Radiocarbon, Vol 65, Nr 4, 2023, p 979–1002 DOI:10.1017/RDC.2023.40

DATING ANCIENT CANAL SYSTEMS USING RADIOCARBON DATING AND ARCHAEOLOGICAL EVIDENCE AT TELLO/GIRSU, SOUTHERN MESOPOTAMIA, IRAQ

Ella Egberts[1,2]* • Jaafar Jotheri[3,4] • Angelo Di Michele[1] • Antony Baxter[1,5] • Sebastien Rey[1]

[1]The British Museum, Department of the Middle East, Great Russell Street, London, WC1B 3DG, UK
[2]School of Archaeology and Ancient History, University of Leicester, University Road, Leicester, LE1 7RH, UK
[3]University of Al-Qadisiyah, Department of Archaeology, Diwaniyah, 88, Iraq
[4]Durham University, Department of Archaeology, Durham, DH1 3LE, UK
[5]Museum of London Archaeology, 46 Eagle Wharf Road, London, N1 7ED, UK

ABSTRACT. Mesopotamia is often regarded the "cradle of civilization." The development of water management practices in the region is thought to have played a key role in the emergence of these early civilizations. We present the first direct dating of a palaeo-canal system at the ancient city of Girsu, Mesopotamia (modern Iraq) (occupied between 4800 and 1600 BC). We describe the use of archaeological and radiocarbon (^{14}C) dating techniques to establish the age of this canal system. Our results show considerable differences between shell ^{14}C dates on the one hand and charcoal ^{14}C dates and archaeological evidence on the other. This likely reflects the impact of freshwater reservoir effects from the Tigris and Euphrates Rivers. Although the FRE from rivers is widely acknowledged, its impact on ^{14}C dates in Mesopotamia is rarely discussed and poorly understood. Our results provide a first indication of its variability and magnitude. With the publication of our results we aim to highlight the problem and re-initiate collaborative research efforts in improving ^{14}C dating in this important region.

KEYWORDS: freshwater reservoir effect, irrigation, Mesopotamia, radiocarbon dating, rivers.

INTRODUCTION

Worldwide, people have developed different canal and irrigation systems to manage their water supply in response to environmental or climatic changes or increased agricultural activities (Jacobsen 1960; Gibson and Downing 1974; Hole 1994; Cremaschi et al. 2016; Nissen 2016; Lang and Stump 2017; Cremaschi et al. 2018; Cajigas et al. 2020). Water management is considered an important technological step in human history and is viewed as one of the "prime movers" behind the emergence of the earliest urban societies in Mesopotamia (Crawford 2004; Rost 2017) which brought about many inventions we recognize as part of our own societies today (e.g., stratified society, a complex administrative system, writing, armies, laws) (Postgate 1992; Algaze 1993; Crawford 2004; Algaze 2008a). Understanding the timing of the development of canal and irrigation systems (water management practices) in ancient Mesopotamia is therefore a fundamental research objective.

Archaeological and textual records from Mesopotamia have been exerted to address this topic (Jacobsen 1960; Algaze 2008b; Rost 2017; Schrakamp 2018; Borrelli 2020). The earliest textual evidence for fully developed irrigation networks and their cuneiform terminology dates from the Early Dynastic IIIb/Presargonic period and stems from the Sumerian city-state of Lagash (ca. 2475–2315 BC) (Schrakamp 2018) (Table 1 for chronology). Earlier textual indications of irrigation systems are probably masked by the ambiguity of early cuneiform writing (Nissen 2016; Schrakamp 2018). The EDIIIb and later texts show that at least by ~2400 BC

*Corresponding author. Email: e.egberts@leicester.ac.uk

Table 1 Chronology of ancient southern Mesopotamia. This table is based on extensive bibliography, the main works are referred to here. Dating for the 6th to the 4th millennium (Ubaid and Uruk phases) is essentially based on the workshop "Delineating the End of a World: Reassessing the Ubaid/post-Ubaid Transition in Greater Mesopotamia" (Baldi, Abu Jayyab 2022) and on new data from Uruk (Van Ess, Heußner 2015). Both base the chronology on new data obtained from ^{14}C samples. The 3rd–1st millennium BC is largely based on the Middle Chronology II proposed by W. Sallaberger and I. Schrakamp for the ARCANE project (Sallaberger and Schrakamp 2015).

Dates AD/BC	South Mesopotamia		Middle East Chronology	
6500–6000 BC	Ubaid 0		Early Chalcolithic	
6000–5700 BC	Ubaid 1			
5700–5300 BC	Ubaid 2		Middle Chalcolithic	
5300–4900 BC	Ubaid 3			
4900–4500 BC	Ubaid 4			
4500–4200 BC	Ubaid 5		Late Chalcolithic	I
4200–3900 BC	Early Uruk			II
3900–3400 BC	Middle Uruk			III
				IV
3400–3100 BC	Late Uruk			V
3100–2900 BC	Jemdet Nasr		Early Bronze Age	I
2900–2600 BC	Early Dynastic I			II
2600–2350 BC	Early Dynastic IIIA			
	Early Dynastic IIIB (Lagash)			III
2350–2200 BC	Early Akkad			IVA
2200–2100 BC	Late Akkad	Gutean		
		Lagash II		IVB
2100–2000 BC	Ur III			
2000–1800 BC	Isin/Larsa		Middle Bronze Age	I
1800–1600 BC	Old Babylonian			II
1600–1200 BC	Kassite		Late Bronze Age	I/II
1200–700 BC	Middle Babylonian		Iron Age	I/II
700–500 BC	Neo-Babylonian			III
500–300 BC	Achaemenid		Persian Period	
300–130 BC	Seleucid		Hellenistic - Seleucid	
130 BC–200 AD	Parthian		Hellenistic /Roman/Parthian	
200–650 AD	Sasanian		Roman/Byzantine/Sasanian	
650–900 AD	Early Islamic		Byzantine - Islamic	

sophisticated "hydraulic landscapes" (cf. Wilkinson et al. 2015:398) formed an integral and key part of the Mesopotamian world (as irrigation system, waterways between cities, (symbolic) delineation of space, as element in warfare and the confirmation of power) (Jacobsen 1960; Algaze 2008b; Rost 2017; Schrakamp 2018; Borrelli 2020).

With limited access on the ground for research projects due to decades of war in Iraq, much of the Mesopotamian landscape has been studied based on remote sensing data (Hritz and Wilkinson 2006; Hritz 2010; Wilkinson et al. 2015; Jotheri 2016). This, combined with results from earlier archaeological surveys (Adams 1965; Adams and Nissen 1972; Adams 1981) has provided a fascinating dataset for Mesopotamia, which presents a complex picture of landscape evolution and human-environment interactions over millennia, spanning the rise of

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urbanism and the development of the earliest water engineering efforts. In search for a chronology, archaeological survey data has been used as a proxy for estimating the age of Mesopotamian landscape features. For example, the alignment of contemporaneous sites, dated based on cultural/typological chronologies of surface finds, revealed shifting settlement patterns which were inferred to reflect shifting watercourses (Adams 1965; Adams and Nissen 1972; Adams 1981). However, without direct dating, integrating palaeo-environmental, geological/geomorphological and archaeological records and distilling interactions, relationships and causality, whilst avoiding circular reasoning, is challenging.

Now that international fieldwork projects are returning to Iraq, direct dating ancient (hydraulic) landscapes and palaeo-environmental records, as well as building an up-to-date ^{14}C database for archaeological evidence, are research priorities to provide a chronology for human-environment interactions and the pivotal processes that led to the emergence of urbanism and the earliest civilizations in Mesopotamia and offer an up-to-date dataset against which pervious theories can be tested.

We present here our efforts of dating the canal system of Girsu, one of the four main cities of the Lagash state (ca. 2475–2315 BC) (Table 1 presents a cultural chronology of southern Mesopotamia), using archaeological and ^{14}C methods, and discuss the versatility of both methods for this context.

BACKGROUND

The site of Tello/ancient Girsu is situated about 55 km north of the modern city of Nasiriyah, in the ThiQar Province in southern Iraq, between the modern Euphrates and the Tigris (Figure 1). The floodplains of southern Mesopotamia consist of 15–20 m of Holocene fluvial deposits (Yacoub 2011). Relics of anastomosing rivers, forming a micro-topography of floodbasins and levees, characterize the landscape. Girsu and many other famous sites in Mesopotamia are found along such relic levees (Adams 1965; Adams and Nissen 1972; Adams 1981) and are clearly visible in the landscape (the tell of Girsu rises ~15 m above the floodplain). Unfortunately, the marsh settlements that must have existed in the floodbasins are deeply buried and mostly unknown (Oates 1960; Jotheri et al. 2022).

French diplomat and archaeologist Ernest de Sarzec rediscovered Girsu in the 1870s and started excavations at the site in 1877. He continued until 1900, after which Gaston Cros took over (1903–1909). Cros was followed-up by Henry de Genouillac (1929–1931) and André Parrot (1931–1933). These early excavations provided the first tangible evidence of the Sumerian civilization as well as large quantities of finds from the Ubaid 4 to the Parthian periods (Cros et al. 1910; Sarzec and Heuzey 1912; Genouillac 1936; Parrot 1948), now on display in many of the world's largest museums. The British Museum has resumed excavations since 2016, focusing on archaeological research (including re-contextualizing previously excavated material), training and collaboration, heritage management and site conservation.

The oldest evidence of human presence at Girsu dates to the Ubaid 4 period (4900–4500 BC) (Genouillac 1936; Parrot 1948). Recent discoveries suggest a complex socio-cultural settlement, which further increased during the following Uruk period (4200–3100 BC) (Genouillac 1936; Parrot 1948; Rey 2019). There seems to be a gap between the Uruk occupation and the Early Dynastic I (ED I) (2900–2600 BC) (Postgate 1986; Algaze 1993). The Early Dynastic period appears to be the most significant one at Girsu; an urban center and vast religious complex developed during this phase. Girsu became the capital of the Lagash Kingdom during the

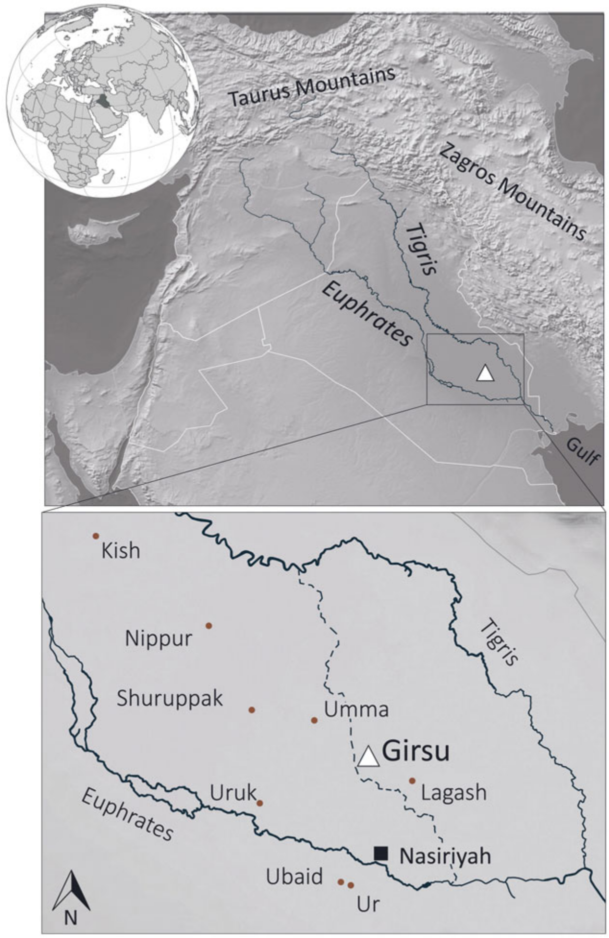

Figure 1 Map of Mesopotamia (modern Iraq), showing the location of Girsu in relation to the modern Euphrates and Tigris Rivers. Detailed map shows Girsu and the main archaeological sites in the region (illustration prepared by the author. Sources: High Resolution Shaded Relief (naturalearthdata.com), waterways (diva-gis.org), JAXA DSM).

second dynasty of Lagash (2200–2100 BC) and remained the religious center of the state after political power shifted to the city Lagash. Girsu declined with the fall of Ur (ca. 2000 BC) and appears abandoned at the beginning of the Old Babylonian period (1800–1700 BC) with a short reuse of the site during the 3rd century BC.

A key landmark at Girsu is the "bridge," which once crossed canal 3 (Figure 2, inset). Its construction is dated to the Early Dynastic and it stayed in use until the abandonment of the site after the Isin-Larsa period. It was partly excavated for the first time between 1929 and 1930 by De Genouillac (Genouillac 1936). Later excavations under Parrot exposed the full structure (Parrot 1948). He provisionally called it a water regulator, but later identified it as a pseudo-tomb for a priest-king (Parrot 1948). Later scholars reinterpreted the structure i.a. as a weir (Jacobsen 1960), or canal regulator (Wilkinson 2013), as a bridge (Margueron 2005; Rey and

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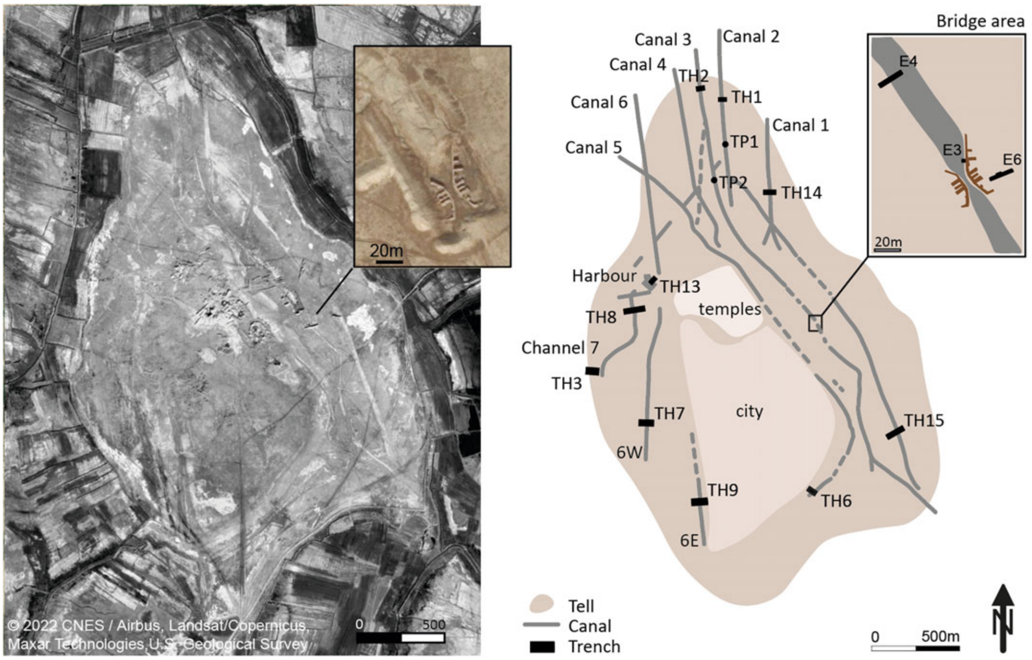

Figure 2 Google satellite image (2022) (gray scale by lightness and enhanced contrast) of Girsu with an inset close-up of the bridge area (left). Illustration of the main canals identified at Girsu, and the location of the excavation trenches (right) (illustration prepared by the author) (See for a more detailed discussion Jotheri et al. submitted).

Lecompte 2020), and most recently as a "throated flume" (Parshall flume) *avant la lettre* (E. Torun, pers. comm. 2021) in which the hydraulic feature also functioned as a bridge. Based on cuneiform textual evidence the bridge has also been interpreted as the head gate or reservoir/bridge of the well-known íd-NINA-šè-DU canal ("the canal going to Nina"), built by Urukagina in his 2nd regnal year (see Rey [2016] and Rost [2011] for a further discussion on the location of the Nina canal and its head gate).

SAMPLE COLLECTION

Radiocarbon dating of shell and charcoal samples collected from fluvial palaeo-canals around Girsu is part of an on-going multidisciplinary research program investigating the palaeo-environment of the ancient city (Egberts et al. submitted). Remote sensing analysis and field walking has provided a detailed palimpsest map of the cities' waterscape, as well as further insights in the layout of the urban area (Jotheri et al. submitted).

We selected trench locations based on our remote sensing data and field observations. Geoarchaeological trenches were excavated across sedimentary sequences to provide stratigraphic cross sections of old canal sediments, lake, and floodplain deposits. All sections were recorded using traditional sedimentological logging techniques and photography. The locations were recorded with a Leica differential global positioning system (DGPS). Environmental, geochemical and ^{14}C samples were obtained from suitable deposits using conventional sampling methods (Campbell et al. 2011; Jotheri et al. 2016). J. Jotheri identified the shell samples. All ^{14}C samples were wrapped in aluminum foil, labeled and sealed in plastic bags.

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A total of 15 ^{14}C samples were collected from 7 different palaeo-canals around Girsu (Figure 2). Samples were collected during excavation and selected from key stratigraphic units. Two samples were collected from ancient lacustrine sediments discovered in the western part of the tell (Figure 2), interpreted as harbor.

Three excavations (E3, E4, E6) were conducted around the ancient bridge (Figure 2, inset). Area E3 consisted of a 2×2 m stratigraphic excavation, placed at the base of one of the bridge walls. The aim was to establish the depth of the bridge foundations and the nature of the underlying deposits. Undisturbed archaeological deposits were found below 180 cm of backfill and slope wash, which accumulated after the French excavations ceased in the bridge area in the 1930s. A dark silt layer including pottery was found directly below the bridge wall (context 13002). Below this, 15–20 cm pale, compact, clean silt was found (context 13003) covering a mudbrick wall (context 13006). The wall enclosed an internal space, which was filled with collapse, covering *in situ* pottery, charcoal, burnt animal bone, shell fragments, burnt mudbrick and a ceramic sickle fragment. Artifacts and pottery from this context date to Ubaid 4 (4900–4500 BC). From this context charcoal and shell ^{14}C samples were collected.

Trench E4 was excavated to the northwest of the bridge, across the westbank of canal 3. The canal fill consisted of 300 cm normally graded, moderately compact sand and silt, with increasing anthropogenic inclusions and ceramics dating to the Late Akkadian/Isin-Larsa period (2200–1800 BC) and Old Babylonian Period (1800–1600 BC). Deposits cut by canal 3 contained *in situ* oven structures (tannurs) and ceramics dated to Ubaid 4.

E6 was excavated as a stepped trench against the oblique west-facing slope of the French excavation cut. Ubaid 4 deposits were exposed at the base of the trench, ~3.3 m below ground surface (8.28 m asl) (context 12156). Overlying Ubaid deposits appear cut during the initial bridge construction. The fill of this cut yielded late third millennium BC pottery and occasional residual Uruk material. This was covered with 230 cm of deposits dated to the Isin-Larsa period (2000–1800 BC).

METHODOLOGY

All samples were analyzed by Beta Analytic by accelerator mass spectrometry (AMS). Pretreatment and analysis were conducted following standard protocols (Beta Analytic 2022). Shell samples were first washed with deionized water. The material selected for ^{14}C dating was then crushed/dispersed, and repeatedly subjected to HCl etching. The pretreatment of the charred material consisted of an acid/alkali/acid or acidic washes (Dunbar et al. 2016) (Table 2). $\delta^{13}C$ and $\delta^{18}O$ were obtained by Beta Analytic using isotope ratio mass spectrometry (IRMS) (Beta Analytic 2022). All dates were calibrated with OxCal v 4.4.4 (Bronk Ramsey 2021), using the IntCal2020 Northern Hemisphere calibration curve (Reimer et al. 2020). Sigmas and conventional radiocarbon ages are rounded to the nearest 10 years. When counting statistics produced sigmas lower than ± 30 years, a conservative ± 30 BP is cited for the result.

Chronological Framework

The chronological framework proposed here is based on geomorphological and archaeological interpretations and is a working hypothesis. The model includes the stratigraphic relationship between samples in case it could be directly observed in section, and dates BC in case the samples could be directly associated with datable archaeological evidence. In addition, a relative chronology for channel activity was reconstructed based on analysis of remote

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Table 2 AMS ^{14}C dates, presented per canal and in stratigraphic order per trench; heights are in meters above sea level. The calculation of the used FRE is discussed in the text.

Context	Trench	Field number	Lab no.	Height (m asl)	Species	Convent. age	IRMS $\delta^{13}C$	IRMS $\delta^{18}O$	(Mat.): pretreatment	Unmodeled (BC) (95.4%)		Modeled (cal BC) (95.4%)		Unmodeled (cal BC), shell FRE corrected		Modeled (cal BC), shell FRE corrected	
										from	to	from	to	from	to	from	to
Canal 1	TH14	TH14-SH1-60	545370	8.7	*Corbicula fluminea*	5840 +/- 30 BP	−8.3	−9.35	(shell): acid etch	4791	4611	4791	4611	4509	4227	4510	4227
Canal 2	TP1	TH10-SH1-80	5.00E+05	7.6	*Melanoides tuberculata*	6050 +/- 30 BP	−7.6	−6.36	(shell): acid etch	5036	4846	5013	4841	4752	4446	4722	4447
	TH1	TH1-SH4-40	508712	7.9	*Corbicula fluminea*	5930 +/- 30 BP	−6.8	−8.3	(shell): acid etch	4897	4719	4902	4721	4615	4317	4609	4341
	TH15	TH15-SH2-35	545369	8.05	*Melanoides tuberculata*	4410 +/- 30 BP	−10.1	1.8	(shell): acid etch	3315	2916	2904	2887	2866	2571	2831	2541
Below canal 3	TH2	TH2-SH1-145	508713	6.75	*Corbicula fluminea*	6860 +/- 30 BP	−6.4	−9.89	(shell): acid etch	5830	5667	5826	5662	5556	5296	5539	5277
Below canal 3/bridge	E3	13012_TG38	553724	6.1	*Corbicula fluminea*	6020 +/- 30 BP	−10.5	−9.1	(shell) acid etch	4999	4803	4904	4800	4717	4412	4702	4499
		13007_TG33	553725	6.1	Charcoal	5710 +/- 30 BP	−24.8		(charred material) acid/alkali/acid	4672	4456	4672	4499	4672	4456	4672	4499
		13009_TG35	555135	6.1	Charcoal	5640 +/- 30 BP	−25.9		(charred material): acid/alkali/acid	4542	4367	4549	4499	4542	4367	4549	4499
	E4	16006	515281	10.36	Organic sediment	5750 +/- 30 BP	−23.7		(organic sediment): acid washes	4691	4502	4691	4504	4691	4502	4690	4504
	E6	TG-E6	545371	8.28	Charcoal	5590 +/- 30 BP	−26.6		(charred material): acid/alkali/acid	4491	4352	4496	4355	4491	4352	4496	4355
Canal 3	TP2	TH12-SH1-40	515279	8.8	*Melanoides tuberculata*	6090 +/- 30 BP	−11.5	−0.16	(shell): acid etch	5206	4853	5208	4905	4801	4489	4821	4501
	E4	16014-SH2-320	515280	10.26	*Melanoides tuberculata*	4150 +/- 30 BP	−7.2	2.16	(shell): acid etch	2876	2627	2887	2666	2536	2221	2562	2241
Canal 5	TH6	TH6-SH5-120	508716	8.5	*Corbicula fluminea*	4440 +/- 30 BP	−7.2	−2.27	(shell): acid etch	3331	2930	2904	2892	2905	2605	2862	2601
		TH6-SH4-100	508715	8.7	*Corbicula fluminea*	6210 +/- 30 BP	−6.3	−5.76	(shell): acid etch	5297	5050	5297	5051	4943	4629	4941	4626
Above canal 6E	TH9	TH9-CH1-70	515277	8.4	*Corbicula fluminea*	4080 +/- 30 BP	−29.1		(charred material): acid/alkali/acid	2857	2492	2857	2492	2857	2492	2856	2492

(Continued)

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Table 2 (*Continued*)

										Unmodeled (BC) (95.4%)		Modeled (cal BC) (95.4%)		Unmodeled (cal BC), shell FRE corrected		Modeled (cal BC), shell FRE corrected	
Context	Trench	Field number	Lab no.	Height (m asl)	Species	Convent. age	IRMS $\delta^{13}C$	IRMS $\delta^{18}O$	(Mat.): pretreatment	from	to	from	to	from	to	from	to
Below canal 6W	TH7	TH7-SH3-100	508718	8.05	*Melanoides tuberculata*	4370 +/- 30 BP	−5.9	−3.01	(shell): acid etch	3091	2906	2904	2885	2828	2523	2796	2486
Canal 6W		TH7-SH2-90	508717	8.15	*Melanoides tuberculata*	4130 +/- 30 BP	−4.9	−6.17	(shell): acid etch	2871	2581	2881	2626	2505	2191	2533	2212
Below Canal 7	TH3	TH3-SH1-400	508714	4.6	*Corbicula fluminea*	6520 +/- 30 BP	−5.6	−9.87	(shell): acid etch	5557	5381	5551	5380	5266	4971	5253	4962
Canal 7	TH8	TH8-SH2-75	508720	8.43	*Melanoides tuberculata*	6280 +/- 30 BP	−3.6	−6.66	(shell): acid etch	5324	5132	5324	5132	5021	4705	5015	4706
		TH8-SH1-60	508719	8.6	*Corbicula fluminea*	4940 +/- 30 BP	−2.5	2.53	(shell): acid etch	3779	3647	3783	3647	3531	3257	3544	3272
Harbor	TH13	TH13-SH6-130	545372	8.9	*Melanoides tuberculata*	4380 +/- 30 BP	−9.1	−4.69	(shell): acid etch	3093	2911	2904	2886	2837	2537	2817	2519
		TH13-SH1-76	545376	9.54	*Melanoides tuberculata*	3850 +/- 30 BP	−7.1	5.29	(shell): acid etch	2456	2204	2459	2207	2120	1810	2133	1852

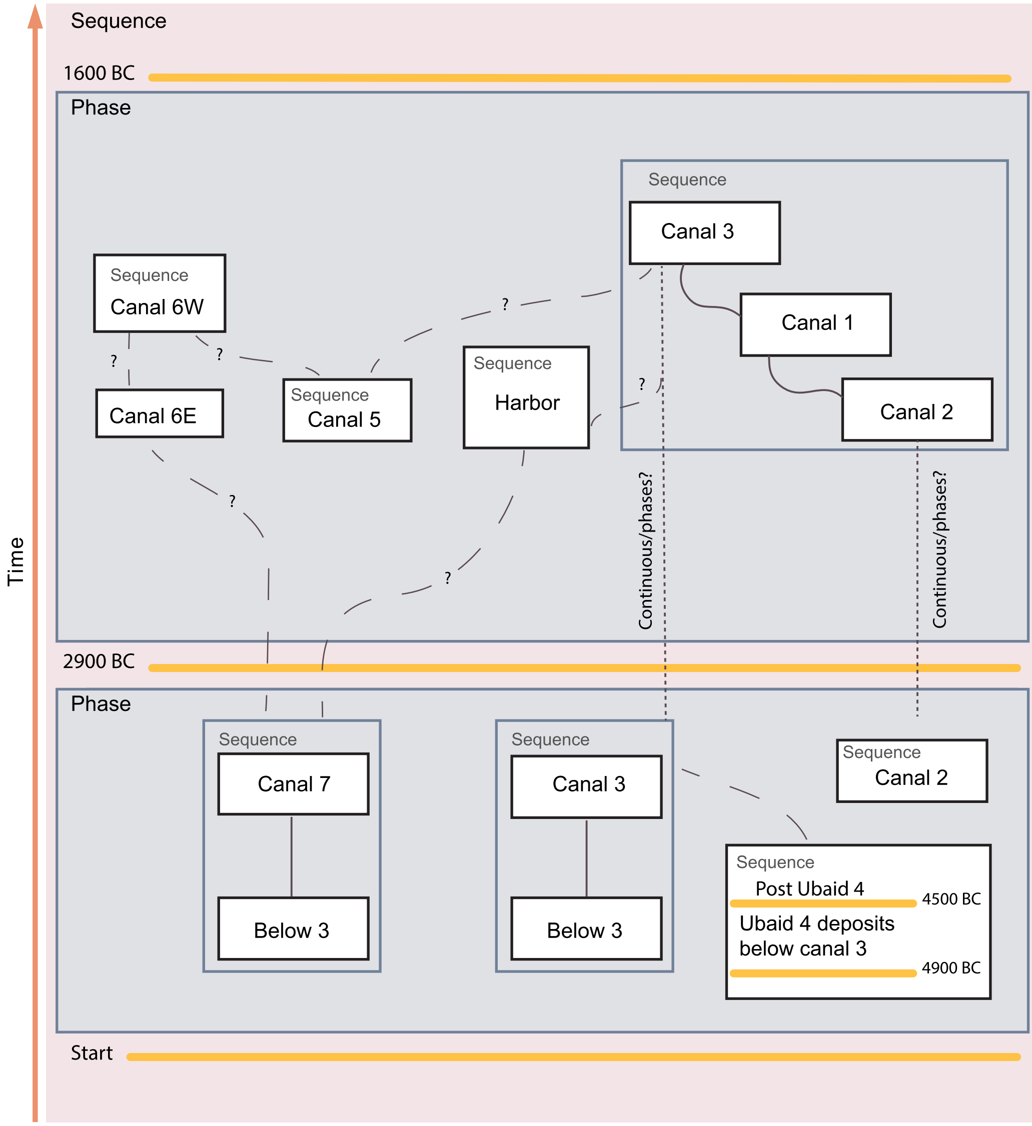

Figure 3 Schematic representation of the OxCal Bayesian model used in this study. Orange lines represent dated boundaries. Solid lines represent direct and stratigraphic relationships within channels, dashed lines represent relative chronological relationships based on remote sensing and field observations.

sensing data, the high-resolution DEM of the site (see Egberts et al. submitted), and field observations. Phases, sequences, and boundaries are used to represent these chronological constraints, as defined in Bronk Ramsey (2009). Bayesian modeling has been performed using OxCal v 4.4.4 (Bronk Ramsey 2021) and the IntCal20 calibration curve (Reimer et al. 2020). Figure 3 shows a schematic representation of the Bayesian model.

A two-phase sequential model is applied. In this framework no hiatus is assumed between the two main phases. Within the main phases some of the dates could be ordered according to stratigraphic or archaeological constraints, or according to the reconstructed relative

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chronology (e.g., the final activity of canal 2, 1 and 3). Samples in the first phase are from below the channel belts and from the earliest phases of channel activity. The second main phase contains all the samples from the canal and lacustrine sediments that were associated with archaeological evidence.

RESULTS

Results are summarized in Table 2. The date list below presents unmodeled calibrated ^{14}C results.

Canal 1

Trench TH14 across palaeocanal 1 (31°34'05.7"N 46°10'43.5"E)

5840 ± 30 BP **4791–4611 cal BC**

545370 - TH14-SH1-60 $\delta^{13}C = -8.3$

Fossil *Corbicula fluminea* shell obtained at 60 cm below ground surface (6.7 m asl). The shell was collected from a thin, finely bedded silt and clay layer within a ~120 cm thick, cross-laminated sand and silt unit filling canal 1. Preceding canal deposits and reddish brown floodplain deposits underlie and are cut by canal 1. Collected 2019 by E. Egberts and J. Jotheri; submitted by E. Egberts and J. Jotheri.

Comment: The date overlaps with a ^{14}C date (carbonized seed [MC-2386]) at Oueili (Huot et al. 1981) from layer Level 2, related to the Ubaid 4 (4900–4500 BC). All pottery recovered from trench TH14 was found below the canal fill and dates to the Ur III/Isin Larsa period (2100–1800 BC). The ^{14}C sample is older than the archaeological evidence obtained from below the canal fill. Considering the freshwater reservoir effect, this sample provides a *terminus post quem* for canal 1 infilling at Girsu.

Canal 2

Trench TH1 across palaeocanal 2 (31°34'25.2"N 46°10'33.3"E)

5930 ± 30 BP **4897–4719 cal BC**

508712 - TH1-SH4-40 $\delta^{13}C = -6.8$

Fossil *Corbicula fluminea* shell obtained at 40 cm below ground surface (7.9 m asl) collected from a 70 cm thick, horizontally bedded fine sand unit filling canal 2. Collected 2018 by E. Egberts and J. Jotheri; submitted by E. Egberts and J. Jotheri.

Comments: The date overlaps with a ^{14}C date at Basra (organic rich sediments, sample AA94339) (Hritz et al. 2012), A ^{14}C date at Oueili, from Z28 Level 1 (charcoal, sample MC-2382) (Huot et al. 1981) and a ^{14}C date at Uruk, from remains of reed from the deepest strata in Eanna, lying on natural soil (reed, sample H138-123) (Münnich 1957). No cultural material was recovered from this trench. This sample provides a *terminus post quem* for canal 2 infilling at Girsu.

Testpit TP1 in paleocanal 2, 230 m south of TH1 (31°34'17.5"N 46°10'33.8"E)

6050 ± 30 BP **5036–4846 cal BC**

515278 - TH10-SH1-80 $\delta^{13}C = -7.6$

Fossil *Melanoides tuberculata* shell obtained at 80 cm below ground surface (7.6 m asl) and collected from a homogeneous, bedded sand unit filling canal 2. The base of the canal fill was not reached and no cultural material was recovered from this trench. Collected 2018 by J. Jotheri; submitted by E. Egberts and J. Jotheri.

Comment: This date is stratigraphically consistent with 508712/TH1-SH4-40 and 545369/TH15-SH2-35, also obtained from canal 2 fill. This date overlaps with charcoal at Oueili, Z28 Level 1 (sample MC-2382) (Huot et al. 1981) and with reed from the deepest strata in Eanna at Uruk (H138-123) (Münnich 1957). Considering the freshwater reservoir effect, this sample provides a *terminus post quem* for canal 2 infilling at Girsu.

Trench TH15 across palaeocanal 2, 2120 m south of TH1 (31°33'23.9"N 46°11'10.1"E)

4410 ± 30 BP **3315–2916 cal BC**

545369 - TH15-SH2-35 $\delta^{13}C = -10.1$

Fossil *Melanoides tuberculata* shell collected at 35cm below ground surface (8.05 m asl) from a 200 cm thick well sorted, horizontally and cross-bedded sand unit filling canal 2. A cultural layer below the canal fill (~6.4 m asl) consisted of compact reddish brown clay and yielded ceramic fragments. Collected 2019 by E. Egberts and J. Jotheri; submitted by E. Egberts and J. Jotheri.

Comment: This date is stratigraphically consistent with 515278/TH10-SH1-80 and 508712/TH1-SH4-40, also obtained from canal 2. The ^{14}C date overlaps with a ^{14}C date at Nippur from Level VIIB, related to the Early Dynastic II (charcoal, sample P.806) (Stuckenrath and Ralph 1965). Archaeological material obtained from a cultural layer below the canal dates to th UrIII/Isin-Larsa period (2100–1800 BC). This ^{14}C age pre-dates the archaeological evidence obtained from below the canal fill. Considering the freshwater reservoir effect, this sample provides a *terminus post quem* for canal 2 infilling at Girsu. Compare with shell ^{14}C sample from TH6 (sample 508716/TH6-SH5-120, see below), showing an overlapping age range.

Below the bridge and Canal 3

Excavation area E3, below the bridge (31°33'43.7"N 46°10'53.0"E)

6020 ± 30 BP **4999–4803 cal BC**

553724 – 13012_TG38 $\delta^{13}C = -10.5$

5710 ± 30 BP **4672–4456 cal BC**

553725 – 13007_TG33 $\delta^{13}C = -24.8$

5640 ± 30 BP **4542–4367 cal BC**

555135 – 13009_TG35 $\delta^{13}C = -25.9$

Two charcoal samples (553725/13007_TG33 and 555135/13009_TG35) and a fossil *Corbicula fluminea* shell (553724/13012_TG38) collected from context 13005 (at 6.1 m asl). Collected 2017 by E. Egberts; submitted by E. Egberts.

Comments: the charcoal samples are in good agreement and overlap with the age of the archaeological evidence. The ceramic sickle is typical for the Ubaid period and all pottery from context 13005 dates to the Ubaid 4 (4900–4500 BC). They are also stratigraphically in good agreement with charcoal samples from E4 and E6 (see 545371/TG-E6 and 515281/16006). The

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shell ^{14}C date also overlaps with the age of the archaeological evidence but dates older than the charcoal samples. 55372513007_TG33 and 555135/13009_TG35 overlap with a ^{14}C date at Oueili (carbonized seed, sample MC-2384) from Y28 black ashy layer Level 2, associated with Ubaid 4 (4900–4500 BC) (Huot et al. 1981). 553724/13012_TG38 overlaps with a ^{14}C date from reed at Uruk (H138-123) (Münnich 1957) and a ^{14}C date from charcoal at Oueili (sample MC-2382), related to Z28 Level 1 (Huot et al. 1981).

The charcoal samples provide a ^{14}C date for Ubaid 4 occupation at Girsu. It is certain that Ubaid material discovered in the 1930s (Genouillac 1936; Parrot 1948) comes from the same or closely associated occupation deposits.

Excavation area E6, east of the bridge (31°33'43.4"N 46°10'54.1"E)

5590 ± 30 BP **4691–4502 cal BC**

545371 – TG-E6 *$\delta^{13}C$= –26.6*

Charcoal collected at ~3.3m below ground surface (8.28 m asl) from an occupation deposit (context 12156) which yielded Ubaid 4 pottery. Collected 2019 by E. Egberts and T. Baxter; submitted by E. Egberts and J. Jotheri.

Comment: this date provides a ^{14}C date for intact Ubaid 4 occupation deposits. The date overlaps with a ^{14}C date from Ubaid 4 deposits at Oueili (carbonized seed sample MC-2384) (Huot et al. 1981). It is highly likely that Ubaid 4 material discovered in the 1930s (Genouillac 1936; Parrot 1948), comes from similar deposits. Although no lateral relationship could be established between Ubaid 4 deposits in E3 and E4 due to previous French excavation cuts, in terms of absolute height (m asl) the dates are generally in stratigraphic agreement.

Excavation area E4, northwest of the bridge (31°33'45.9"N 46°10'50.9"E)

4150 ± 30 BP **2876–2627 cal BC**

515280 - 16014-SH2-320 *$\delta^{13}C$= –7.2*

Fossil shell *Melanoides tuberculata* collected from 320 cm below the surface (10.26 m asl) from bedded sandy silt. Collected 2018 by E. Egberts and T. Baxter; submitted by E. Egberts and J. Jotheri.

Comments: This date overlaps with sample p.798 from Level IXB low, at Nippur, ED I, and with sample p.810 from Level V, ED II/III (Stuckenrath and Ralph 1965). It also overlaps with charcoal at Girsu UGAMS-8185 (G-1) from the *Maison de Fruits* (Hritz et al. 2012).

Considering the freshwater reservoir effect, 515280/16014-SH2-320 provides a *terminus post quem* for canal 3 infilling at Girsu. Archaeological material from the overlying sediments dates to the Isin/Larsa period (2000–1800 BC).

5750 ± 30 BP **4691–4502 cal BC**

515281 – 16006 *$\delta^{13}C$= –23.7*

Charcoal collected from the oven structure exposed in the bank of canal 3, at 10.36 m asl. Collected 2018 by T. Baxter; submitted by E. Egberts and J. Jotheri.

Comments: This date overlaps with a ^{14}C date for Ubaid 4 at Oueili (carbonized seed, sample MC-2384 (Huot et al. 1981). Sample 515281/16006 provides a ^{14}C date for intact Ubaid 4 deposits at Girsu. Although no lateral relationship could be established between Ubaid 4 deposits in E3 and E4 due to previous French excavation cuts, in terms of absolute height (m asl) the dates are generally in stratigraphic agreement.

Canal 3

Trench TH2 across palaeocanal 3 (31°34'27.5"N 46°10'28.2"E)

6860 ± 30 BP **5830–5667 cal BC**

508713 - TH2-SH1-145 $\delta^{13}C = -6.4$

Fossil *Corbicula fluminea* shell collected at 145 cm below ground surface (6.75 m asl) from a reddish brown clay unit below a stratified cross-bedded sand unit and normally graded silt and clay units filling canal 3. No cultural material was recovered from this trench. Collected 2018 by E. Egberts and J. Jotheri; submitted by E. Egberts and J. Jotheri.

Comment: This date is stratigraphically consistent with sample 515279/TH12-SH1-40, also from canal 3 infill. The date overlaps with *Melanoides tuberculata* shell (sample EP3-4) at Eridu (Hritz et al. 2012) where the shell is associated with possible Ubaid 2/3 pottery. The sample also overlaps with a shell ^{14}C date at Tell al-Oueili (Valladas et al. 1996) (sample Ly-4550), thought to be associated with Ubaid I deposits. Considering the freshwater reservoir effect, this sample provides a *terminus post quem* for canal 3 infilling at Girsu.

Testpit TP2 in palaeocanal 3, 520 m south of TH2 (31°34'10.8"N 46°10'31.5"E)

6090 ± 30 BP **5206–4853 cal BC**

515279 - TH12-SH1-40 $\delta^{13}C = -11.5$

Fossil *Melanoides tuberculata* shell collected at 40 cm below ground surface (8.8 m asl) from a homogeneous, bedded sand unit filling canal 3. The base of the canal fill was not reached and no cultural material was recovered from this trench. Collected 2018 by J. Jotheri; submitted by E. Egberts and J. Jotheri.

Comment: This date is stratigraphically consistent with sample 508713/TH2-SH1-145, from the same canal. The date overlaps with a ^{14}C date at Eridu (shell, sample EP3-1) (Hritz et al. 2012), and with ^{14}C dated reed remains at Uruk, obtained from "the deepest strata in Eanna lying on natural soil" (Münnich 1957) and with a ^{14}C date at Oueili (charcoal, sample MC-2385) (Huot et al. 1981). Considering the freshwater reservoir effect, this sample provides a *terminus post quem* for canal 3 infilling at Girsu.

Canal 5

Trench TH6 across palaeocanal 5 (31°33'12.8"N 46°10'51.4"E)

6210 ± 30 BP **5297–5050 cal BC**

508715 - TH6-SH4-100 $\delta^{13}C = -6.3$

4440 ± 30 BP **3331– 2930 cal BC**

508716 - TH6-SH5-120 $\delta^{13}C = -7.2$

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Two fossil *Corbicula fluminea* shells; sample 508715/TH6-SH4-100 was collected at 100 cm below ground surface (8.7 m asl) from a bedded red clay unit interbedded with laterally graded sand lenses filling canal 5. Canal sediments were found overlying compact gray clay, which yielded ceramics, charcoal, shells and bones. Sample 508716/TH6-SH5-120 was collected at 120 cm below ground surface (8.5 m asl) from this cultural layer. Collected 2018 by E. Egberts and J. Jotheri; submitted by E. Egberts and J. Jotheri.

Comment: sample 508715/TH6-SH4-100 overlaps with charcoal at Oueili (samples MC-2383 and MC-2385) (Huot et al. 1981), with shell EP3-1 at Eridu (Hritz et al. 2012), and with ^{14}C dated reed at Uruk (sample H-138-123) (Münnich 1957). Pottery obtained from the cultural layer below the fill of palaeocanal 5 (from which 508716/TH6-SH5-120 was also obtained), dates to the Ur III/Isin-Larsa period (2100–1800 BC). Both shell samples date older than the archaeological context. The stratigraphic inconsistency between the samples may indicate reworking or variations in the freshwater reservoir effect.

Canal 6E

Trench TH9 across palaeocanal 6E (31°33'10.9"N 46°10'28.0"E)

4080 ± 30 BP **2857–2492 cal BC**

515277 - TH9-CH1-70 $\delta^{13}C = -29.1$

Charcoal collected at 70 cm below ground surface (8.4 m asl) from reddish brown and gray clay deposits interpreted as levee deposits and irrigation soils. This unit was found stratigraphically above and to the east of well sorted, bedded, medium sand, filling palaeocanal 6E. Stratified clay, silt and sand below and alongside the west bank of paleocanal 6E represent preceding canal and levee deposits. Collected 2018 by E. Egberts and J. Jotheri; submitted by E. Egberts and J. Jotheri.

Comment: This date overlaps with a ^{14}C date (charcoal, sample P.810) at Nippur associated with the EDII/EDIII period (2600–2350 BC) (Stuckenrath and Ralph 1965). Ceramics obtained from below the earlier canal deposits date to the Early Dynastic I (2900–2600 BC). Ceramics found adjacent to the second canal belt date to the Isin-Larsa (2000–1800 BC) period.

The ^{14}C date is consistent with the stratigraphic position of the sample, above EDI deposits.

Canal 6W

Trench TH7 across palaeocanal 6W (31°33'26.4"N 46°10'16.4"E)

4370 ± 30 BP **3091–2906 cal BC**

508718 - TH7-SH3-100 $\delta^{13}C = -5.9$

4130 ± 30 BP **2871–2581 cal BC**

508717 - TH7-SH2-90 $\delta^{13}C = -4.9$

Fossil *Melanoides tuberculata* shell (sample 508718/TH7-SH3-100) collected at 100 cm below ground surface (8.05 m asl) from gray clay deposits yielding pottery, charcoal, bone and shell. This cultural layer was stratigraphically below 100 cm of bedded sand filling palaeocanal 6W. A second fossil *Melanoides tuberculata* shell (sample 508717/TH7-SH2-90) was collected at 90 cm below the ground surface (8.15 m asl), near the base of a stratified, laminated sandy fill of palaeocanal 6W. A cultural layer cut by this palaeocanal yielded ceramics dating to Ur III and

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the Old Babylonian period (2100–1600 BC). Collected 2018 by E. Egberts and J. Jotheri; submitted by E. Egberts and J. Jotheri.

Comment: the date of sample 508718/TH7-SH3-100 overlaps with a ^{14}C date (charcoal, sample P.806) from Level VIIB, related to EDII (Stuckenrath and Ralph 1965). Sample 508717/TH7-SH2-90 overlaps with a ^{14}C date (charcoal, sample P.810) at Nippur from sounding P, Level V, related to the ED II/III (Stuckenrath and Ralph 1965). The ^{14}C dates of the shells are stratigraphically consistent. Both samples are older than the archaeological evidence obtained from below the canal fill, which dates to 2100–1600 BC. Considering the freshwater reservoir effect, these samples provide a *terminus post quem* for canal 6W infilling at Girsu.

Canal 7

Trench TH8 across palaeocanal 7 (31°33'47.7"N 46°10'13.4"E)

6280 ± 30 BP	**5324–5132 cal BC**
508720 - TH8-SH2-75	$\delta^{13}C = -3.6$
4940 ± 30 BP	**3779–3647 cal BC**
508719 - TH8-SH1-60	$\delta^{13}C = -2.5$

Fossil *Melanoides tuberculata* shell (508720/TH8-SH2-75) collected at 75 cm below ground surface (8.43 m asl), from a sand lens interbedded in reddish brown clay and silt, fill of palaeocanal 7. A second fossil *Corbicula fluminea* shell (508719/TH8-SH1-60) was collected at 65 cm below ground surface (8.6 m asl), from the same stratified sand unit filling in this palaeocanal. No cultural material was recovered from this trench. Collected 2018 by E. Egberts and J. Jotheri; submitted by E. Egberts and J. Jotheri.

Comment: Sample 508720/TH8-SH2-75 overlaps with a ^{14}C date at Oueili (charcoal, sample MC-2383) (Huot et al. 1981). Sample 508719/TH8-SH1-60 compares with a ^{14}C date at Uruk, obtained from the Eanna Temple C-I, associated with the Early Middle Uruk (3900–3500 BC) (Boehmer 1991). The ^{14}C age difference between the shells is considerable, given their stratigraphic provenance from the same bed. This could indicate general variations in the freshwater reservoir effect, or inter-species variations in FRE. Considering the FRE, these samples provide a *terminus post quem* for canal 7 infilling at Girsu.

Trench TH3 next to palaeocanal 7 (31°33'35.9"N 46°10'05.1"E)

6520 ± 30 BP	**5557–5381 cal BC**
508714 - TH3-SH1-400	$\delta^{13}C = -5.6$

Fossil *Corbicula fluminea* shell collected at 400 cm below ground surface (4.6 m asl) near the base of a massive reddish brown clay unit. Stratified gray clay and silt was found below this unit. No cultural material was recovered from this trench. Collected 2018 by J. Jotheri; submitted by E. Egberts and J. Jotheri.

Comment: this overlaps with ^{14}C dates at Shatra (sample GX- BB1) B – (11–11.5) m (Aqrawi 1995) and with a date at H3 (charcoal, sample AA-42171(GU-9301)) associated with Ubaid 2/3 material (Carter and Crawford 2002). It also overlaps with sample P1498 at Tell Uqair, probably from House A (Lawn 1973). Considering the FRE, this date indicates that floodplain

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deposits just outside the tell of Girsu post-date the start of Ubaid 2 and span the period of occupation of the site.

Lacustrine deposits

Trench TH13, "harbor" west of the temple complex (31°33'51.6"N 46°10'18.3"E)

3850 ± 30 BP	**2456–2204 cal BC**
545376 - TH13-SH1-76	$\delta^{13}C = -7.1$
4380 ± 30 BP	**3093–2911 cal BC**
545372 - TH13-SH6-130	$\delta^{13}C = -9.1$

Fossil *Melanoides tuberculata* shell collected from stratified gray clay with shell inclusions, at 76 cm (sample 545376/TH13-SH1-76) and 130 cm (sample 545372/TH13-SH6-130) below ground surface (9.54 m and 8.9 m asl, respectively). Green and reddish brown clay were found stratigraphically below the gray clay unit. Collected 2019 by E. Egberts and J. Jotheri; submitted by E. Egberts and J. Jotheri.

Comment: the ^{14}C dates of these samples are stratigraphically consistent but pre-date the archaeological material found in the reddish clay at the base of the trench. This consisted of complete conical bowls and fragmented ceramics dated to the Late Akkadian period (2200–2100 BC) until the end of the Isin-Larsa period (2000–1800 BC), with the majority of the pottery being characteristic of the Ur III period (2100–2000 BC).

Sample 545372/TH13-SH6-130 overlaps with a date at Nippur from ED II deposits (sample P.806) (Stuckenrath and Ralph 1965). Sample 545376/TH13-SH1-76 overlaps with a ^{14}C date from reed remains from the ziggurat of Urnammu at Uruk (Münnich 1957). The mat derives from construction work under Urnammu, the first king of the 3rd dynasty, or under his son Schulgi. A period dated by W.F. Albright to between 2070–2000 BC (Münnich 1957).

DISCUSSION

Comparing Radiocarbon Dates and Archaeological Evidence

Table 3 summarizes the results of our radiocarbon dating and archaeological dating evidence. Most ^{14}C dates are stratigraphically coherent, within the individual trenches as well as according to absolute heights across the site.

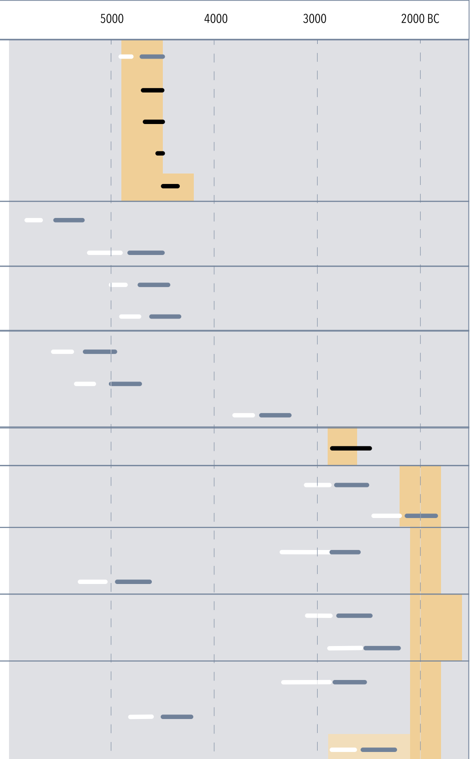
All ^{14}C dates fall between the beginning of the Ubaid 1 and the end of the Early Akkadian period (Table 1 and 2). The earliest ^{14}C dates were obtained from floodplain deposits below the canal system, and pre-date the thus far known earliest occupation at Girsu (from Ubaid 4 [Genouillac 1936; Parrot 1948]).

The oldest cultural layers excavated are Ubaid 4 deposits found below the bridge and canal 3, at ~6 m asl to ~10 m asl. The thickness and variation in elevation of these deposits suggest an Ubaid tell existed at this location. Excavations indicate that the Ubaid deposits were cut during the building of the bridge and the digging of the canal, demonstrating that these hydraulic features obviously post-date the Ubaid 4.

The four charcoal ^{14}C dates obtained from these deposits range from 4691–4502 cal BC (E4) to 4491–4352 cal BC (E6), overlapping with the Ubaid 4/5, consistent with the archaeological

Table 3 Comparison of ^{14}C dates (modeled and calibrated BC dates (95.4%) and modeled and reservoir corrected calibrated BC dates (95.4%) and archaeological evidence, discussed in this research. Results are presented per association (e.g., below the canal system, associated with canal 3, etc.), per trench, and according to stratigraphic and geomorphological interpretation and increasing height above the floodplain. The diagram on the right shows the age range of shell ^{14}C (white lines), charcoal ^{14}C (dark lines), the reservoir corrected ^{14}C shell dates (gray lines), and the archaeological evidence (orange).

Association	Sample no.	m asl.	Archaeology	Modeled calBC	R Modeled calBC
Ubaid below CH3	13012_TG38	6.1	4900-4500 BC	4904-4800	4702-4499
	16006	10.36		4691-4504	4690-4504
	13007_TG33	6.1		4672-4499	4672-4499
	13009_TG35	6.1		4549-4499	4549-4499
Ubaid 4/5	TG-E6	8.28	4900-4200 BC	4496-4355	4496-4355
Below CH3	TH2-SH1-145	6.75		5826-5662	5539-5277
Canal 3	TH12-SH1-40	8.8		5208-4905	4821-4501
Canal 2	TH10-SH1-80	7.6		5013-4841	4722-4447
	TH1-SH4-40	7.9		4902-4721	4609-4341
Below CH7	TH3-SH1-400	4.6		5551-5380	5253-4962
Canal 7	TH8-SH2-75	8.4		5324-5132	5015-4706
	TH8-SH1-60	8.6		3783-3647	3544-3272
Canal 6E	TH9-CH1-70	8.4	2900-2600 BC	2857-2492	2856-2492
Harbor	TH13-SH6-130	8.9	2200-1800 BC	2904-2886	2817-2519
	TH13-SH1-76	9.5		2459-2207	2133-1852
Canal 5	TH6-SH5-120	8.5	2100-1800 BC	2904-2892	2862-2601
	TH6-SH4-100	8.7		5297-5051	4941-4626
Below CH6W	TH7-SH3-100	8.0	2100-1600 BC	2904-2885	2796-2486
Canal 6W	TH7-SH2-90	8.15		2881-2626	2533-2212
Canal 2	TH15-SH2-35	8.0	2100-1800 BC	2904-2887	2831-2541
Canal 1	TH14-SH1-60	8.7	2100-1800 BC	4791-4611	4510-4227
Canal 3	16014-SH2-320	10.26	2100-1800 BC	2887-2666	2562-2241



evidence. The shell from context 13005 returned a 4999–4803 cal BC ^{14}C date (overlapping with Ubaid 3/4).

The oldest ^{14}C date from the fluvial system was obtained from palaeocanal 7, 5324–5132 cal BC (Ubaid 3). The ^{14}C dates from the canal system range from 5297–5050 cal BC (canal 5) (outlier, see below) and 5206–4853 cal BC (canal 3) to 2871–2581 cal BC (canal 6W), spanning the Ubaid 3 to ED IIIA periods. The youngest ^{14}C date, 2456–2204 cal BC, was obtained from the lacustrine deposits, and overlaps with the Early Akkadian period.

The oldest archaeological evidence found in association with the canal system is ED I (2900–2600 BC) pottery from palaeocanal 6E. The initial construction of the bridge, associated with canal 3, is also thought to date to this period. All other archaeological evidence associated with the canal system dates from the Late Akkadian to the Ur III and Isin-Larsa periods (2200–1800 BC). All shells returned older ^{14}C dates than the age ranges of the associated

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cultural layers based on pottery chronology (Table 3). The only ^{14}C date (515277/TH9-CH1-70) in broadly stratigraphic agreement with the archaeological evidence and connected with the canal system is from charcoal. Our results show a clear discrepancy between ^{14}C shell dates and the age of the archaeological evidence.

A Relative Chronological Model

Bayesian modeling of the new ^{14}C data from Girsu shows a generally good internal agreement (Table 2 and Supplementary materials). There are two clearly outlying calibrated results (508715/TH6-SH4-100 and 545370/TH14-SH1-60). Already based on stratigraphic, archaeological and geomorphological considerations these results were regarded as problematic. 508715/TH6-SH4-100 was found stratigraphically above the younger sample 508716/TH6-SH5-120. 545370/TH14-SH1-60 was expected to post-date samples from CH2 based on geomorphological observations and was found in association with Isin-Larsa pottery. These samples were therefore marked as outliers in the model.

Archaeological evidence found in association with the ^{14}C samples found in Ubaid levels was used to define a dated upper and lower boundary for this sequence. Sample 545371/TG-E6 from trench E6 is placed after the Ubaid 4 end boundary, based on the pottery from this layer, which included Ubaid 4/5 material. The addition of these boundaries caused sample 1555135/3009_TG35 to fall just below the 60% threshold (A= 59.8%), potentially highlighting some refinements could be made to the cultural chronology of the Ubaid.

The integration of archaeological information was also tested by adding a dated chronological boundary between the two main phases. The date of this boundary was based on the archaeological evidence found in association with the channel fills linked to Phase 2. The pottery from these channel fills mainly dates to 2100–1800 BC, with some material dating to 2900–2600 BC. However, even with a conservative boundary of 2900 BC between Phase 1 and 2 the agreement indices of four samples in Phase 2 (545372/TH13-SH6-130, 508715/TH6-SH4-100, 508718/TH7-SH3-100, TH15-SH2-35) fell below the 60% threshold (0.9%, 0.0%, 2.0%, and 0.1% respectively). Integration of the archaeological evidence in the model again suggests an offset of the shell ^{14}C dates. However, the general internal agreement may indicate that the offset is relatively constant.

Freshwater Reservoir Effect

Several explanations can be put forward for the offset in the ^{14}C shell dates, such as reworking or bad preservation of the used shells. Reworking is not consistent with the generally coherent, though old, ^{14}C dates across the site (Table 3), neither is bad preservation as the selected shells were in good condition. The variations in calibration curves, its wiggles and radiocarbon offsets, though important for correlations with historical events, are of a different order of magnitude (Manning et al. 2017, 2020). The most evident explanation is that the shells are affected by the freshwater reservoir effect (FRE) (Philippsen 2013; Philippsen and Heinemeier 2013). The otherwise good match between the charcoal ^{14}C dates and the archaeological evidence supports this explanation.

Although the FRE is a widely recognized phenomenon (Philippsen 2013; Svyatko et al. 2022), also for river systems (Philippsen and Heinemeier 2013; Yu et al. 2018), its influence has been mostly dismissed in ^{14}C shell dating in geological and archaeological contexts in Mesopotamia (Hritz et al. 2012; Jotheri 2016; Wilkinson and Jotheri 2021) also when clear age differences between shell ^{14}C and cultural evidence existed (Hritz et al. 2012). Others recognized the FRE in shell samples and refrained from publishing the ^{14}C data (Zaina 2015).

In general, the number of ^{14}C dates for Mesopotamia is limited (Wencel 2017) and due to poor preservation of organics, and financial considerations, shell radiocarbon dating has remained the go-to method (e.g., Jotheri 2016; Al Ameri and Briant 2018; Wilkinson and Jotheri 2021). Arguments generally put forward in favor of using shells in Mesopotamia diminish the potential impact of FRE for the following reasons (e.g., by Hritz et al. (2012): there are no carbon outcrops in the vicinity of the site (Hritz et al. 2012) or are deeply buried (Al Ameri and Briant 2018); correlations or corrections are not possible (no pre-bomb specimens or living specimens available) (Hritz et al. 2012:75; Jotheri 2016:185–186); the marine reservoir effect from the Gulf is considered limited (Hritz et al. 2012:75); the environmental context (not a lake or sea) is assumed not to cause a FRE (Hritz et al. 2012:75). These are inadequate reasons and dismiss the FRE in river systems. The Tigris and Euphrates Rivers are to our knowledge not discussed with regard to the FRE on radiocarbon ages in the region, even though their importance for life on the floodplain, human history, as well as landscape formation in Mesopotamia is rarely understated. Both rivers cut through several limestone formations before entering the Mesopotamian floodplain and the water of both rivers is classified as hard to very hard (Al-Mallah et al. 2006).

The best option for assessing the impact of FRE at Girsu, is provided by the two ^{14}C charcoal dates and one shell from an Ubaid 4 close context (excavation area E3). The difference between the ^{14}C age of the aquatic reservoir under study and the ^{14}C age of the contemporaneous atmosphere is the reservoir age R and can be calculated by subtracting the atmospheric ^{14}C age from the aquatic ^{14}C age, provided that the ^{14}C age of the atmosphere can be estimated from a charcoal sample and that the charcoal sample and aquatic sample are contemporaneous (Philippsen 2013). The charcoal dates are in good agreement with the associated archaeological evidence and found in clear association with the aquatic shell sample.

Thus:

$$R = {}^{14}C_{\text{shell}} - {}^{14}C_{\text{atmosphere}}$$

$$R_1 = 13012\_TG38 - 13007\_TG33 = 6020 - 5710$$

$$R_2 = 13012\_TG38 - 13009\_TG35 = 6020 - 5640$$

The uncertainty is:

$$\sigma = \sqrt{\sigma^2{}_{\text{shell}+}\sigma^2{}_{\text{charcoal}}}$$

$$\sigma = \sqrt{30^2 + 30^2} = 42, 43$$

(see Table 2 for standard deviations)

$$R_1 = 310 \pm 42^{14}C\,\text{years}$$

$$R_2 = 380 \pm 42^{14}C\,\text{years}$$

This suggests a FRE of between 310 ± 42 and 380 ± 42 ^{14}C years.

We ran the model again (Supplementary materials), applying this reservoir R ($(R_1+R_2)/2 \pm \sqrt{42^2+42^2} = 345 \pm 60$ ^{14}C years) to the Intcal20 calibration curve for all the shell samples. The

https://doi.org/10.1017/RDC.2023.40 Published online by Cambridge University Press

FRE in hard-water rivers can be variable and vary over time and between species (Philippsen and Heinemeier 2013; Kulkova et al. 2015; Schulting et al. 2022; Svyatko et al. 2022) so this is an over simplistic representation of the FRE around Girsu, but offers an initial correction (Table 2).

The reservoir correction of the shell samples brings all the ^{14}C dates from the fluvial system within the period of known occupation at Girsu. The samples assigned to channel activity in the first phase of the model now overlap with the Ubaid 4 period, the samples assigned to the second phase of the model now all date after 2900 BC and agree with the archeological age boundary. The youngest date, from the lacustrine deposits, now overlaps with the age range from the associated archaeological evidence (2100–1800 BC). This exercise demonstrates the validity of the model and the initial FRE correction. However, in most instances the calibrated and corrected shell ^{14}C dates still pre-date the associated archaeological material (Table 3) showing that the FRE at Girsu is indeed more variable and complex and should be further characterized with additional analysis.

CONCLUSIONS

Dating the canal system at Girsu using ^{14}C and archaeological evidence has shown that a large difference exists between the two dating methods which likely reflects the FRE from the Tigris and the Euphrates. The shell ^{14}C dates therefore only provide a *terminus post quem* for final canal activity. The archaeological evidence suggests that the canals were in use from at least the EDI period, which agrees with the textual evidence. The youngest archaeological evidence found below several canal fills dates to the Isin-Larsa period (2000–1800 BC). This indicates that the canals fell out of use at or shortly after this time, when Girsu becomes largely abandoned (at the beginning of the Old Babylonian period).

The use of cultural chronologies remains a widely used dating method in Mesopotamia. It has proven informative in the case of Girsu and obviously provides a clear link with the cultural history. However, it does not provide absolute dates and due to the wide age ranges for cultural periods does not offer a high enough chronological resolution for short-term changes.

Shell ^{14}C dating remains useful as shell is the most widely available organic material in geological/environmental and geoarchaeological contexts in Mesopotamia and offers the possibility to obtain high resolution absolute dates. However, as our results indicate, FREs are a major drawback, and need to be better assessed for the region.

The fact that FREs in hard-water rivers can be large and variable (Philippsen and Heinemeier 2013), vary geographically and over time, between and within species (Kulkova et al. 2015; Schulting et al. 2022; Svyatko et al. 2022) and affects shells, water plants, fish, and animals (and humans) whose subsistence was based on freshwater fish or water plants (Philippsen 2013; Philippsen and Heinemeier 2013; Svyatko et al. 2022), together with the scarceness of other radiocarbon dating material in Mesopotamia, can be disheartening when seeking to improve absolute chronologies in the region. As the Euphrates and Tigris are the source of life in the Mesopotamian floodplain, FREs from these rivers will never be far away. With an increasing interest in geoarchaeological approaches to studying past waterscapes in Mesopotamia (e.g., the "Sumer and the Sea" ARWA International Research Workshop, D'Agostino and Romano 2018; Fassbinder et al. 2019; Hammer 2022), understanding the FREs in the region becomes even more relevant. Sufficiently characterizing FREs in river systems requires a comprehensive research program (cf. Philippsen and Heinemeier 2013), which as yet has to be established in Mesopotamia. This is exactly the argument for publishing this paper: to highlight the problem, and re-initiate collaboration to create a database for paired terrestrial and freshwater ^{14}C dates and archaeological evidence.

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/RDC.2023.40

ACKNOWLEDGMENTS

The Girsu Project is funded by the J. Paul Getty Trust. Our thanks go to the Iraq Ministry of Culture's State Board of Antiquities and Heritage and the Iraqi Ministry of Higher Education and Scientific Research for their support, as well as to colleagues from Iraq, the British Museum Middle East department, and the Tello/Girsu team. The model was discussed with Maarten Blaauw, Queen's University Belfast, to whom we are indebted for his guidance. We also thank our good friend and colleague Chikako Watanabe for her continuous support.

COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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