions from WJ-22 are three and four centuries older (respectively) than the uncalibrated age of the twig sample, which is a similar age offset to that identified between the same OM fractions from watermill WJ-05. These substantial age offsets are attributed to a soil reservoir carbon response from the soil clay binder.

WT-02

Attempts to successfully obtain macrocharcoal ages from separate samples failed. The single BOF age of cal AD 550–644 (2σ) is similar to the BOF ages obtained from WJ-05 and the carbonate from WJ-07 in the Watergate cluster but less well constrained. It is also close to the ^{14}C charcoal age ("530–680 AD") obtained from a chute watermill at Ein Gedi on the Dead Sea (Hadas 2001:77). The BOF age suggests that WT-02 may predate the eighth-century Umayyad chute watermills in Ma'an and southern Syria (see Table 2).

Summary of Watermill Construction Dates

The ^{14}C dates obtained in the study were analysed to provide the best estimate of the watermill construction dates, although dates from carbonised materials can only provide a TPQ for the construction context. The interpreted TPQ dates for each watermill are summarized in Figure 16. The TPQ date for each watermill is the oldest calibrated date of the most reliable fraction in the 2σ range rounded to the nearest 10 years.

The dating results show that the arubah watermills fall into two distinct chronological groups. Excluding the possible dated repair from WJ-17, the youngest group comprises four arubah watermills (WED-01, WJ-02, WJ-06, and WJ-22) with a calibrated TPQ construction age from the late 12th to the mid-15th century, coinciding with the Ayyubid–Mamluk (Middle Islamic) period. Three watermills in this group have TPQs determined from macrocharcoal samples. The construction dates for WED-01 (TPQ AD 1180) and WJ-22 (TPQ AD 1260) are derived from twig samples and are considered the most reliable in the study on account of the selectivity and short-lived nature of this fraction. The distribution of the Ayyubid-Mamluk watermills demonstrates that they were constructed broadly contemporaneously throughout much of the Jarash Valley. The dating of similar watermills in the Ajlun district (MacKenzie (2000, 2002, 2003) suggests that the surge in watermill construction in the Ayyubid-Mamluk period encompassed the entire Ajlun highland region.

The older arubah watermill group comprise watermills WJ-05 and WJ-07 in the Watergate cluster dated from BOF samples to the Byzantine-Early Islamic transition period (fifth–ninth centuries). The lack of carbon source selectivity renders BOF dates less reliable than macrocharcoal dates. However, the clustering of the BOF dates from different architectural contexts and mortar types, particularly the near-coincidence of BOF dates from WJ-05 hydraulic and aerial mortars (Beta-657592 and Beta-661669) and the significant chronological hiatus between the two arubah watermill groups, supports the plausibility of the early dates from WJ-05 and WJ-07. The calibrated BOF dates from WJ-07 yield a possible TPQ construction age of AD 580–660, while comparable calibrated BOF dates from WJ-05 yield a slightly earlier possible TPQ construction age of AD 430–480 (Figure 17).

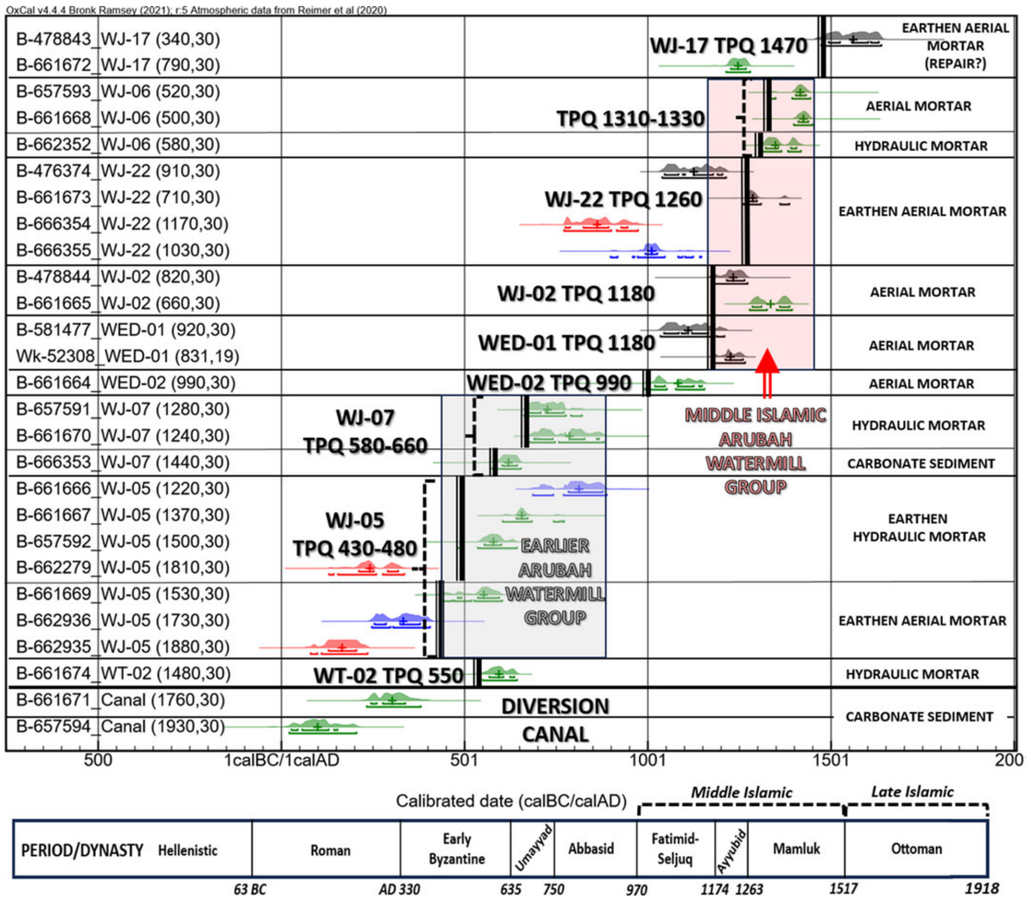

Figure 16 Calibrated ^{14}C dating results from all case study sites in descending date order, showing each site's interpreted TPQ construction date (gray, charcoal fraction; green, BOF fraction; red, humic fraction; blue, humin fraction).

These dates fall within the fifth–ninth century period previously noted by Wilson (2007) as having little archaeological evidence of watermill construction and maybe up to three centuries earlier than the arubah watermill at Khirbat al-Khawam (Syria) dated to the eighth–ninth century (Blanc and Genequand 2007; Genequand 2016). The calibrated dating results suggest a construction hiatus in the Watergate cluster of circa five centuries between WJ-07 and the construction of WJ-06 in the 14th–15th century. This hiatus includes the Early Islamic period when the city area was probably permanently occupied (Rattenborg and Blanke 2017; Blanke 2018; Blanke et al. 2022). It is likely that other watermills, such as those supplied by the perennial Qairawan spring, operated in the city area during this period.

The limited ^{14}C results from the two chute watermills suggest different construction dates. A possible TPQ of AD 550 for watermill WT-02 in Wadi Tannur suggests construction roughly coeval with arubah watermills WJ-05 and WJ-07 in the Watergate cluster in the Jarash Valley. In contrast, the possible TPQ AD 990 construction date for WED-02 falls within the lengthy hiatus separating the Medieval arubah watermills from the earlier arubah watermills in the Watergate cluster.

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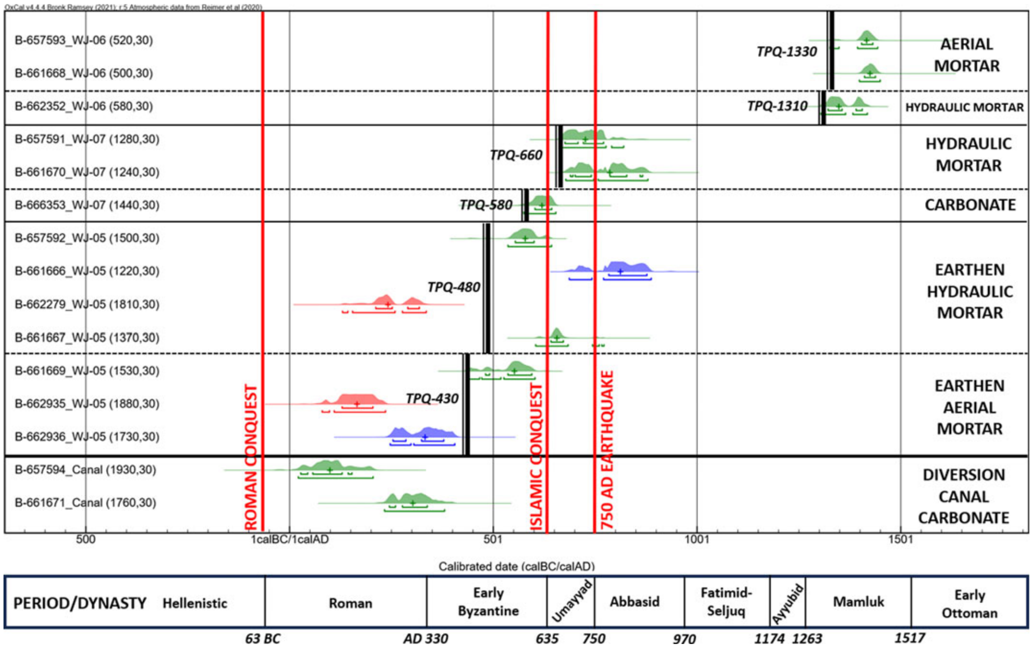

Figure 17 Calibrated ^{14}C dates and interpreted TPQ construction date from the Watergate arubah watermill cluster presented in descending date order (color legend as for Figure 16).

Soil Reservoir Carbon Response in Earthen Mortars

The significant age differences between the humic/humin fractions in earthen aerial mortar from WJ-05 and WJ-22 and ABA-pretreated macrocharcoals and BOF from the same mortars reflect different carbon sources. These results contrast with the ^{14}C dating results from similar fractions from Bronze Age and Iron Age sites in the Middle East, which found close agreement in the dates of humic, humin and ABA-pretreated OM (Wild et al. 2013; Falconer and Fall 2016). The results from hydraulic and aerial mortars in WJ-05 imply a similar old carbon source in the humic fraction despite the differing architectural contexts. These mortars both have an earthen component that is probably a soil clay binder and would have been mixed around the same time during watermill construction. It is hypothesized that the early humic dates from earthen mortars used in constructing WJ-05 and WJ-22 reflect a soil reservoir carbon response derived from this clay binder.

The humic dates are the oldest carbon fraction in the WJ-05 and WJ-22 earthen aerial mortars, but there is a circa seven-century offset in their uncalibrated ages (1880 ± 30 BP and 1170 ± 30 BP, respectively). These watermills are 7 km apart, and a significant offset might be expected. Nevertheless, there is a comparable younger age offset between the paired humin dates in the earthen aerial mortars from these two watermills. The offset in uncalibrated age between humic and humin dates is 150 years for the aerial mortar from WJ-05 and 140 years for the aerial mortar from WJ-22. The ^{14}C results from the small humin fractions in earthen aerial mortars in WJ-05 and WJ-22 suggest that the origin of the humin carbon source is similar to that of the humic fraction in each case. It is hypothesized that the carbon sources for the humic and humin fractions reflect an "old carbon" soil reservoir response from the clay binder. According to the soil provenance, this soil reservoir response will vary with each earthen mortar site.

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The WJ-22 results provide insight into the relative usefulness of humic and humin-dated fractions compared to macrocharcoal dates on the same sample material. It also assists in interpreting the humic and humin ages from WJ-05 in the Watergate cluster, which has no macrocharcoal dates from aerial or hydraulic mortars. While the humic/humin results come from only two watermills, it is tentatively concluded that soil clay binders in watermill construction mortars will probably result in humic and humin fraction dates significantly older than the watermill construction date. For this reason, it is suggested that non-earthen mortars, particularly gray mortars with many macrocharcoal inclusions, are the preferred type for use in watermill ^{14}C dating studies.

Arubah Watermill Architecture

The study identified several architectural differences that may assist in discriminating arubah watermills constructed in the Middle Islamic period from those such as WJ-05 and WJ-07 that were probably constructed earlier. Basic architectural features shared by the other arubah watermills in the study area other than WED-01 include a head race substruction, an arubah tower comprising a central arubah set in a core of cemented cobbles, and a tower faced with squared masonry. Features that separate WJ-05 from most of the other arubah watermills include a small tower footprint, a narrow all-masonry head race substruction, and an arubah shaft lined with shaped masonry blocks rather than a plastered shaft lined with field stones. A shaped masonry block was also found in the arubah wall in WJ-07. A more detailed architectural comparison between WJ-05 and WJ-07 is impossible as WJ-07 has an arubah but no extant tower.

Two other installations in the study area share similar architectural features to WJ-05 and may, therefore, have a late Roman/early Byzantine construction date. The first is watermill WJ-17, which has a very small tower footprint. The calibrated charcoal date from WJ-17 (Beta-478843) shows that the watermill was used in the 15th–17th century period, and a calibrated BOF date (Beta-661672) implies possible earlier use in the 13th century. However, archaeological evidence shows that the medieval installation modified an earlier one supplied by an all-masonry head race substruction similar to that which supplied WJ-05. The second installation (WJ-12) was identified as a possible arubah watermill from historical plans and photographs (Boyer 2022:157). It is located on the west bank of Wadi Jarash between the West Baths and the North Gate. The site is one of two parallel masonry features projecting from the wadi bank shown on various historical and modern aerial photographs and plans drawn in the 1930s as part of archaeological investigations led by Yale University (Dura-Europos Gerasa Collection circa 1931, Negative 1938.5999.5004.47, Negative gerasa-b217~01 b-217). A general plan of the city shows the features to be "Christian" in date (Kraeling 1938: pl. 1), which, in the context of Yale University's investigations, placed their date between the fourth and seventh centuries (Figure 18a). A plan of the probable arubah watermill drawn based on an interpretation of aerial photography is presented in Figure 18b. Features that WJ-12 shares with WJ-05 include a small tower footprint and a solid masonry head race substruction. No written site description has been located, and the justification for the Christian date is unknown. An aerial photograph of the site in 1918 shows a slender, well-built, stepped masonry tower circa 5 m high and circa 1.6 m square in plan connected to the wadi bank by a narrow masonry substruction circa 1.2 m wide (Boyer 2022:157, Figure 6.34b). The top of what may be an arubah is visible on the tower. The photograph shows remnants of a similar parallel structure circa 4 m to the south.

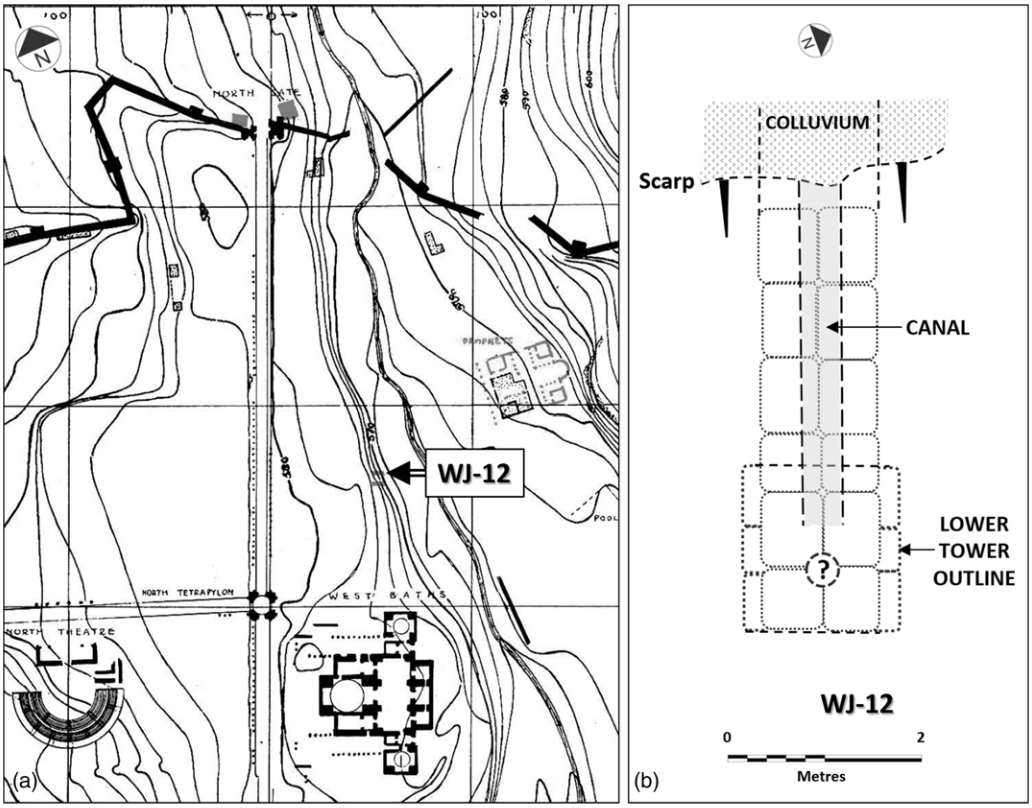

Figure 18 WJ-12: (a) Location of the structure identified as “Christian” in date on site of WJ-12 on a plan of Gerasa (Kraeling 1938, Plan 1); (b) Architecture of WJ-12 interpreted from a historical photograph (Dura-Europos and Gerasa 1931 Negative number gerasa-b217~01 b-217).

Carbonate Deposits

The preserved stratigraphy of carbonate deposits precipitated on arubah surfaces in watermills WED-01, WJ-05, and WJ-22 provides direct insights into the nature and frequency of water flow and the management practices employed during watermilling operations and indirectly on the environment. Unlike carbonate deposits lining open-channel aqueducts, which were periodically removed (Sürmelihindi et al. 2023), carbonate deposits in arubah watermills are more likely to be preserved due to the extreme difficulty in removing the carbonate deposits in such a cramped space. They are a valuable data source as they represent a unique record of water flows into the arubah over the entire life of the watermill. The accumulation of carbonate deposits progressively reduced the arubah’s diameter and holding capacity, ultimately impairing its hydraulic efficiency. Studies of carbonate deposits lining Roman aqueducts and watermill installations have shown that alternating light and dark laminae form couplets representing deposition from alternating wet and dry season water flows, respectively (Sürmelihindi et al. 2013; Sürmelihindi et al. 2021; Passchier et al. 2021: Sürmelihindi and Passchier 2023). Viewed macroscopically, the carbonate deposits lining the arubah of WED-01, WJ-05 and WJ-22 also comprise alternating light and dark-colored laminae, suggesting deposition from wet-season and dry-season flows. The macroscopic evidence suggests that water flowed through the arubah in these watermills for much of the year. However, the extent to which this flow was utilized for milling activities is unknown.

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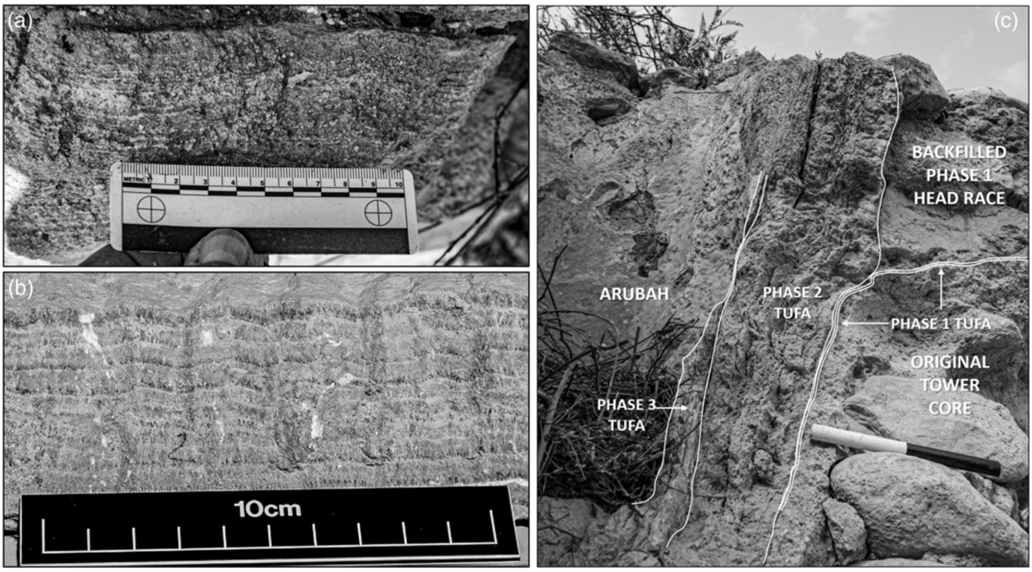

Figure 19 Carbonate deposits deposits: (a) Carbonate deposits lining WJ-05 arubah circa 2 m below the top of the tower; (b) Section of carbonate deposits lining a Roman aqueduct to Jarash; (c) Detailed view of the eastern wall of the arubah of WJ-22 showing the three phases of carbonate deposition (scale 20 cm).

Macroscopically, the stratigraphy of the 10-cm thick carbonate deposits in WJ-05 (Figure 19a) show similarities with the carbonate deposits recorded in a Roman aqueduct to Jarash studied by Passchier et al. (2021) (Figure 19b). Figure 19c shows the internal stratigraphy of the carbonate deposits in WJ-22 to be uneven, reflecting three separate water sources over the life of the watermill. Phase 1 was brief, perhaps only one or two years. After significant alteration to the tower, a new source was accessed in phase 2 and operated for an estimated 20–25 years before being replaced by a phase 3 source that operated for approximately 10 years until the watermill's abandonment. The phase 2 carbonate stratigraphy is irregular, with hard, thin, pale laminae alternating with mainly thicker, highly porous bands reflecting an asymmetric cascading water flow into the arubah. A cascading flow indicates that the arubah was often only partially full in phase 2. The carbonate stratigraphy suggests a regular and perhaps reduced water flow resumed in phase 3, with increasing amounts of suspended clay. The trouble taken to maintain the operation of WJ-22 despite repeated and ongoing water supply issues points to the underlying value of this watermill to its owners and the local community.

Chute Watermills

Watermills WED-02 and WT-02 are poorly preserved but nevertheless represent an opportunity to study a watermill type rarely observed in Jordan and poorly represented among the recorded watermill sites in the southern Levant. Globally, chute watermills are typically found in mountainous terrain with reliable perennial water supplies. The relative scarcity of perennial water sources meant there was little scope for the widespread adoption of this watermill type in the southern Levant. It is suggested, however, that the type enjoyed a wider distribution than the archaeological evidence suggests. The large cluster of multi-chute watermills at Tell Shihab in southern Syria in the late Ottoman period demonstrates that the technology remained popular where the water sources and topography were particularly favourable and, unusually, was sometimes used in conjunction with arubah watermill technology (Schnitzer 2002).

In contrast to the strongly constructed arubah towers, chute watermill installations have less structural substance to ensure their preservation. The WED-02 and WT-02 sites have low visibility. The general lack of suitable perennial water sources means it is unlikely that chute watermills were ever as common as arubah watermills in the study area, an observation also made by Avitsur (1971:406) for the area west of the Jordan River. However, many relict spring sites in the study area indicate that spring flows were stronger in Antiquity (Boyer 2022:61–68). Poor preservation means that chute watermill ruins are difficult to distinguish from other stone-built features in the landscape. Their actual distribution is, therefore, probably underestimated, especially downstream of the historically perennial springs of Maghasil and Birketein in the Jarash Valley.

Common architectural features shared by WED-02 and WT-02 include a masonry head race substruction with outer walls reinforced with concrete. Nevertheless, the dating evidence presented in Table 3 suggests that they date to two different periods. The poor preservation means that a direct architectural comparison with the better-known early chute watermills in Syria is impossible, although the downstream end of the head race preserved in WT-02 has similar dimensions to those recorded in the double-chute Umayyad watermills at Khirbat al-Khawam in Syria and al-Hammam near Ma'an in Jordan (Genequand 2016:520–25). However, broad comparisons with the Syrian examples can be drawn concerning dating, water supply, overall size, and ownership.

Water supply was a critical factor in the case of the WED-02 and WT-02. WT-02 was supplied directly from the perennial Tannur spring, one of the few remaining perennial springs in the study area today. Water was delivered to WED-02 by diversion canals from the Wadi ed Deir stream, primarily supplied from the strong Birkeletin springs. Of the five Umayyad chute watermill sites described by Genequand (2016), the Ma'an watermill is the only mill supplied by a perennial spring. The other Umayyad watermills were supplied from substantial reservoirs that stored water from ephemeral sources and formed part of sophisticated water management systems adjacent to aristocratic settlements. In contrast, WED-02 and WT-02 were modest installations, each probably owned and managed by a small community nearby.

Water Supply

Watermill use represents a measure of water availability and is a proxy for the prevailing hydroclimate. This use would have been constrained by water availability, with ephemeral water sources generally limiting operation to only part of the year: a reliable, long-term water source such as a perennial spring or stream would, therefore, have been highly prized. The surge of watermill construction throughout the Jarash Valley in the Middle Islamic period, evidenced from the study, coincided with the onset of wetter climatic conditions that followed the drier Medieval Climate Anomaly period between AD 1000 and AD 1200 (Lüning et al. 2019; Kushnir and Stein 2019). Watermill use would have again been constrained by the drier climatic conditions that returned in the mid-14th century (Xoplaki et al. 2018), and this situation may have persisted until the late Ottoman period when limited water availability was recorded by Schumacher (1902:119) and Huntington (1911:280).

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Relative Chronology of Watermill Technologies

The close association of a vertical watermill and examples of arubah and chute watermills in the study area provide a rare opportunity to consider the chronology of the diffusion of various milling technologies. The oldest possible TPQ construction dates in the study are from BOF OM in samples from arubah watermill WJ-05 and chute watermill WT-02. These samples have calibrated BOF OM dates (2σ) that range from the fifth to the ninth centuries. This date range overlaps with the late sixth-century vertically-wheeled sawmill (WJ-01) in Jarash. However, the variable reliability of the dated OM fractions creates uncertainty, and the dating evidence does not yet confirm the timing of introducing simple chute watermill technology into the study area. The plausible but not yet proven coexistence of vertically-wheeled water-powered stone-saw technology and two types of horizontal watermill technology in the Byzantine–Early Islamic period in the study area is consistent with the idea that, by this time, the choice between the available technologies depended on the nature of the task, water availability, cost, and human skillsets available. The impressive development of both arubah and chute watermills at Tell Shihab is a late 19th-century example of such a choice (Schnitzer 2002).

CONCLUSIONS

The case study demonstrated the feasibility of identifying horizontal watermill construction dates based on ^{14}C dating of OM fractions in construction mortars, with the veracity of the dating influenced by the mortar type and the integrity of the dated OM fraction. The dating of all mortar types was challenging due to the relatively small OM content and the severe loss of macrocharcoal material—the preferred fraction—during conventional pretreatment. Humic and humin fractions in earthen mortars are unlikely to yield ages related to watermill construction: the study found that the humic and humin fractions in these mortars yield significantly older dates than macrocharcoal or BOF fractions, which is attributed to "old carbon" contamination of the soil clay binder. It is recommended that watermill mortar samples collected for dating be large enough to overcome the problems posed by the small macrocharcoal content and inevitable pretreatment sample losses. There is potential for future research to refine the pretreatment protocols to enhance the survival of fragile macrocharcoal OM in watermill construction mortars.

The arubah watermills fall into two distinct chronological groupings. Three arubah watermills in the Jarash Valley have reasonably reliable TPQ construction dates from the Middle Islamic Mamluk period (late 12th–late 13th centuries) based on calibrated macrocharcoal ages, including two dated from short-lived twigs. Less reliable but plausible calibrated BOF ages from two other watermills cluster in the 13th to 15th century period. A chronological hiatus of approximately four to six centuries separates these watermills from an earlier group represented by WJ-05 and WJ-07 in the city's Watergate cluster. These two watermills have plausible calibrated BOF ages in the fifth–ninth-century period, which spans the Byzantine–Early Islamic transition. Although less reliable than macrocharcoal ages, these BOF ages are among the earliest arubah watermill dates in the southern Levant. Other than a smaller tower footprint and an all-masonry head race substruction—a feature shared with the chute watermills—these early arubah watermills share the same basic architecture as those constructed in the Middle Islamic period.

The ^{14}C results from the two chute watermills are not definitive; however, the possible sixth/seventh-century TPQ date from the chute watermill at Tannur spring is not inconsistent with published dates for similar installations in the southern Levant. An important conclusion is that the coeval use of vertically wheeled and horizontally wheeled (chute and arubah) water-powered technologies in the sixth–seventh centuries in the study area is plausible, although not yet proven.

All seven arubah watermills in the study were modest-sized installations with a single arubah and probably operated a single pair of millstones. They were supplied from stream diversion canals or springs. A relatively short operational life is indicated for several watermills in the study; however, at least one other operated intermittently over many centuries. Later structural changes are common features of arubah watermills, and mortar samples from the arubah and arubah towers that formed part of the original architecture will likely yield dates closest to the watermill construction date. More detailed research of arubah carbonate deposits could clarify watermill operating parameters and provide valuable hydroclimate proxy data similar to that obtained from aqueduct carbonate deposits.

ACKNOWLEDGMENTS

The assistance of the Director General and staff of the Jordanian Department of Antiquities in facilitating fieldwork and issuing permits is gratefully acknowledged. The field research was partially funded through Rodney R. T. Prider Travel Scholarships and school grants from the University of Western Australia. The author is indebted to the Jarash Hinterland Survey (JHS) for making their survey results available and for JHS funding two ^{14}C samples. The balance of the ^{14}C program was self-funded.

COMPETING INTERESTS

The author declares he is unaware of any competing interest concerning this submittal.

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