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RESEARCH ARTICLE OPEN ACCESS

New Insights Into Early Islamic Hydro-Agricultural Strategies in Northwest Arabia: A Geoarchaeological Study of al-Bint Dam (Sadd al-Bint)

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ABSTRACT

The Sadd al-Bint is one of the largest known ancient dams in Saudi Arabia, and yet, its construction date, function and collapse remained uncertain. This study presents the first numerical chronology for the dam, integrating radiocarbon dating, Bayesian modelling, geomorphological analysis and hydrological modelling to reconstruct its history. Results indicate a multiphase construction, with initial building between 596 and 686 CE, followed by repairs or extensions between 725 and 907 CE, and a final maintenance phase between 947 and 1015 CE. Structural and sedimentological evidence suggests that the dam's collapse was not due to poor engineering but rather prolonged lack of maintenance, leading to progressive infiltration until a sudden hydrological event triggered failure. Hydrological reconstructions confirm a maximum reservoir capacity of 12 million m³, potentially supporting extensive irrigation at nearby al-Thamad oasis. The study brings new insights on the dating of Arabian dams, perhaps its most challenging issue, demonstrating a major hydraulic investment during the Rashidun and Umayyad periods and its continuity into the Abbasid period. The dam's strategic location and its role in regional water management suggest a broader state-driven infrastructure policy in early Islamic Arabia. These findings enhance our understanding of long-term water management strategies in northwestern Arabia and their socio-political implications.

1 | Introduction

Dams have been a fundamental element of the water management systems and hydraulic structures constructed and maintained by human societies over the past six millennia in the Arabian Peninsula (Wilkinson and Rayne 2014). Owing to the very limited rainfall typical of these arid regions, communities have developed dams—permanent large-scale structures designed

to store and regulate substantial volumes of water—and check-dams, which are semipermanent structures primarily intended to slow down water flow, reduce soil erosion and facilitate ground-water recharge (Khan and al-Mughannam 1982). In this way, such structures also enabled communities to protect settlements from flash floods and to use the retained water for crop irrigation. They are closely related to *sayl* irrigation, which involves capturing run-off water from seasonal floods by raising the water level

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using dams and diverting it into irrigation channels to feed crops (Wilkinson 2003; Harrower 2008a).

Much research into water management systems in the Arabian Peninsula has focused on southern Arabia, notably Yemen, where dams have been documented since the 4th millennium BCE, with the construction of the first check-dams coinciding with the decline in the intensity of the summer monsoon rains, and continuing into the Himyarite period ca. 100 BCE–500 CE, allowing agricultural intensification in the highlands and agricultural development in the more desert regions (McCorrison et al. 2002; Robin and Dridi 2004; Charbonnier 2012). In addition to primary agricultural functions, check-dam structures were intended to inhibit run-off, capture sediments and increase the infiltration of water into the soil (Harrower 2008a, 2008b). The development of these hydraulic systems rapidly increased the supply of fodder for livestock and large-scale agriculture on the peninsula (Fedele et al. 1990). Finally, the Himyarite period represented a certain apex of irrigation development, with not only around 60 dams constructed in the Yemeni highlands between the 1st and 4th centuries CE, but also, without doubt, the most famous and largest example of a massive hydraulic structure—the Marib Dam—which was repeatedly rebuilt and expanded by Himyarite kings following a series of breaches between the 4th and 6th centuries, until its final abandonment after a last rupture at the end of the 6th century (Chanson 2004; Darles et al. 2014).

In northwestern Arabia, only a few check-dams have been numerically dated to the 7th millennium BCE in southern Jordan (Fujii 2007), and to the 3rd millennium BCE at Qurayyah, where it is thought to have been used to control flash floods and redirect water towards cultivated areas (Lüthgens et al. 2023). The more recent emergence of large-scale dam structures with retention basins is evidenced by the distribution of several dozen gravity dams along the mountain ranges bordering the Red Sea, where the hydrographic network is well developed (notably in the regions of Medina and Taif), as well as along the ancient trade routes extending from the Sarawat Mountains to the Levant (Kay 1978; Gilmore et al. 1982; Gawlikowski et al. 2021). Several of these structures display impressive dimensions, such as the Harbaqa dam in Jordan (345 m long and 20.5 m high), and the dams of al-Bint (212 m long and 23.6 m high), al-Uraydah (225 m long and 3 m high) and al-Darwaish (150 m long and 10 m high) in Saudi Arabia. Such large-scale structures stand as a testament to a substantial collective investment by human societies aimed at adapting to the significant physical and climatic constraints of their environment (e.g., Calvet and Geyer 1992; Genequand 2012). Calvet and Geyer (1992) stated that the most challenging issue in the study of these ancient dams was their dating. This remains true, as none of these gravity dams in western Arabia has been dated using a chronometric method. In the absence of numerical dates, the prevailing hypothesis is that these gravity dams in western Arabia and the Levant are generally pre-Islamic, and supposedly Roman (Calvet and Geyer 1992). Subsequent studies have, however, called this into question, and attribute these structures to the early Islamic period or later (Genequand 2006). Very rarely, dating evidence is available, in all cases corresponding to inscriptions marking the foundation of the structure, which attribute these constructions to specific Umayyad caliphs (Miles 1948; al-Rashid 2008). Successfully dating these dams is of great importance, as the construction of such large-scale structures requires not only advanced construction techniques

but also a high level of organisation within a community, given the substantial initial labour demands and the continuous maintenance required. Chronologically attributing these socio-political investments holds significant historical value, whether for pre-Islamic periods or the early stages of Islam.

In this context, this article focuses on the Sadd al-Bint, located south of Khaybar oasis in northwest Arabia, one of the largest and most iconic dams in Saudi Arabia. Using a multi-disciplinary approach combining drone acquisition, archaeological survey, architectural study, geomorphological mapping and observations, GIS, hydraulic modelling, anthracology and radiometric dating, this study aims to gain a better understanding of its function, obtain a robust chronology of its construction and use and discuss water management systems on a regional scale.

We present here the first study of one of these gravity dams in western Arabia dated using chronometric methods, revealing a long history of use and maintenance in the early Islamic period, before its sudden destruction likely in the tenth or eleventh century. We address the questions raised by such findings: To which caliphates do the phases of foundation and maintenance correspond? When was the dam destroyed, and what caused its collapse? Finally, we examine these issues on a broader regional scale, by comparing this dam with others in northwestern Arabia and discussing their functions and water use during the early Islamic period, thereby paving the way for the development of a regional agricultural scheme of historical relevance for the beginnings of Islam.

2 | Materials and Methods

2.1 | Geographical Setting

The Sadd al-Bint (coordinates: 39.362682 E, 25.484966 N) is located in northwestern Arabia, south of the present-day town of al-Thamad and 25 km south of the historical oasis of Khaybar (Figure 1A). The dam is constructed across a valley of the Wadi al-Gharas, one of the main tributaries of the extensive catchment of Wadi al-Hamd (ca. 100,000 km²), that cuts through Plio-Quaternary basaltic flows of the Harrat Khaybar. The wadi passes through the town of al-Thamad and extends northward until it converges with other wadis of Khaybar, south of Jabal Duham, in an area known as Ghadir al-Tair. The upstream catchment of the dam, covering an area of ca. 3000 km², drains the southern portion of the *harra*, with minor contributions from Precambrian rhyolites and sandstones of the Arabian Shield.

The dam is currently partially destroyed on its northeastern side, with Wadi al-Gharas flowing through a breach approximately 70 m wide (Figure 1B). A remnant of the dam remains perched at the top of the plateau on the eastern slope.

2.2 | Historical Sources and Previous Work

The dam was initially mentioned as ‘Beny el-Bint’ by Doughty in *Travels in Arabia Deserta* (Doughty 1888: 181) following his visit to

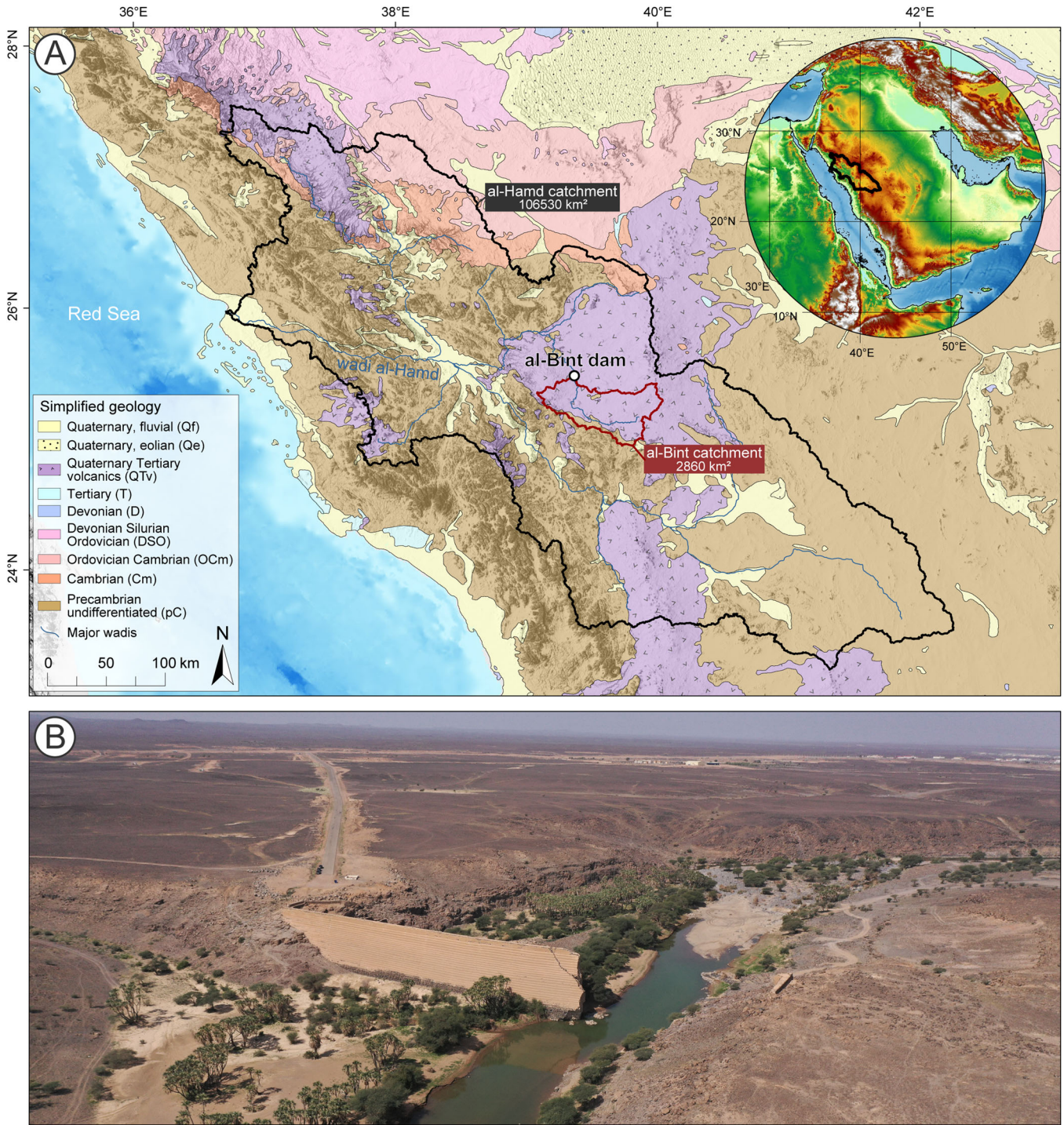


FIGURE 1 | Geographical setting. (A) Location of the Sadd al-Bint and its catchment, within the topographic and geologic frame of the Arabian Peninsula. (B) Drone view of the Sadd al-Bint from the south, built in the Wadi al-Gharas incised valley in the basaltic Harrat Khaybar plateau. Note cars for scale.

Khaybar in 1876. Doughty located it near ‘Kheybar in Wadi Thammud’, describing the remains of large dams in the area, including the nearby ‘el-Hassid’. Later, Huber referenced the dam in his *Journal d’un Voyage en Arabie* (1891), naming it ‘Qasr al-Bint’ but providing little further detail.

In 1957, Philby provided a more comprehensive description after visiting the site following his examination of the Al-Hasid dam (Philby 1957). He noted that ‘Qasr al-Bint’ was significantly

larger than Al-Hasid, with a portion on the right bank washed away by floods, indicating that the deterioration that we now see in the dam was evident more than 130 years ago, before Philby’s journey across Saudi Arabia in 1917. The intact structure stood about 50 feet high, with a width of 13.5 feet at the top, doubling at the base, and was built from basalt blocks held together by gypsum mortar. Philby reported the dam’s length as 500 feet and observed a cement coating on its upstream face, the base of which had been destroyed and washed away by floods. He found

no evidence of sluice gates and speculated that irrigation likely occurred upstream, where desert vegetation and a plantation of palm trees then thrived. He also mentioned a downstream platform whose purpose was unclear. Additionally, Philby noted that Wiban (a local from Khaybar) 'had no memory of any great flood in this valley; but local legend has it that twice within living memory floods in Wadi Hasid had topped and flowed over the dam, once 20 years ago, and once about 5 years before that' (Philby 1957).

In 1967–1968, Parr visited the site and documented it extensively. His collection, including approximately 1000 photographs, is now stored by the Royal Commission for AlUla, with seven historical images of the dam (RCU.2019.21.1-17).

Finally, the Saudi Archaeological Comprehensive Survey recorded the site in 1981, assigning it the number 205-43 in the national records. Gilmore et al. (1982) referred to the dam as 'Sadd Qasr al-Bint' or 'Sadd Al-Qusaybah' and identified it as the largest of three dams in the region, alongside 'Sadd Al-Hašid' (205-44) and 'Sadd az-Zayda' (205-46), and one of the largest ancient dams in the Kingdom. They noted that Qasr al-Bint originally spanned 205 m across a narrow tributary of Wadi al-Gharas in Harrat Khaybar, with a 45-m section washed away at the northern end. The dam stands 25 m high on the downstream side but has been silted up to 10 m from the top on the upstream side (Gilmore et al. 1982).

2.3 | Archaeological, Drone and Geomorphological Surveys

A systematic survey of the dam and areas within a 500-m radius was conducted to document the preserved remains of archaeological structures and specifically search for inscriptions and hydraulic installations potentially associated with the Sadd al-Bint. It was carried out as part of the Khaybar Longue Duree archaeological project in March 2023. Drone photography was conducted over an area of 2.7 km², resulting in the production of a 4 cm/pixel orthophoto and a 7 cm/pixel digital elevation model (DEM) of the entire area using Agisoft Metashape. Additionally, a 5 cm/pixel orthophoto of the section revealed by the dam's breach was also generated. The modelling of the dam's capacity, as well as the surface area and volume of the reservoir, was performed using ArcGIS Pro software.

Based on this aerial survey, a geomorphological survey was carried out downstream of the dam over a 1 km stretch to investigate potential sedimentary deposits indicative of hydrological events responsible for the destruction of the Sadd al-Bint. The breach created in the northeastern section of the dam exposes a cross-section of its internal masonry. We were only able to study the stratigraphy and masonry of the first two visible metres in this section, as the installation of scaffolding was not feasible due to the highly unstable sandy terrain at the water's edge.

2.4 | Chronology

Twelve AMS radiocarbon dates were derived from charred materials (Table 1). Ten samples were collected at the base of

the dam, from the first two visible metres of the section exposed by the breach (SB01). Two additional samples were taken from dam remains located at the top of the right bank of the wadi (SB02). Fine charcoal fragments were extracted from the sediment under a binocular stereoscopic microscope (Nikon SMZ645, magnification up to ×80) and analysed for taxonomic identification using a reflected light microscope (Olympus BX51M, magnification up to ×1000). Identification was carried out by observation of the three anatomical sections of wood (transverse, tangential and radial sections) and following the morphological features standardised by the International Association of Wood Anatomists (IAWA; Wheeler et al. 1989) and adapted to arid vegetation, for which the specific morphological characteristics have been outlined by Neumann et al. (2000). Criteria were compared with modern reference collections available at the National Museum of Natural History of Paris, as well as wood illustrations and descriptions from wood anatomical atlases (Jagiella and Kürschner 1987; Neumann et al. 2000). All radiocarbon ages were calibrated using the IntCal20 curve (Reimer et al. 2020).

The radiocarbon dates (referred to as 'events') were subjected to Bayesian analysis using ChronoModel V3.2.7 software (Lanos and Dufresne 2019), enabling a chronological model of the construction and utilisation of the dam to be produced in which the stratigraphic information was integrated.

3 | Results

3.1 | Architecture of the Dam

3.1.1 | Morphology

Our study provides a detailed characterisation of the Sadd al-Bint. It is a near-rectilinear gravity dam, measuring 212 m in length (before breaching) and 23.6 m in height, with a thickness of 19 m at the base and 6.2 m at the crest. These dimensions make it one of the largest dams in Saudi Arabia before the modern era. The dam spans the Wadi al-Gharas perpendicularly, reaching the top of the adjacent basalt plateau at an elevation of 800–801 m a.s.l.

Contrary to the curved form suggested by Gilmore et al. (1982), the dam shows a composite profile. Although its downstream face is rectilinear, the upstream face is defined by three regular straight sections: a central section, 31 m in length, positioned perpendicular to the valley axis, and two outer sections, measuring 94 and 78 m, respectively, which display a slight inward angle. This design helps direct water flow towards the valley sides, somewhat akin to an arch dam (Figure 2).

3.1.2 | Masonry

The dam is constructed using rubble masonry and mortar, laid in courses and enclosed between two facings. The upstream facing is entirely covered with a plaster, except for the lower 2–3 m, reflecting an effort to waterproof the dam at the point of contact with the reservoir. The absence of plaster at the base,

TABLE 1 | Detailed results of the AMS radiocarbon dating (¹⁴C dates in italics are rejected due to incomplete treatment of the sample).

Lab no.	Sample ID	Phase	Dated material	Building material	Identification	Age ¹⁴ C BP ($\pm 1\sigma$)	Age cal. CE (2σ)
DeA-45676	SB001-001 (a) <Sample 1>	Plastering	Wood charcoal	Coating	Ziziphus sp. (Jujube)	1090 \pm 18	893–1014
DeA-45677	SB001-002 (a) <Sample 3>	Core section	Wood charcoal	Mortar	Vachellia sp. (Acacia)	1406 \pm 18	605–658
DeA-45678	SB001-002 (b) <Sample 4>	Core section	Stipe charcoal	Mortar brick	<i>Phoenix dactylifera</i> (Date palm)	1398 \pm 18	606–662
DeA-45679	SB001-003 (a) <Sample 5>	Core section	Wood charcoal	Mortar	Vachellia cf. nilotica (Nile acacia)	1431 \pm 18	601–650
DeA-45680	SB001-003 (c) <Sample 7>	Core section	Stipe charcoal	Mortar brick	<i>Phoenix dactylifera</i> (Date palm)	1298 \pm 18	664–773
DeA-45681	SB001-004 (a) <Sample 8>	Core section	Wood charcoal	Mortar	Vachellia sp. (Acacia)	1282 \pm 17	673–774
DeA-45682	SB001-005 (a) <Sample 10>	Core section	Wood charcoal	Mortar	Vachellia cf. nilotica (Nile acacia)	1391 \pm 18	607–664
DeA-45683	SB001-005 (b) <Sample 11>	Core section	Wood charcoal	Mortar	Vachellia sp. (Acacia)	1447 \pm 18	589–648
*DeA-45673	SB001-006 (a) <Sample 13>	Core section	<i>Stem charcoal</i>	<i>Mortar brick</i>	<i>Areaceae (palm type)</i>	1285 \pm 19	670–774
*DeA-45674	SB001-006 (c) <Sample 14>	Core section	<i>Petiole charcoal</i>	<i>Mortar brick</i>	<i>Phoenix dactylifera</i> (Date palm)	1188 \pm 19	774–890
DeA-45684	SB002-001 <Sample 17>	Eastern upper construction	Stem charcoal	Mortar	Monocotyledon (Areaceae type)	1216 \pm 19	708–883
DeA-45685	SB002-002 (b) <Sample 19>	Plastering	Wood charcoal	Coating	Ziziphus sp. (Jujube)	1055 \pm 18	903–1025

which has been destroyed, is likely due to erosion caused by the repeated action of water. The downstream facing features only partial plaster, with exposed stonework. It predominantly reveals small masonry blocks, complemented by larger blocks arranged in a staggered pattern, all made from local basalt. Terracotta bricks are also used in the dam facings, likely to enhance the structural strength of the edifice.

The exterior faces of the dam reveal a minimum of 60 courses, each averaging approximately 40 cm in height. Every two courses, a slight setback in the masonry is observed (Figure 3A). Both facings show this gradual inward step as the wall rises, resulting in a stepped profile. This morphology is typical of gravity dams, as Genequand (2006) explains: ‘Gravity dams counteract the horizontal pressure and uplift of water with vertical force. Therefore, if the base is sufficiently wide, it is unnecessary to maintain the same width throughout the structure’s height, allowing for significant savings in materials and labour.’

The cross-section exposing the internal masonry, created by the breach, reveals, aside from some specific features at the base of the section (see Section 3.2.1), a relative homogeneity in the architecture. This is characterised by a succession of courses linking both facings from side to side (Figure 3). This confirms that the dam was largely constructed course by course up to its summit, within a defined time frame and using consistent construction techniques.

A parapet, 1.30 m in height, crowns the upstream side of the dam along its entire length, at an altitude of 802.2 m a.s.l. at its centre and 802.8 m a.s.l. at its south-western end. The remaining portion of the summit features a flat platform, open towards the downstream side. A series of small buttresses are attached to the parapet, spaced at regular intervals of approximately 12 m, three of which are equipped with staircases leading up to the parapet (Figure 2). Notably, this platform also includes a staircase descending to the eighth course and opening into the void on the downstream side, the function of which remains unknown.

3.1.3 | Hydrology

Uncertainties remain, particularly regarding the management of the water storage of the reservoir and extreme flow events. No sluice gate or spillway has been clearly identified, which may be due to the significant breach that has destroyed nearly the entire eastern half of the dam. Furthermore, if sluice gates had been constructed at the base of the structure, they would no longer be visible today, as the base of the dam is inaccessible. It is covered upstream by a substantial accumulation of reservoir sediments, several metres thick, deposited after the dam’s construction (Figure 2). On the downstream side, deposits of masonry blocks, resulting from the dam’s collapse—whether from the breach opening or the destruction of other associated

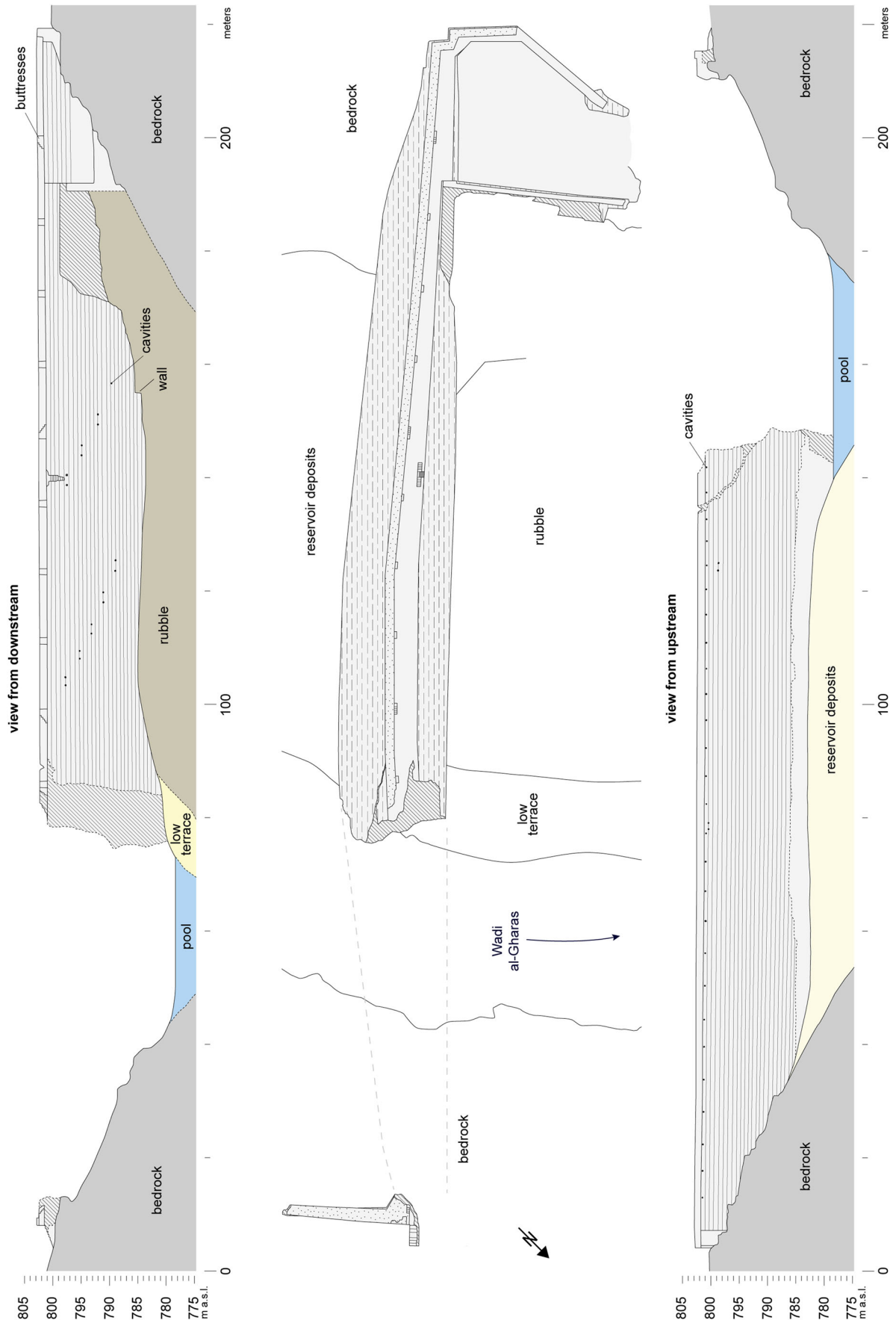


FIGURE 2 | Illustration of the Sadd al-Bint from downstream, from above and from upstream.

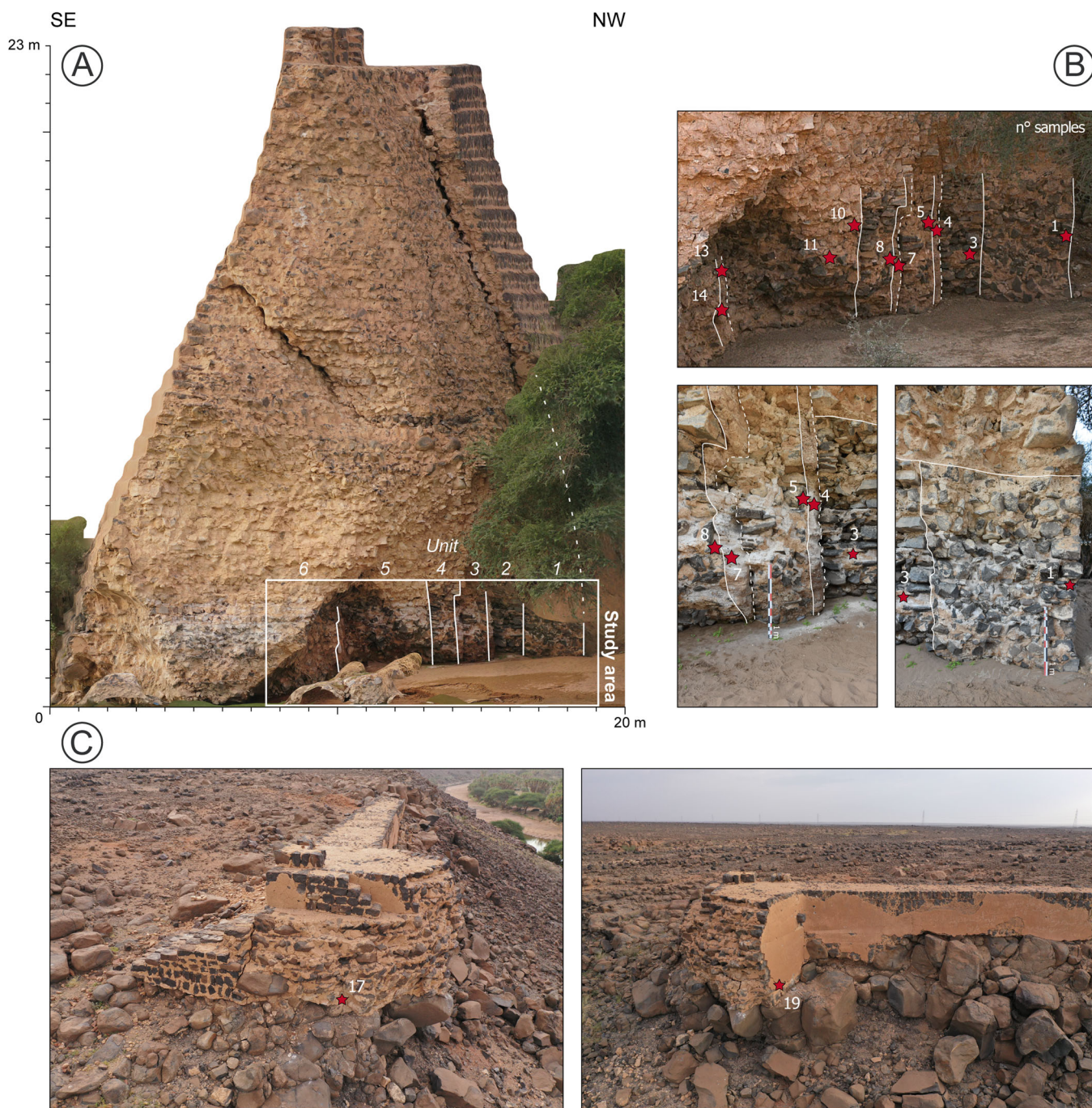


FIGURE 3 | Mortar samples for dating. (A) Orthophoto of the cross-section of the dam exposed by the breach, with the position of the study area and its architectural units. (B) Close-up views showing the position of the samples and their numbering. (C) Drone view of the north-east remains on the right bank, with the position of the samples and their numbering.

structures on the south-western side—have also accumulated to several metres in thickness.

It is important to note the presence of numerous round cavities, 15–20 cm in diameter, within the masonry on both the upstream and downstream faces (Figure 2). On the upstream side, a series of 27 cavities is located at the base of the parapet, spaced approximately every 5 m, between altitudes of 800.6 and 801.4 m. Additionally, two pairs of cavities, spaced about 1.5 m apart, are observed at the interface between two courses. On the downstream face, eight pairs of cavities, spaced between 1.3 and 1.8 m apart, along with a

single cavity of similar dimensions, are also positioned at the intercourse interfaces. These are distributed along the full height of the structure but are staggered laterally. The number and positioning of these cavities at the base of the upstream parapet suggest that they may have functioned to allow water to flow out in the event of overflow. The presence of similar cavities on the downstream facing of the dam indicates that they could have served a similar purpose, potentially functioning as outlets. However, for this to be the case, the cavities would need to be continuous through the dam, a feature that cannot be confirmed due to the more recent plastering on the downstream face, which obscures this detail.

The structures adjacent to the dam, located to the south-west of the downstream face, may correspond to water management and storage systems. At least one 'terrace' situated at the end of the dam, enclosed by two walls perpendicular to the dam and the basalt slope, is relatively well preserved. This feature could represent a basin, measuring 26 by 30 m, potentially used for irrigation, given its elevated position, which would facilitate long-distance water transport by gravity. Another structure was attached closer to the centre of the dam but is now completely destroyed, leaving only traces visible on the downstream facing. Additionally, a wall attached to the base of the dam, oriented westward and almost entirely buried under debris, may correspond to the foundations of this structure. Its function remains unknown, though it could represent a second basin, related to the first, but situated at a lower elevation.

Finally, on the opposite side of the breach, a remnant of the dam clings to the top of the basalt plateau. Only a small portion remains, primarily characterised by a wall perpendicular to the dam, extending upstream. Currently measuring 22 m in length, its end is destroyed, and its original length remains unknown. The wall is 2.30 m wide at its junction with the dam, narrowing slightly to 2.10 m at its broken end. Positioned at an altitude of 802.3 m a.s.l., it appears to be an extension of the dam's parapet. The preserved section of the structure reveals a first staircase leading from the plateau to the platform and a second staircase ascending from the platform onto the wall. The function of this wall remains uncertain. As the only structure situated upstream of the dam, it may have served to guide water flow and prevent overflow onto the plateau.

Another important, yet unresolved, aspect of the dam's operation concerns the distribution of water from the reservoir. No irrigation channels originating from the dam have been identified thus far, either within the valley or along the basalt slopes. This absence of channels may indicate the existence of alternative strategies of conveying water to cultivated areas downstream.

3.2 | Stratigraphy, Charcoal Analysis and Chronological Data

The breach created in the north-eastern section of the dam has exposed a cross-section of its internal masonry. It should be noted that the area examined does not correspond to the actual base of the dam, which is covered by several metres of sediment all around—comprising alluvial deposits on the upstream face and collapse debris on the downstream face. Additionally, as the wadi contained water at the time of the study, only the western part of the dam's base could be examined.

3.2.1 | Stratigraphy

As mentioned above (see Section 3.1.2), the general stratigraphy of the section reveals an overall homogeneous structure built through successive courses linking one facing to the other. However, the basal part, which was studied in greater detail, shows a different construction technique. Specifically, the downstream face of the base of the dam features several sub-vertical faced walls built adjacent to one another (Figure 3A). These different walls have been assigned unit numbers (from 6 to

1, respectively, from the centre towards the exterior, with 6 being the oldest and 1 being the most recent). The construction sequence leaves little room for doubt, as each new unit was built against the outer face of the preceding one, slightly leaning upon it. The contact between adjacent units displays a gentle dip, indicating the later construction of the outer units. It is noteworthy that units 2, 4 and 5 are characterised by a construction method that includes the application of a plaster layer over the exterior facing of the previous unit against which they were built.

Unit 1 features an external facing and an internal core composed of small blocks (approximately 15–20 cm in diameter) laid relatively flat, built against Unit 2. Unit 2 has a double facing made of relatively flat blocks measuring 30–40 cm, with a very narrow internal core limited to the upper part of the wall. Both units appear truncated along a plane with a slight slope at around 3 m in height and are overlaid by different masonry composed of larger, rounded blocks (30–40 cm and above), less tightly packed and set within a substantial mass of mortar. Unit 3 shows a plaster layer adhered to an external facing and an internal core comprising variously sized blocks (30–40 cm modules and smaller blocks of 15–20 cm), combined with poorly arranged mortar. Unit 4 also shows a plaster layer on the external facing, characterised by an offset at around 3 m in height. This unit includes an internal facing of relatively flat blocks (30–40 cm) and a core of mixed blocks and poorly arranged mortar. Unit 5 displays a different construction technique from the previous units, consistent with the method used for the rest of the dam, namely, the use of large blocks laid in successive, regularly sized courses. Finally, Unit 6 represents the remnants of an earlier construction phase, made of mixed blocks and poorly arranged mortar, overlaid by Unit 5. Additionally, Unit 6 displays pronounced slopes and a plaster layer with several offsets, suggesting significant disturbance of the original structure.

3.2.2 | Charcoal Analysis

Samples were collected from each construction phase, and the charcoal that they contained was extracted and identified, before radiocarbon dating (Table 1). Two additional samples were collected from the north-eastern remnant of the dam. In total, six charcoal samples originated from mortar, four from interior plaster and two from exterior coatings.

Samples 13 and 14 from Unit 6—the oldest one—are, however, slightly more recent than the other dates (Table 1). This can be explained by (1) incomplete laboratory processing compared to the other dated samples and (2) a risk of contamination. Indeed, Unit 6 is particularly close to the water zone and, unlike the rest of the section, the mortar shows signs of degraded preservation, including evidence of alteration and current moss growth. These factors indicate that significant processes of runoff and dissolution affect the mortars in this zone, potentially leading to contamination of the samples by CO₂ from recent rainfall, resulting in artificially younger radiocarbon dates due to the introduction of modern carbon. These samples were therefore excluded from the model.

The anthracological identifications provide valuable insights, systematically showing that acacia (*Vachellia* sp.) was used in the preparation of mortar, whereas date palm

(*Phoenix dactylifera* L.) was exclusively used for interior mortar or plaster bricks and jujube (*Ziziphus* sp.) was solely used for exterior coatings (Table 1). Although the number of samples is limited, these data may indicate a preferential selection of certain species for specific types of construction materials.

TABLE 2 | Results of Bayesian modelling in ChronoModel V3.2.7, calibrated in years CE with Intcal20.

Phase	Median	HPD start	HDP end
Core section begin	596	556	637
Core section end	686	639	742
Eastern upper cons.	820	725	907
Plastering begin	947	876	1019
Plastering end	1015	943	1086

Note: HPD, highest probability density region at 90% for phase start and end dates.

3.2.3 | Chronological Data

The Bayesian model is constructed based on the architectural and stratigraphic data of the dam, showing that the oldest phase is located at the core of the structure, with subsequent walls added progressively towards the exterior.

Three phases have been identified (Table 2, Figure 4), corresponding to dates from the core of the dam (at the base of the section), the top of the dam (within the masonry of the north-eastern remnant attached to the slope) and the exterior coatings on the upstream and downstream faces. The model results are clear and, for the first time, establish a chronological framework for the construction of the Sadd al-Bint:

- The model highlights an initial construction phase of the Sadd al-Bint between 596 and 686 CE, based on dates obtained from the core section. It indicates the contemporaneity of the architectural units observed at the foundation of the structure. However, for this architectural ensemble, it is difficult to

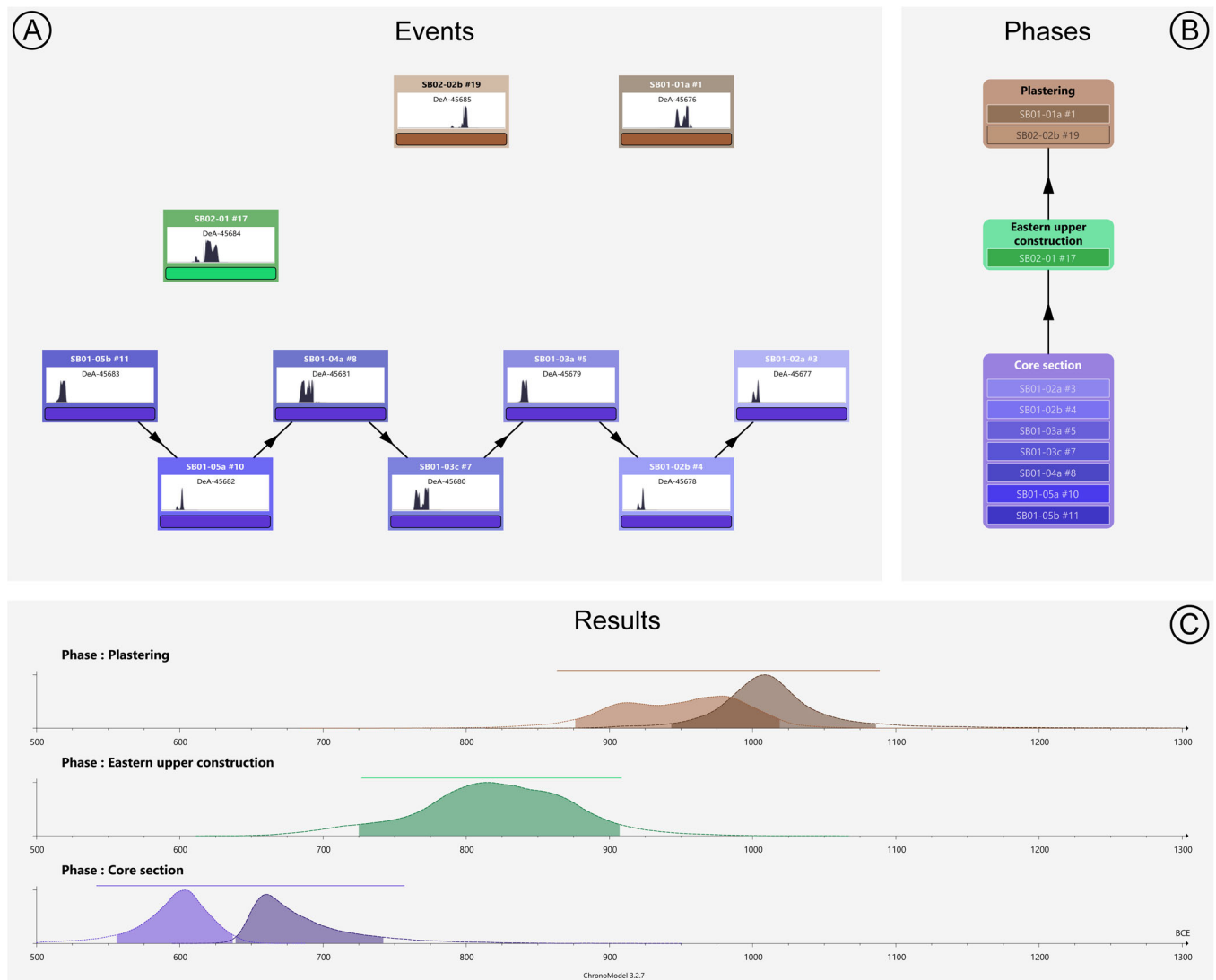


FIGURE 4 | Schematic representation of the Sadd al-Bint Bayesian model in ChronoModel V3.2.7. (A) Set of dated ‘events’ between which stratigraphic constraints can be applied (arrows), (B) grouped by phase for which a succession constraint is applied and (C) a posteriori phase start and end distributions and 90% phase time range (horizontal bar above the two distributions).

specify an internal chronology among the different stratigraphic units described above and linked to the dam's construction, as the calibrated raw dates suggest either an interval of approximately 600–660 CE or 660–770 CE.

- Phase 2 suggests that parts of the dam were likely constructed between 725 and 907 CE, as evidenced by the construction of the north-eastern summit remnant. This may indicate either that the dam's construction spanned several decades or that there were potential reconstructions or extensions. At this stage, uncertainty remains, although it seems unlikely that construction would have extended over such a long period, given the high exposure of the site, located at the bottom of Wadi al-Gharas, to the risk of flooding.
- Finally, Phase 3 indicates that the exterior coatings of the dam date between 947 and 1015 CE, significantly later than the dates obtained from the core masonry. The two samples collected from distinct locations—on the upstream facing near the dam's summit and at the base of the downstream facing—show contemporaneous ages. These findings suggest that the dam's coatings were frequently reapplied to ensure the structure's waterproofing, and this final state likely occurred shortly before the dam's eventual destruction.

3.3 | Hydrogeomorphological Features

3.3.1 | Mapping and Stratigraphy of the Geomorphological Features

Geomorphological survey and mapping were undertaken in order to understand the organisation of sedimentary deposits and to search for geomorphic evidence of the dam's rupture and the subsequent release of the reservoir water (Figure 5). This study was complemented by the high-resolution DEM of the area acquired by photogrammetry.

Aside from the basaltic colluvium originating from the steep slopes of the plateau, an initial, undefined sedimentary formation—potentially predating the dam—is located downstream of the study area. However, it is primarily the formations linked to the dam's chronology that have captured our attention. Upstream of the dam, a silty-sandy formation has accumulated against its facing, extending several hundred metres upstream. Probably deposited following the dam's construction, this formation represents the sedimentary filling within the reservoir when it was full of water. Preserved at several metres thick, this deposit has been gullied by regressive erosion, currently forming a terrace on the left bank due to the recent incision by Wadi al-Gharas. In the absence of a detailed study of this fill, we must also consider the possibility that these deposits were formed following the dam's failure.

The dam's destruction through the creation of a breach and the subsequent emptying of the reservoir led to the formation of high-energy deposits, characteristic of an intense hydrological event, which will be detailed in the following section. These deposits formed a debris-flood fan extending more than 500 m downstream from the breach, occupying the entire width of the wadi bed. Additionally, collapse deposits originating from the destruction of various structures on the south-western side of the dam have accumulated below the downstream facing.

Following the breach, a sandy formation was deposited 200 m immediately downstream. This formation, which takes the form of a low terrace, is significantly later than the other deposits, as it is inset into earlier deposits linked to the dam's destruction. Finally, the recent incision of Wadi al-Gharas has remobilised this formation as well as the debris-flood fan, where two channels have subsequently developed.

3.3.2 | The Geomorphological Evidence of a Sudden Failure

The surveys focused downstream to characterise the deposits resulting from the outbreak flood triggered by the dam's failure. Several key features, mapped in Figure 5, were observed either on the surface or in section along an outcrop extending over 300 m, formed by the incision of the present-day wadi (Figure 6C). These elements are characteristic of a debris flood, which is typical following a dam failure (Church and Jakob 2020). These deposits take the form of a debris fan, extending across the entire width of the wadi (Figure 5).

First, the presence of imposing masonry blocks positioned at the foot of the dam and sometimes projected several hundred metres downstream from the breach suggests that the sudden failure of the dam resulted in the release of water from the reservoir in the form of one or more high-energy waves, powerful enough to transport entire sections of the dam over a distance of 200 m, for example, a ca. $2 \times 2 \times 2$ m block with an estimated mass of 21.6 tonnes, based on the minimum density of basalt (2.7 g/cm^3) (e.g. Figure 6H).

In addition to the presence of projected masonry boulders, the survey reveals a second indication of a high-energy flow event. Indeed, the right bank exposes an accumulation of basalt blocks arranged in imbrications (median angle of 40°) in a highly sandy matrix. These blocks are systematically oriented against the main flow direction, with elongated clasts positioned both parallel and transverse to the main flow (Figure 6A,B,E,G). Amongst them, a notable quantity of blocks is partially covered by mortar (Figure 6A,D,E), indicating that they originate from the dam's masonry. Finally, sporadic but repeated occurrences of pottery sherds are observed positioned between the stones and basalt blocks (Figure 6F). This imbrication fabric, characteristic of a debris flood (Brenna et al. 2024), was formed following an outbreak flood with very high discharge, capable of mobilising all clast sizes from the channel bed and noncohesive banks, which may have caused substantial damage to human settlements in the valley.

In summary, all these elements, indicative of an extreme hydrological event, were deposited during the abrupt failure of the dam, which resulted in the formation of a breach and the subsequent emptying of the reservoir. This suggests that at the time of the dam's failure, the reservoir must have been sufficiently filled with water and may have still been operational.

3.3.3 | Modelling Storage Capacity

Drone acquisitions also facilitated the modelling of the reservoir's storage capacity, taking into account the architectural

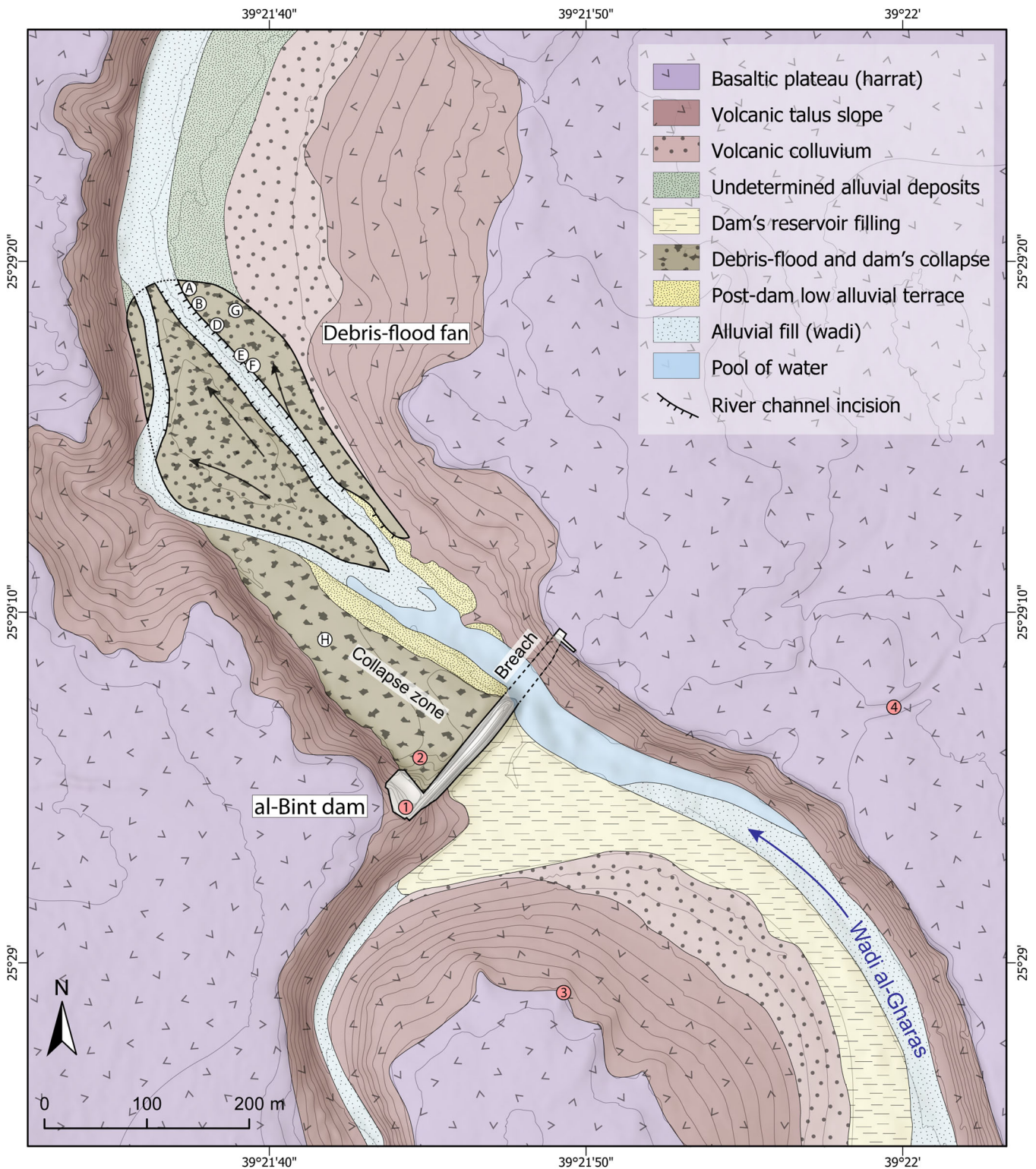


FIGURE 5 | Map of the superficial sedimentary formations of the studied area of the Wadi al-Gharas, including the debris-flood fan that resulted from the failure of the dam, with the location of features documented in Figure 6A–H and 8(1–4). The contours lines are 2 m apart.

data of the dam and the hypothetical functioning of the outlets. If the cavities indeed served as outlets, their presence at regular intervals on the downstream facing could have allowed for the regulation of the reservoir's water level. To maintain a specific water level, it would have been sufficient to block the outlets below that level while leaving those above it open. In this context, the stepped architecture would have made it relatively

easy to move along the facing, and the staircase descending from the top of the dam to a pair of cavities may have served this purpose (Figure 2).

Based on these parameters, the reservoir's water level was modelled using the two extreme water height values (Figure 7), corresponding to the altitudes of the lowest outlet (789 m a.s.l.) and

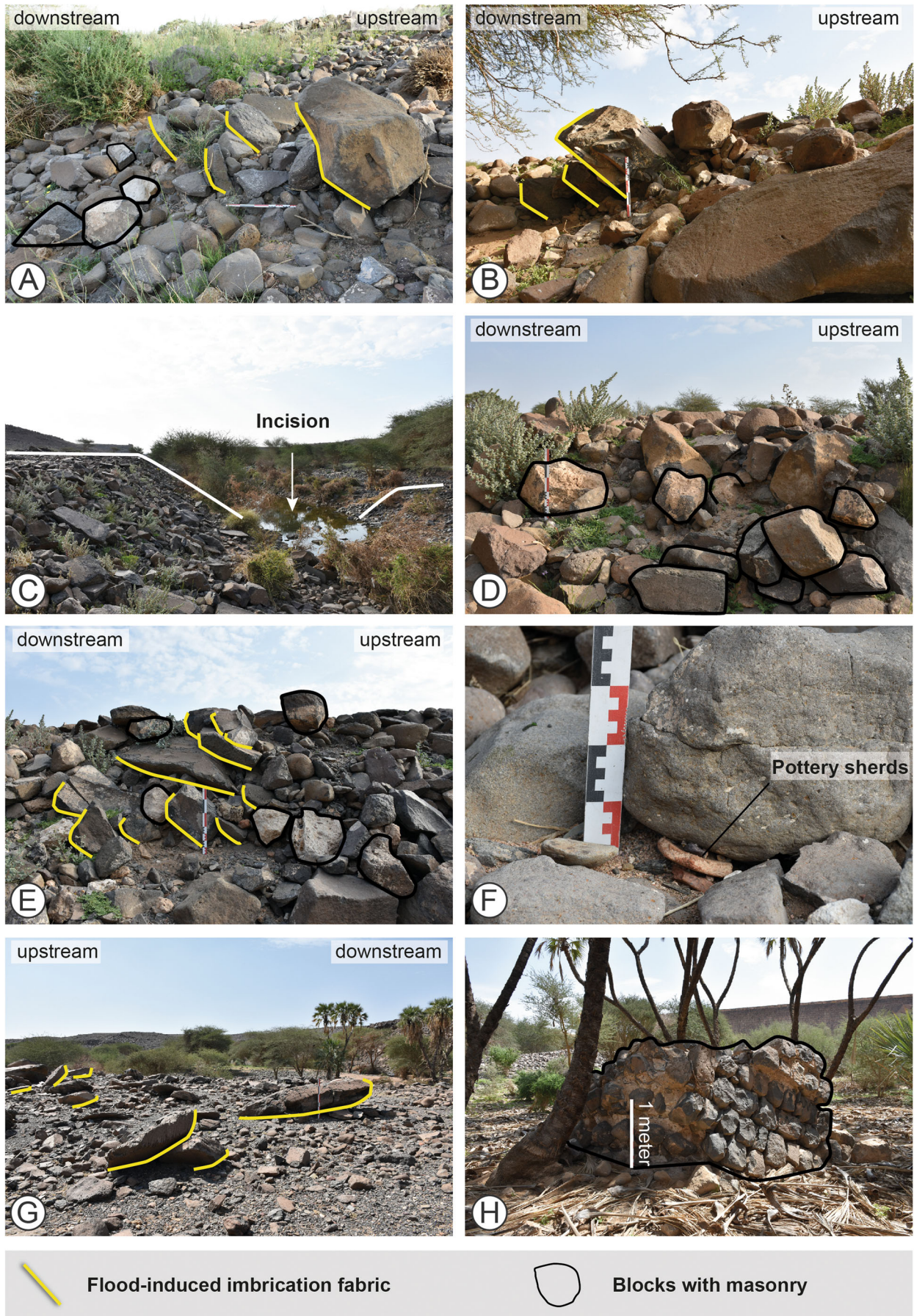


FIGURE 6 | Set of field pictures (mapped on Figure 5) showing several examples of flood-induced imbrications fabric and masonry blocks found within or atop the debris-flood fan.

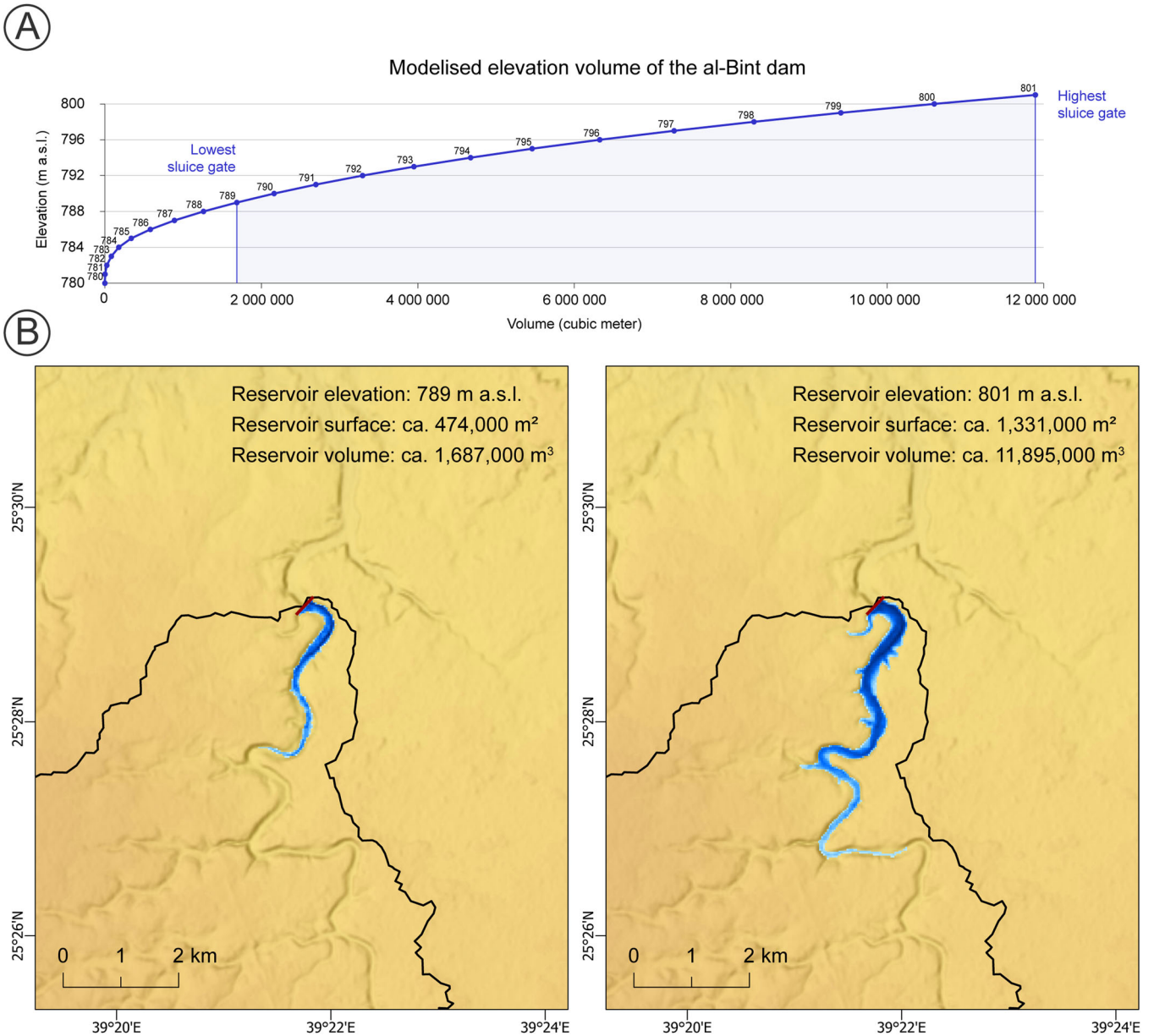


FIGURE 7 | Modelling storage capacity. (A) Volume of the Sadd al-Bint reservoir as a function of the height of the water body determined by the two lowest and highest outlets. (B) Mapping of the spatial extent of the reservoir according to these two extremes, with their elevation, surface area and volume parameters.

the highest outlet (801 m a.s.l.). This allows us to provide a range for the theoretical capacity of the reservoir depending on its operational state. Under the assumption of minimal use, the reservoir's surface area would cover 474,000 m² with a volume of 1,687,000 m³ (Figure 7). Under the assumption of maximal use, the reservoir's surface area would extend to 1,331,000 m² with a volume of 11,895,000 m³. Excluding the effects of evaporation on the retained volume, the Sadd al-Bint's reservoir could have provided the local population with between approximately 2,000,000 and 12,000,000 m³ of water, representing a significant water source in an arid environment, although the exact modalities of water use remain uncertain. It is important to note that topography plays a crucial role in the reservoir's capacity: the initial metres are confined within the narrow valley with steep slopes, whereas from around 785 to 786 m in altitude, the gentler slopes cause the reservoir capacity to increase exponentially (Figure 7). The absence of

outlets below 789 m a.s.l. suggests that the builders were aware of the influence of this topographic effect.

3.3.4 | Dam Stability and Flood Flow Calculations

The stability calculations for the Sadd al-Bint were conducted to estimate the resistance of this gravity dam and to clarify the reasons for its failure. These calculations are based on the dam's geometry, including its cross-section with upstream and downstream slopes, as well as the physical properties of the constituent materials (with a minimum basalt density of 2.7 g/cm³). For a gravity dam to remain stable, it must withstand two main forces: the horizontal force exerted by the water (F), and the gravitational force of the dam itself (W), which depends on its volume (V) and the

area of its cross-section (A). These parameters are calculated as follows:

For the cross-sectional area, considering a section composed of a rectangle and two triangles formed by the slopes:

$$A = b_s \cdot h + \frac{1}{2} \cdot (p_d \cdot h) \cdot h + \frac{1}{2} \cdot (p_v \cdot h) \cdot h,$$

where b_s is the upper base, h is the dam height and p_d , p_v are the slopes of the upstream and downstream faces, respectively.

For the volume of the dam:

$$V = A \cdot L,$$

where L is the length of the dam.

For the weight of the dam:

$$W = V \cdot \rho_b \cdot g,$$

where ρ_b is the density of the material (in kg/m^3) and g is the gravitational acceleration (in m/s^2).

For the hydrostatic pressure, the total force is obtained by integrating over the entire submerged surface, given by

$$F = \frac{1}{2} \cdot \rho \cdot g \cdot h^2 \cdot L,$$

where ρ is the density of water (in kg/m^3).

Finally, for the stability calculation, the condition for equilibrium is

$$M_{\text{stabilising}} > M_{\text{destabilising}}.$$

The stabilising moment is produced by the weight of the dam and acts at the centre of gravity of the lower base:

$M_{\text{stabilising}} = W \cdot d_{\text{cg}}$, where d_{cg} is the horizontal distance of the centre of gravity relative to the downstream base.

The destabilising moment is produced by the force of the water, which acts at one-third of the water height from the base:

$$M_{\text{destabilising}} = F \cdot \frac{h}{3}.$$

Thus, the maximum water height before dam failure is determined by equating the moments.

The calculation of these parameters yields the following results:

- Cross-sectional area: 297 m^2 .
- Total volume of the dam: 63,000 m^3 .

- Total weight of the dam: 1,670,000,000 N.
- Stabilising moment: 10,575,000,000 Nm.
- Destabilising moment (for a water height of 23.6 m): 4,555,000,000 Nm.
- Maximum water height before failure: 31.25 m.

As the pressure exerted by water on the dam wall increases with depth, the Sadd al-Bint is structurally stable under the given hydrological and topographical parameters and would only fail under a water height of 31.25 m. These results are significant, as they confirm the high quality of the Sadd al-Bint's construction, with its design and dimensions effectively counteracting both the horizontal hydrostatic force and the vertical gravitational force. This demonstrates the advanced technical and scientific expertise of early Islamic engineers. Additionally, these findings support our hypothesis of water management via the outlets, even in its maximum operational mode with the reservoir filled to 801 m a.s.l. (Figure 7). Finally, they suggest that the dam's failure was not due to poor construction but rather a lack of maintenance, which allowed water infiltration to occur repeatedly, causing cracks that weakened the structure until the breach formed upon failure.

Given the weakening of the structure, the failure could have been triggered by long-term wear, which reduced the dam's resistance to the hydrostatic pressure of the reservoir's water mass. The sudden emptying of the reservoir through the breach subsequently generated an exceptional outbreak flood event downstream. The failure of a dam is a complex hydrological phenomenon, where the characteristics of the resulting flood are primarily governed by the failure mechanism and the dam's structural properties. In the case of gravity dam breaches, which show a simple geometry, reasonable estimations of peak flood discharge at failure can be obtained (Costa 1988). It should also be noted that the dam may have collapsed as a result of a sudden high-flow event that filled the reservoir, caused overtopping and led to the failure of the structure at its weakest point.

Based on a dataset of historical dam failures with known parameters (height, volume at the time of failure and peak discharge), Costa (1988) identified strong correlations between these parameters, allowing him to establish simple regression equations. For constructed dams, the author found that the best correlation ($r^2 = 0.80$) for reconstructing past flood peak following dam failure is based on dam height, with the following equation:

$$Q_{\text{max}} = 10.5H^{1.87},$$

where Q_{max} is the peak discharge in m^3/s and H is dam height in metres.

Another equation, which accounts for reservoir volume but is less well suited, is

$$Q_{\text{max}} = 325(HV)^{0.42},$$

where V is the reservoir volume in $\text{m}^3 \times 10^6$.

The two equations yield respective results of 3877.3 and 3468.6 m³/s, respectively. Based on other examples of dam failures and correlations between these parameters (Costa 1988), for a Q_{\max} estimated between 3500 and 3900 m³/s, the reservoir volume at the time of failure is estimated between 14,000,000 and 18,000,000 m³. These results validate our previous models, which estimated that in the maximum operational mode, with the reservoir filled up to 801 m a.s.l., a total volume of 11,895,000 m³ was technically feasible. Such a volume is therefore consistent with the dimensions of the Sadd al-Bint and would not have posed a structural risk to the edifice.

3.4 | Other Archaeological Structures

The archaeological survey of the Sadd al-Bint and its surrounding area yielded different archaeological features (Figure 5):

- Clusters of fired bricks and ceramics were found adjacent to the northeastern upper remnant of the dam (KL-SB 100), which are of mixed 7th–8th century CE and medieval age. It is worth noting that the fired bricks were also found within the mortar used to build the dam (Figure 8(1)). In addition to this area, surface collections from two other locations on the right bank of the wadi (KL-SB 101 and KL-SB 103) revealed ceramics, which, upon preliminary rapid examination, belong to a likely 7th–8th century horizon.

- A stone dam mechanism (KL-SB 107), whose function remains unknown, was found with rubble in the collapse zone (Figure 8(2)) which was also mentioned in al-Shilali (2019) and al-Rshedi (2023).
- Surveys also identified possible quarry areas along the south bank of the dam, in columnar jointing (KL-SB 106, KL-SB 108) (Figure 8(3)).
- Finally, a few structures were identified, notably a five-celled linear stone structure 8 m wide (KL-SB 103) along the north river bank, with rubble packed walls and, interestingly, a structure potentially related to the dam (SB 111), located 350 m east, with the same architectural style and mortar (Figure 8(4)). The latter consists of two pillars built with an opening to the southwest, between two small basalt outcrops.

4 | Discussion

4.1 | Insights Into the Function and Uses of Water From the Sadd al-Bint

Our study has, for the first time, provided a numerical chronology for the Sadd al-Bint. Constructed between 596 and 686 CE, it subsequently underwent a phase of extension or repair between 725 and 907 CE. However, the dam's architecture and construction techniques suggest that it was originally



FIGURE 8 | Photographs of the main archaeological features (mapped on Figure 5) discovered during surveys around Sadd al-Bint. (1) Fired bricks found within the mortar of the dam, (2) a stone dam mechanism, (3) possible quarry area along the south bank of the dam and (4) a structure potentially related to the dam.

built within a limited timeframe. The final coatings on both facings indicate a last refurbishment between 947 and 1015 CE. Following its failure and the sudden emptying of its reservoir—which destroyed nearly half of the structure—the dam was never repaired. This failure was not due to poor construction but was most likely the result of a lack of maintenance, leading to the development of cracks that progressively weakened the structure until the breach formed. The exact date of its destruction remains uncertain, though it is assumed to have occurred soon after its last use, as the reservoir still contained water at the time of failure.

Furthermore, our calculations and modelling confirm the high quality of the dam's construction, illustrating the advanced technical expertise of early Islamic engineers, as well as its well-adapted dimensions, even under maximum operational conditions, with a full reservoir estimated at nearly 12,000,000 m³. These results, particularly the dam's exceptional storage capacity, highlight the crucial role of the Sadd al-Bint in regional water management. However, uncertainties remain concerning the management of extreme flow events and water distribution, as no outlet or spillway has been definitively identified. Some adjacent structures could correspond to water storage basins, and yet, no canals or other drainage systems have been observed. This raises important questions regarding the function and positioning of the dam, as well as the utilisation of the stored water, which could be further explored by comparing our findings with other dams studied in the Khaybar oasis and similar regional hydraulic structures.

An analysis of the topography of the Harrat Khaybar provides valuable insights into the location of the Sadd al-Bint (Figure 9). The exceptional dimensions of this structure correspond to the significance of Wadi al-Gharas, the primary wadi in the region, which drains the entire basaltic massif from south to north. Positioned across its deeply incised valley, the Sadd al-Bint is located 5 km upstream of a depression area, filled with sediments and enclosed by the surrounding basalt plateaus, now occupied by the oasis of al-Thamad. At the scale of the *harra*, whose surface is predominantly covered by lava flows, this depression represents the largest cultivable area in the region. This strategic location appears to be a key factor in explaining the substantial investment required for the dam's construction: by controlling the flow of the region's main wadi, it was possible to create a significant water reserve upstream of a rare, extensive cultivable zone, ensuring controlled water distribution for agricultural purposes.

This spatial organisation, based on a deep understanding of local geography, hydrology and topography, appears to follow a regional pattern (Figure 9). Notably, the positioning of the two dams of Sadd al-Hasid, also upstream of this depression, further supports the hypothesis of a planned hydrological management system for the al-Thamad area. This regional hydraulic strategy is further reinforced by the identification of a similar system in the Khaybar oasis, which represents the second major cultivable zone on the western side of the basaltic massif. The two main dams, Sadd al-Zaidiyyah and al-Mashquq, which we have studied and dated to the same period, are also located within deeply incised valleys in the basalt flows, before they open onto the extensive agricultural area of the Khaybar oasis (Figure 9,

McPhillips et al. [forthcoming](#)). Thus, the construction of the Sadd al-Bint, along with other regional dams, appears to be the result of a major political investment and a unified water management strategy implemented across the region.

Regarding the water supply to the al-Thamad cultivated area, the absence of irrigation canals in their immediate vicinity, as mentioned above (see Section 3.1.3), could be explained by the fact that the collapse deposits from the dam cover the former alluvial plain under several metres of sediment. However, the lack of canals even downstream of these deposits raises questions, requiring us to reconsider the water transport system and the method of supplying the irrigated area further downstream. In this regard, data from other regional dams provide valuable insights. The systematic absence of irrigation canals, including at the Khaybar dams, which remain relatively well preserved, casts doubt on their use as primary means of water distribution. Given the distances between the dams and the irrigated zones—5 km in the case of al-Bint and the cultivated area of al-Thamad—it is possible that water was simply transported along controlled wadi flows, with strategic diversions of their course into cultivated areas to irrigate the fields. This would imply that the dams served a dual function: regulating wadi flow to support agricultural practices, ensuring a controlled water supply over time, and protecting downstream irrigated areas from extreme hydrological events, such as flash floods, which are common in arid regions.

4.2 | A Regional Hydro-Agricultural Expansion in the Early Islamic Period

The Sadd al-Bint stands out in its size alone, both in length and height, in comparison with dozens of other dams identified in the regions of Medina and Ta'if, the largest of which include al-Uraydah, Hakkar and al-Darwaish (see Section 1, Gilmore et al. 1982; Khan and al-Mughannam 1982; al-Zahrani et al. 2002; Eskoubi 2006; al-Subhan 2006; Eskoubi et al. 2012). On the Harrat Khaybar, three other dams are notable for their size: the Sadd al-Zaidiyyah (28 m long and 8.6 m high) and the Sadd al-Mashquq (134 m long and 2.8 m high), both located within the Khaybar oasis, as well as the Sadd al-Hasid (82 m long and 10 m high), situated 7 km north-east of the Sadd al-Bint and forming part of the same hydrological basin (Figure 9). Now covered with concrete, a photograph of the latter taken by Philby during his expedition (Philby 1957) shows a construction technique that appears to be quite similar, characterised by a stepped profile and the use of cut basalt blocks embedded in mortar (Figure 10). More importantly, the photograph reveals an arched outlet at the base of the dam. This feature is significant, as it suggests that a similar structure may have existed at Sadd al-Bint before its destruction or is buried by the rubble, thereby addressing uncertainties regarding its water management system.

As we have seen, numerous stone-built gravity dams occur across a substantial area of northwestern Arabia, and although numerical dating evidence is currently lacking for these, the evidence that does exist is quite convincingly seventh century in all four cases. Both Sadd al-Zaidiyyah and Sadd al-Mashquq, located in the Khaybar oasis, which we presume to be part of unified water management strategy, are dated to the seventh

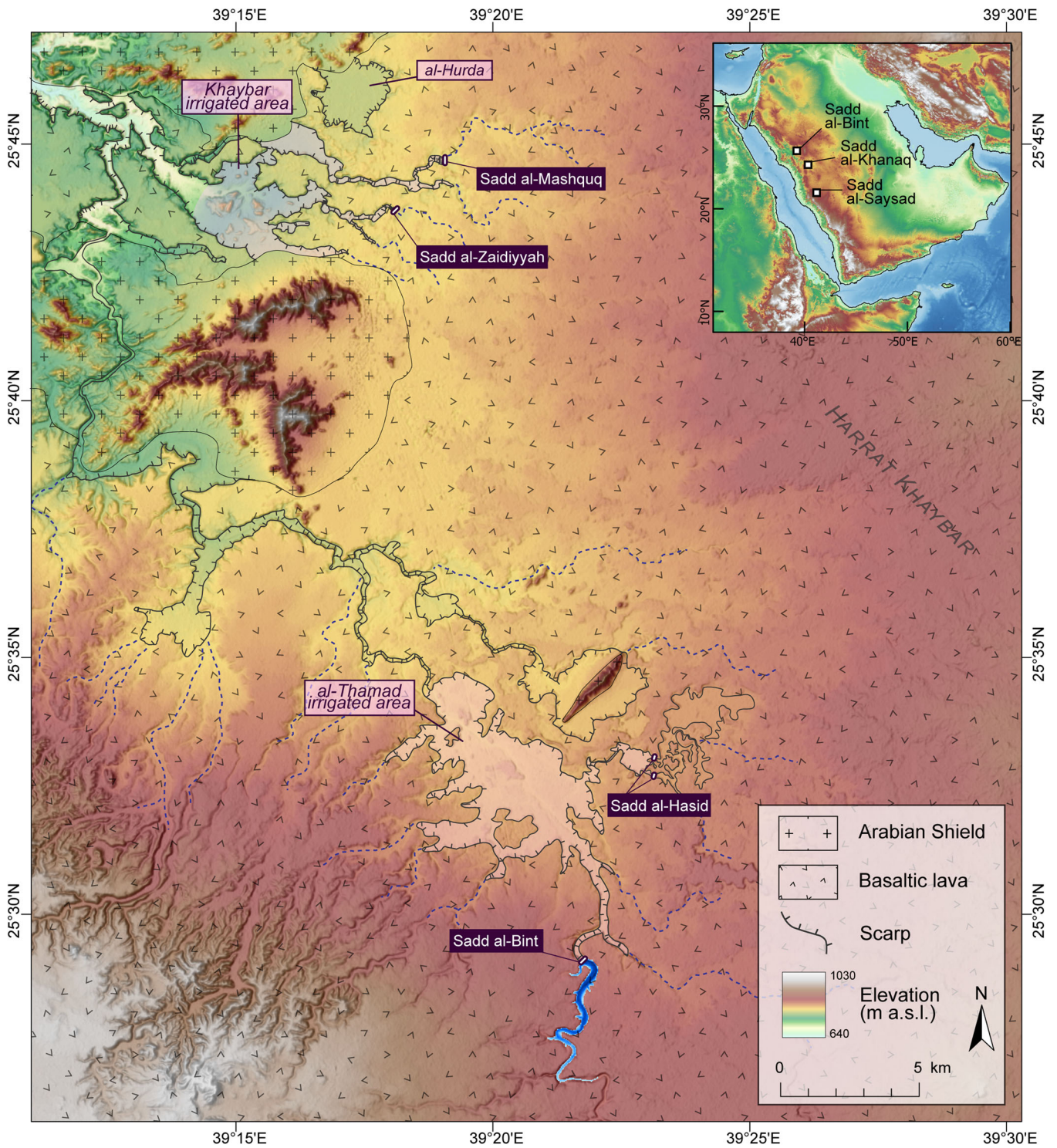


FIGURE 9 | Map of the main dams in the region within the topographic and geologic frame of the Harrat Khaybar, highlighting their positions upstream of sedimentary depressions constituting the main cultivable areas of the region. The inset shows the location of the dams in Northwest Arabia with dating evidence, namely, the Sadd al-Khanaq in the Medina region and the Sadd al-Saysad in the Taif region.

century (Figure 11, for more details, see McPhillips et al. [forthcoming](#)). Two other regional examples, which share a similar construction technique that includes fired bricks, are associated with foundation inscriptions—a rare feature that provides insight into their construction date: the Sadd al-Khanaq near Medina and the Sadd al-Saysad in the Taif region, east of Mecca (Figure 9). These two dams can be dated to the early Umayyad period (late seventh century CE), as their

inscriptions mention Caliph Mu'awiya (who ruled from 661 to 679 CE), with the latter specifically indicating the year 677–678 CE (Figure 11, Miles 1948; Khan and al-Mughannam 1982; al-Rashid 2008). As yet, it is not possible to associate these dams with other hydro-agricultural infrastructure in the landscape, owing to the lack to date of comprehensive landscape survey work. This is likely to change, given the expansion of new projects, as, for example, in the oasis of Khaybar, a large quantity of check dams, and



FIGURE 10 | Photograph taken in the 1950s of al-Hasid dam from its downstream side (after Philby 1957). Note the presence of an arched sluice gate at the base of the dam.

potentially canalisation of wadi systems, appear to accompany the programme of dam building there (McPhillips et al. [forthcoming](#)). The historical context of what represents undisputedly a major reorganisation of the regional agricultural landscape is more than likely linked to the influx of revenues from the Islamic conquest that was invested in land holdings and agricultural projects in the Rashidun and Umayyad period, documented in the Madina region, and perhaps implied in the wider Khaybar region by historical texts detailing the redistribution of lands in the oasis following the conquest (Munt 2018).

Recent archaeological studies of dams in the Levant commonly indicate an early Islamic date to be likely or at least highly feasible,

in contrast to the conclusions of earlier twentieth century studies, which considered them to be antique. The Harbaqa gravity dam, published in the early twentieth century by Schlumberger (Schlumberger 1939), in the vicinity of the important Umayyad ‘desert castle’ site of Qasr al-Hayr al Gharbi, is the only structure larger than the Sadd al-Bint, at 345 m in length, 18 m in width at its base, although at 20.5 m, and several metres lower in height. Genequand (2006, 67) has convincingly argued it to be Umayyad in date, probably from the reign of Hisham b. Abd al-Malik (who ruled from 724 to 743 CE), owing to its incontestable role alimending the hydraulic systems providing for the adjacent ‘Desert Castle’ complex of Qasr al-Hayr al-Gharbi situated at some 20 km distance. Beyond its similar dimensions, it has a superstructure that resembles that of

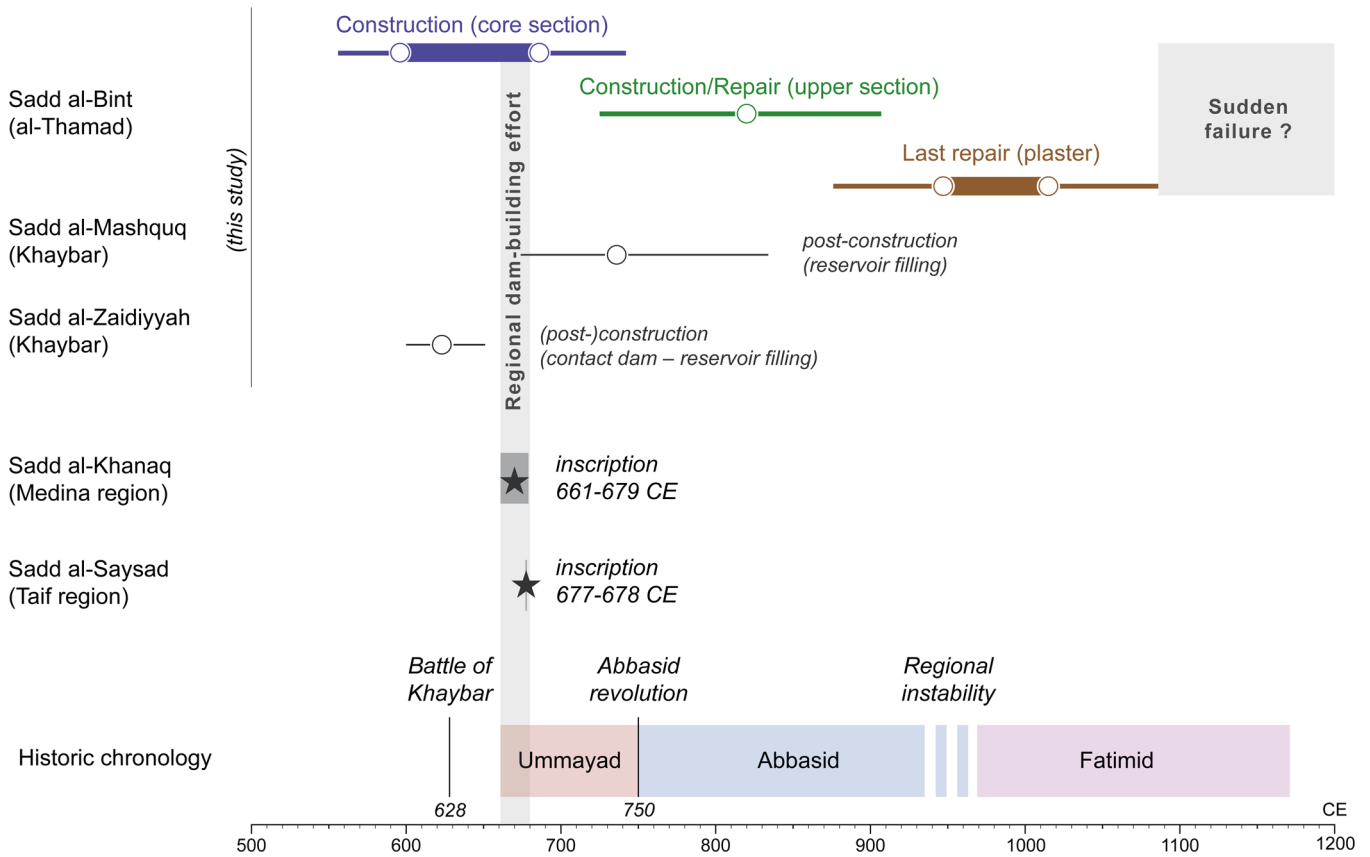


FIGURE 11 | Chronological synthesis of the dams in Northwest Arabia in relation to the dynastic periods and historical events. The white circles correspond to the medians of the ¹⁴C dates.

Sadd al-Bint, and significantly, possesses features that are not visible in the latter structure: two sluice gates at its base and a water channel that was fed 11 m below its top. In addition, Poidebard observed an overflow mechanism allowing pressure to be relieved on the structure in periods of peak water supply (Poidebard 1934).

Inland regions of the Levant, in modern Syria and Jordan, and indeed attested in new landscape work in northern Iraq, provide an expanded geopolitical context in which to place the Sadd al-Bint. The major phenomenon of hydroagricultural expansion across the Arabian Peninsula is clearly part of, or a precursor to, massive programmes installing new irrigation systems in the newly conquered central Islamic lands from the seventh century CE. As in Arabia, new impetus was provided by an injection of economic resources derived from the Islamic conquest. In addition to dams, archaeological survey and excavations are indicating that canal systems and watermills dotting much of the Arabian Peninsula were also part of this seventh century floruit (Berthier 2001; Tonghini and Usta 2021: 100). Much of this infrastructure had typically been assumed to be of pre-Islamic date (e.g., Schlumberger 1939), or in the case of watermills, only the most recent Ottoman period utilisation had been detected.

4.3 | Longevity and Destruction in the Abbasid and Fatimid Periods

The high quality of the construction of the Sadd al-Bint and its use for at least three or four centuries correspond to a long

period of use that is difficult to demonstrate for other dams. It raises questions about the reasons for its abandonment and lack of maintenance, which are thought to be the cause of its destruction.

The indications that the Sadd al-Bint may date to the seventh century, potentially even predating the Umayyads, raises the interesting possibility that it may be related to the shifts in land ownership in the Khaybar oasis that textual sources state took place directly after the conquest, with the installation of part of the Prophet's own family in the southwestern part of the oasis. The installation of the Umayyad dynasty in Damascus in 661 does not signify a total withdrawal of power from the Arabian Peninsula, and this dynasty retained ties in Northwest Arabia from which it originated. Moreover, controlling the Haramain was an imperative for the Umayyads, who sought to strengthen their legitimacy, especially following the Zubayrid insurrection (684–692), when they had lost control of the region (Bouali 2021). The same period saw the development of land and sea routes and landed estates around Medina, Mecca and al-Taif (el-Ali 1959; Munt 2018), some of them belonging to the caliphal family (al-Harbi 1969). This has been characterised as an agricultural boom, but the nature of this production remains poorly documented and it is not known whether production was intended for local or interregional markets. The building of dams underlay an agricultural expansion. The Sadd al-Bint facilitated a massive expansion in irrigated agriculture on the southern margins of the Khaybar oasis, on the largest wadi in the Khaybar system, contemporaneous with the building of two dams closer to the oasis core. The Sadd al-Bint may have also played a

symbolic role in demonstrating the new caliphal power, asserting the sovereign's ideology through the mastery of the landscape and in its very monumentality. The most spectacular element in a regional architectural programme, it also belongs to an interregional phenomenon attested in Bilad al-Sham (Genequand 2006, 2012).

The abandonment of the dam, whether contemporaneous with the breaching event or not, occurred in a period that has often been characterised as one of socioeconomic decline in north-west Arabia linked to the weakening of Abbasid power. From the 10th century onwards, archaeological evidence and accounts in historical sources (Tabari/ed. Saliba 1985) suggest regional instability. Caliphal power was weaker (Waines 1977; Campopiano 2012), certain tribes created a climate of insecurity and the hajj was interrupted on several occasions as the region came under Fatimid influence (Peters 1994; Webb 2022). The Caliphate's interest in the region changed and the logic behind the construction of the dams was no longer the same. One might assume that the economic context did not allow these structures to be maintained, as they were presumably expensive to run and required regular maintenance and repair. In the local archaeological record in Khaybar, there is something of a 'loss of signal' in chronological continuity apparent by the twelfth century (McPhillips et al. forthcoming), whereas elsewhere at urban sites in western Arabia such as Mabiyyat and Rabadha are abandoned altogether (al-Rashid 1979, 1986). The archaeological evidence from Sadd al-Bint is exceptional in revealing for the first time chronological evidence of the continued use and maintenance of a large gravity dam in the Middle East, through to the traces of its breaching and abandonment. The evidence points to the other gravity dams in northwestern and southwestern Arabia going out of use around the same time, along with many of the hydraulic systems in the more arid regions of Bilad al-Sham and Iraq. This may have some reflection in the wider trends in the central regions of the Islamicate world, although this did not happen when this infrastructure continued to be essential to sustain large urban populations, such as the large dam which irrigated the horticultural areas around Homs, or lay in the hinterland of newly flourishing population centres such as Mosul under the Zangid dynasty in the twelfth century (Tonghini and Usta 2021).

5 | Conclusion

This study provides the first numerical chronology for the Sadd al-Bint, one of the largest known ancient dams in Saudi Arabia, shedding new light on the engineering, use and failure of this water management system in the early Islamic period. Through a multidisciplinary approach, integrating radiocarbon dating, Bayesian modelling, geomorphological analysis and hydrological simulations, we establish a three-phase construction sequence. The dam was initially built between 596 and 686 CE, followed by repairs or extensions between 725 and 907 CE, and a final maintenance phase between 947 and 1015 CE, before its collapse.

The structural assessment shows the high quality of the dam's construction, illustrating the advanced technical expertise of early Islamic engineers, as well as its dimensions being well adapted to natural parameters, even under maximum operational

conditions. Structural weakening rather than engineering malfunction suggests that lack of maintenance played a key role in the final failure, in conjunction with a high-flow event. Sedimentological analysis downstream reveals debris–flood deposits, confirming that the dam failed suddenly when the reservoir was full, causing an exceptional outbreak flood downstream.

Hydrological modelling reveals that the dam's reservoir could store up to 12 million m³ of water, supporting the al-Thamad oasis, probably the largest cultivable area in the Harrat Khaybar region. A comparison with the other dams in Northwest Arabia, some of which we have also dated, shows that they were built at the same time, and that they were constructed according to a similar spatial pattern. This suggests a strategic role in regional flood regulation and irrigation management, which appears to be the result of a major political investment and a unified water management strategy implemented across the region, in the Rashidun and Umayyad periods. However, from the 10th century onwards, political instability, weakening Abbasid control and changing economic priorities potentially led to its abandonment and lack of maintenance, mirroring a broader decline of hydraulic systems in western Arabia, Bilad al-Sham and Iraq.

Author Contributions

B.D., M.alM., S.C., S.McP. designed research. B.D., M.alM., S.C., S.McP., G.C.-T., K.G., S.alS., M.alD., F.alR., K.alK. and C.F. conducted fieldwork and surveys. B.D. and S.C. were responsible for sampling and recorded field sedimentological and stratigraphic data. M.alM., S.McP. and G.C.-T. were responsible for archaeological surveys. K.G. was responsible for the drone imagery and the photogrammetry. B.D. carried out the modelling work and the calculation of hydraulic parameters. B.D. wrote the overall paper and M.alM., S.C., S.McP., G.C.-T. contributed to the writing and editing of the paper. E.C. conducted identification and interpretation of the anthracological data, and wrote corresponding sections of the paper. R.C., G.C. and M.alM. led the KLDAP project in which this study was carried out. M.alM. and G.C. obtained authorisation to study the dam in collaboration with the Heritage Commission. All authors discussed and commented on the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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