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Flood-Damaged Canals and Human Response, A.D. 1000–1400, Phoenix, Arizona, USA

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ABSTRACT

The scale of prehistoric canal construction in the North American Southwest peaked in A.D. 450–1450, during what has been named the Hohokam Millennium. Explanations for the eventual Hohokam “collapse” remain elusive. Environmental disturbances, such as floods, that were once manageable may have become unmanageable. Recent archaeological excavations of Hohokam canals in Phoenix identified stratigraphic evidence for three destructive floods that date to A.D. 1000–1400 within two large main canals in System 2, Hagenstad and Woodbury’s North. Woodbury’s North Canal was flood-damaged and abandoned sometime after A.D. 1300. Thereafter, no main canals of similar size were constructed to supply villages within System 2 and the area was depopulated. Our investigation provides the first stratigraphic evidence for a destructive flood during the late Classic period in the lower Salt River Valley and is compatible with the hypothesis of diminished resilience to environmental disturbance at the end of the Hohokam Millennium.

KEYWORDS

Hohokam; canals; floods; stratigraphy; American Southwest

Introduction

Factors contributing to the success or failure of any society are complex, involving a mixture of social, environmental, and historical circumstances. Despite decades of multidisciplinary research, explanations for what happened to the Hohokam remain elusive. An agricultural society that lived in the lowland deserts of the North American Southwest in A.D. 450–1450, the Hohokam are known for their earthen constructions, including ball courts and later platform mounds; distinctive red-on-buff pottery; and large canal systems. The Hohokam sphere of influence was centered in the Phoenix Basin near the confluence of the Salt and Gila rivers but extended across a broad area that, by A.D. 1100, reached ca. 100,000 km², including much of central and southern Arizona and the northern edges of Sonora, Mexico. This 1000-year period has been referred to as the Hohokam Millennium (Fish and Fish 2007), and although many aspects of the Hohokam way of life changed during their long tenure, they remained a distinctive cultural entity that successfully adapted to the arid landscapes of the Sonoran Desert. Key to successful adaptation was a mixture of diverse subsistence strategies (Fish and Fish 1994; Masse 1991) that included sophisticated water control for irrigation.

Despite 1000 years of successful subsistence, Hohokam population began to decline in the A.D. 1300s, and by A.D. 1450, what we know as Hohokam ended (SUPPLEMENTAL MATERIAL 1). Considerable research has been conducted to determine how this happened and how it relates to broader demographic decline in the Southwest (Hill et al. 2004). Because many Hohokam settlements, particularly those located along large rivers, were heavily reliant on canal irrigation, a viable hypothesis is that climate variability played an important role in demographic decline during the late Classic period (Abbott 2003; Graybill et al. 2006; Ingram and Craig 2010; Loendorf and Lewis 2017; Woodson 2016). The two

climatic factors of most concern are flood and drought, the former damaging irrigation infrastructure and the latter reducing the amount of water available for crop production. Particular attention has been given to the destructive impacts of flooding (Graybill et al. 2006; Masse 1991: 222; Nials et al. 1989). Undoubtedly, the Hohokam witnessed multiple floods and droughts over the course of their 1000-year habitation. A question arises: was something intrinsically different about flooding and drought in the A.D. 1300s or alternatively, about the Hohokam and their ability to respond to environmental uncertainty at this time? That is, did they become less resilient to environmental perturbations due to sociocultural factors? Increased climate variability coinciding with relatively low population densities and diverse food production/procurement strategies would ostensibly have a less negative impact than during a period of population aggregation and overreliance on a single food production strategy, such as canal irrigation (Redman et al. 2009). Additional stress may have been created by increased immigration from the north during the Classic period (Hill et al. 2015). One approach for testing the notion of changing Hohokam resilience through time is to identify evidence for past environmental perturbations detrimental to food production and differential cultural response to those disturbances.

Given the substantial labor investment in the construction and maintenance of large canal systems, large floods were undoubtedly an environmental perturbation for the Hohokam. Whereas small or seasonal floods play a vital role in maintaining soil fertility through deposition of nutrient-rich detritus (Sandor et al. 2007), large floods that have a statistical recurrence of one every 50–100+ years can risk the ability to deliver water to crops as a result of damage to irrigation canal infrastructure. Historically, large floods resulted in economic hardship along the Salt and Gila rivers (FIGURE 1) prior to construction of dams for flood control (Davis 1897:

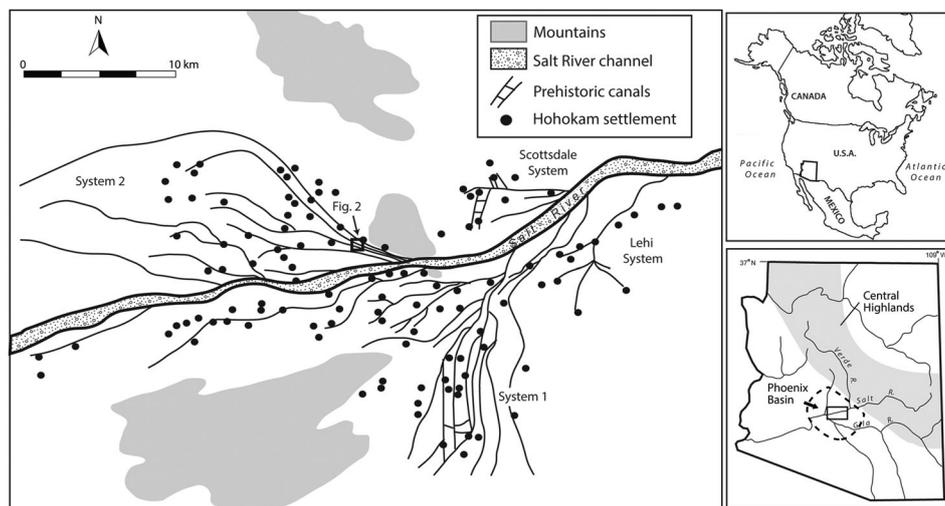


Figure 1. Major Hohokam canal systems and settlements in the lower Salt River Valley, Arizona (adapted from Hunt and colleagues [2005: fig. 2]).

52; Woodson 2015; Zarbin 1997). Dendrohydrological reconstructions (Graybill et al. 2006; Nials et al. 1989) and floodplain stratigraphic studies (Birnie 1994; Huckleberry et al. 2013; Waters and Ravesloot 2001) suggest that the frequency of large floods changed through time on the major irrigating rivers of Arizona, although not necessarily at the same time. Despite the certainty of periodic flood damage, evidence for destructive flooding in Hohokam canals has been somewhat elusive. The most unequivocal evidence for destructive flooding would be damaged intakes on the river and flood deposits filling much of the main canal alignment. Hohokam canal intakes have long ago been destroyed by flooding and channel widening, and long distance tracing of canal channel fills is limited given that only short segments of Hohokam canals, often separated by kilometers, are ever available for stratigraphic analysis. A previous stratigraphic investigation of 45 Hohokam canal segments located in the lower Salt River Valley failed to identify any clear signal of destructive flooding (Huckleberry 1999a), suggesting either that flooding was not a recurrent problem, that flooding in Hohokam canals does not produce an obvious stratigraphic signature, or that the expected stratigraphic sequence is missing because of erosion or other disturbance processes.

Excavation of historical canals with documentary evidence of flood destruction indicate complexity in flood stratigraphy, suggesting that no single stratigraphic criterion exists for

identifying past flooding in Hohokam canals (Huckleberry 1999b; Woodson 2015). Nonetheless, recent excavations of historical canals near their intakes suggest that certain stratigraphic properties are commonly associated with large historical earthen canals damaged by uncontrolled flooding (Huckleberry 2011) (TABLE 1). These include thick, poorly sorted sandy deposits with matrix-supported clasts of finer grained material suggesting turbulent flow and erosion of previous channel fill and bank material.

Deposits indicative of turbulent and uncontrolled streamflow were recently identified in large Hohokam canals near their intakes within the Salt River floodplain (Huckleberry 2015, 2017) in an area known as Park of Four Waters (FIGURES 1–2) located adjacent to Phoenix Sky Harbor International Airport. These canals were part of a large concentration of canal channels collectively referred to as Canal System 2 (FIGURES 1, 3) constructed over several centuries to provide water for Hohokam agricultural settlements north of the Salt River (Hunt et al. 2005). These sandy deposits with matrix-supported clasts of finer-grained material fill the middle to upper channels of two main canals, as well as the channels of associated secondary (distribution) canals into which water was diverted from each main (Henderson 2017b).

Here we make the case that these sandy deposits represent three separate Salt River flood events that damaged primary canals within System 2. We combine previously established settlement chronologies within System 2 with new radiocarbon, luminescence, and artifactual dating of the two main canals and conclude that these floods occurred in A.D. 1000–1400. The last flood filled the main alignment for several kilometers sometime after A.D. 1300, thus representing the first direct physical evidence for the destruction of a main Hohokam canal during a time of depopulation and cultural decline. Stratigraphic relationships between the flood deposits and canals at Park of Four Waters indicate that the Hohokam responded differently to the three floods with respect to canal operation and repair: they repaired or excavated replacement canals after the first two floods but appear not to have replaced the last canal in the A.D. 1300s. Hohokam response to the destruction of their main canals in System 2 changed through time, likely in response to factors that extend beyond climate.

Table 1. Stratigraphic evidence for identifying flood damage within riverine earthen canals (Huckleberry 2011).

Conclusive Evidence	Strongly Suggestive Evidence	Equivocal Evidence
Coarse textured (gravel > 1 cm diameter) deposits that require water velocities beyond the range of channel stability (e.g., > 1 m/s).	Sandy deposits in channels fed by impounded water, e.g., diversion dams.	Sandy deposits in channels fed by weirs and simple diversions.
Alluvial deposits that fill the channel and extend beyond adjacent berms.	Textural discontinuity with a sudden jump in mean grain size, e.g., coarse deposits overlying fine-textured deposits.	Multiple channels within a single alignment.
	Deposits containing intraclasts of silt and clay supported in a sandy matrix.	
	Eroded channel walls and berms (deviations from parabolic and trapezoidal channel shapes).	

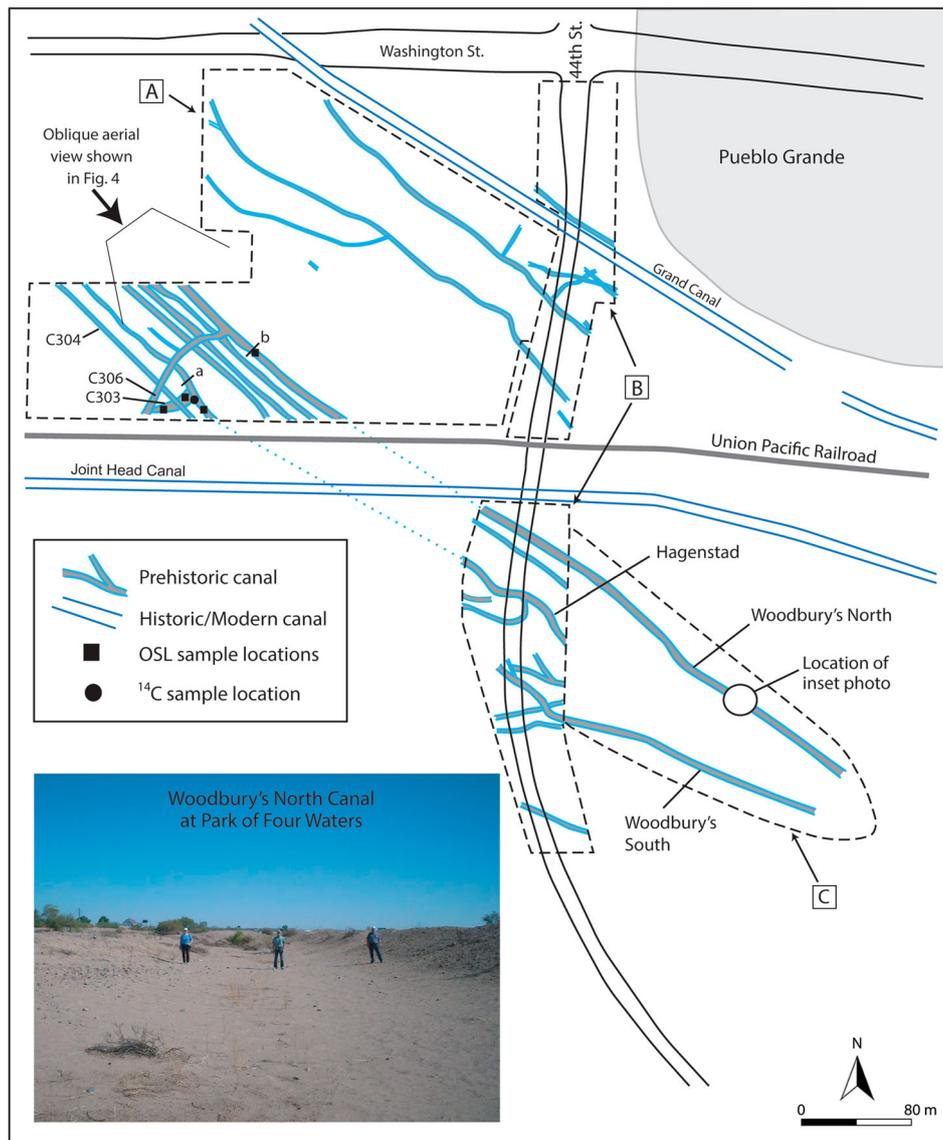


Figure 2. Prehistoric canals documented in Park of Four Waters and Pueblo Grande area. A) Area of Desert Archaeology investigations (Henderson 2015, 2017b). Canals C303, C304, and C306 provide stratigraphic cross-cutting relationships for evaluating construction history; “a” and “b” indicate locations of Trench 117 and Trench 123 profiles (see text). B) Area of Hohokam Expressway investigation (Bradley 1999; Masse 1981). C) Park of Four Waters study area (Woodbury 1960). A segment of Woodbury’s North Canal is still visible at the ground surface (lower left photograph) at Park of Four Waters.

Cultural Setting

Palaeoindian and Archaic lifeways in the Southwest (SUPPLEMENTAL MATERIAL 1) changed with the arrival of maize through diffusion from Mexico around 2100 B.C. (Merrill et al. 2009). Water control involving the construction of canals began ca. 1500 B.C., reflecting greater time investment in food production. Although the Hohokam are best known as the great canal builders of the desert Southwest (Doolittle 2000: 368–408; Scarborough 2003: 125–129), they inherited an almost 2000-year legacy of water control and management. Expanding upon this knowledge, they constructed hundreds of kilometers of canals in large alluvial valleys of south-central Arizona in support of irrigation agriculture. Large villages, some containing over 1000 people, were constructed on terraces overlooking the Salt and Gila rivers (FIGURES 1, 3). These and other smaller villages were part of larger irrigation communities, connected by canal alignments that provided water for domestic and agricultural use (Gregory 1991; Hunt et al. 2005). Despite sophisticated hydraulic engineering and large socially-integrated irrigation communities, the

Hohokam did not attain a state level of political organization with bureaucratic authority but instead lived as ranked, decentralized communities with well-developed trade networks (Fish and Fish 2007).

Hohokam canal systems vary in size and structure depending on local geomorphology and hydrology. The Hohokam diverted water from perennial and ephemeral streams through the construction of weirs made of rock and vegetation that were prone to frequent wash-outs (Ackerly et al. 1987; Masse 1991). The largest canals were constructed along the lower Salt and middle Gila rivers (FIGURE 1). Water was diverted into the primary or main canal channel, which in turn supplied branching distribution canals. Headgates composed of rock and vegetation controlled water entering distribution canals and field laterals that delivered water to field areas. Most Hohokam canals are located at or near the modern surface and thus have suffered considerable recent disturbance. Due to their greater size, main and distribution canals are better preserved and more easily detected in the subsurface than canal field laterals and agricultural fields (Henderson 2015).

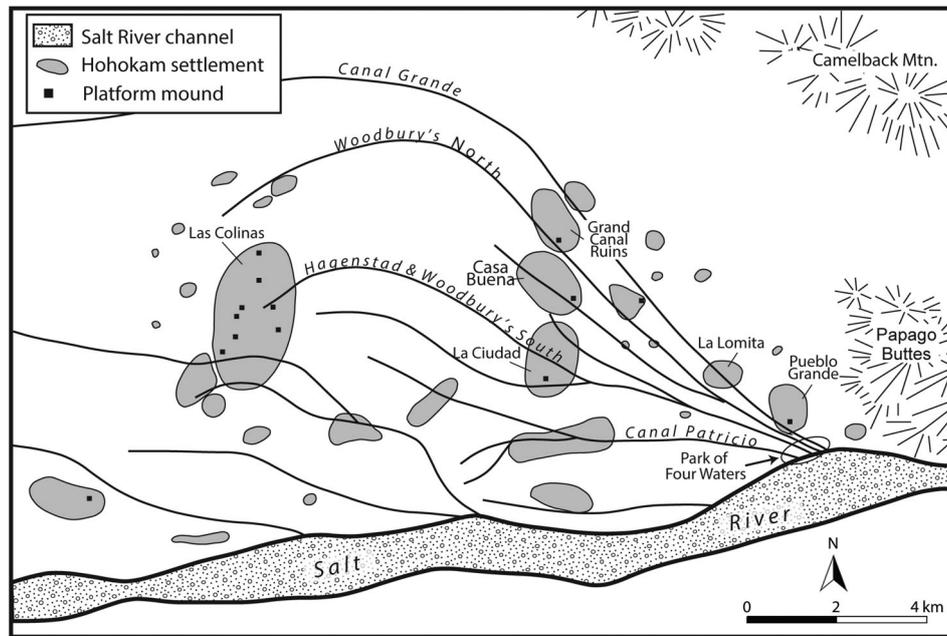


Figure 3. Hohokam settlements within Canal System 2.

Following centuries of demographic expansion, Hohokam settlements pulled back to a core area centered around the lower Salt and middle Gila rivers in the A.D. 1200s. This coincided with broader population and settlement changes related to migration of northern groups from the Colorado Plateau to the desert basins of southern Arizona (Clark 2001; Hill et al. 2015; Neuzil 2008), potentially increasing competition for water and biotic resources. Population within the lower Salt River Valley appears to have peaked at ca. 11,000 around A.D. 1300 (Nelson et al. 2010), with possibly ca. 4000 living within System 2. The concentration of the population into fewer and larger aggregated settlements resulted in more intensive agriculture and appears to have had negative consequences, including nutritional stress and resource degradation within Canal System 2 (Abbott 2003). Dendrohydrological reconstructions of seasonal and annual discharge on the lower Salt River (Graybill et al. 2006; Nials et al. 1989) suggest that a sustained period characterized by few large floods and, by extension, stable floodplain conditions, ended in A.D. 1381. Destructive flooding combined with drought and socio-economic stress may have catalyzed breakdown of Hohokam irrigation communities (Masse 1991: 222; Redman 1999: 155). If floods stressed the Hohokam in the late Classic period, then the canals should contain stratigraphic evidence of such destructive deluges.

Park of Four Waters represents the main diversion point for several large Hohokam main canals within Canal System 2 (FIGURES 2, 3). Segments of two large canals are still preserved at the surface, immediately south of the major Hohokam village of Pueblo Grande (Abbott 2003; Masse 1981). The intakes for these two canals were long ago destroyed by flooding. The rest of Canal System 2 has been plowed at the surface and buried by the city of Phoenix. The northern of the two extant canal segments is known as Woodbury's North Canal, named after Richard Woodbury (1960), who first excavated this canal. Woodbury's North Canal provided water to multiple villages, passing between the Hohokam settlements of Casa Buena and Grand Canal Ruins and reaching the northern margins of Las Colinas (FIGURE 3). Archaeological excavations during the 1970s in association with the

construction of the Hohokam Expressway immediately west of the two preserved canal segments (FIGURE 2) resulted in the identification of 19 canals beneath the surface (Bradley 1999; Masse 1976, 1981). The two largest canals were Woodbury's North Canal and another located to the south named the Hagenstad Canal. The Hagenstad Canal supplied water to the long-lived site of La Ciudad and vicinity (FIGURE 3), first along branches that fed northern portions of the larger settlement during the Colonial and Sedentary periods, then along a southern branch during late Sedentary–early Classic periods (Howard 1991; Huckleberry 2017). Sometime during the early Classic period, Hagenstad was apparently replaced by Woodbury's South Canal, with the two canals tracking along a similar alignment but diverging downstream. Excavations indicate that Woodbury's North Canal is stratigraphically higher than the Hagenstad Canal and consisted of a single large channel similar to that documented by Woodbury (1960). The Hagenstad Canal contained at least three major nested channels, forming a composite ca. 10 m wide and 3 m deep (Masse 1976, 1981: fig. 4).

Hydrological Setting

Water in the perennial Salt River is derived mostly from rain and snow in the Central Highlands of Arizona, where mean annual precipitation may exceed 100 cm in areas above 3000 m elevation (FIGURE 1). The winter–early spring rainy season (November through March) is associated with Pacific storms that periodically track across southern California and Arizona. These storms tend to produce gentle but geographically extensive precipitation and more importantly generate snowpack in the high country. Whereas winter rain and snow in the upper Salt River basin account for less than half of the annual precipitation, they produce ca. 73% of the stream flow that reaches the Phoenix area (Graybill and Nials 1989: 11).

Salt River peak monthly discharge and the largest documented floods occur in late winter and early spring. Thus, flood deposits that penetrate Salt River Hohokam main canals are likely to be the result of winter–early spring flooding. Such

floods occur prior to the primary growing season (Hunt et al. 2005), allowing the Hohokam some time to repair canal damage before crops required most of their irrigation. To what degree such repairs could have been completed in time depended on the scale of the damage and the availability of labor to perform the work. Considerably more effort would have been required if flooding caused changes to the location and geometry of the Salt River primary channel (Ackerly et al. 1987). Indeed, geomorphic changes related to large floods had significant potential to disrupt water control along perennial rivers in Arizona's lower desert (Nials et al. 1989; Waters and Ravesloot 2001; Woodson 2015).

Slight changes in climate can result in significant changes in flood frequency and magnitude (Redmond et al. 2002). Past changes in Salt River flood regime during the late Holocene are indicated by both tree-ring and stratigraphic evidence. Most of the stratigraphic evidence is derived from the Central Highlands where channel boundaries tend to be confined (i.e., the stream channel is incised into bedrock that does not readily expand through scour), allowing for reconstruction of both flood size and frequency. A regional synthesis of late-Holocene alluvial chronologies from slackwater sites in the Southwest suggest that large flood frequency increased after 400 B.C., with particular peaks in flood intensity around A.D. 900–1100 and after A.D. 1400 (Ely 1997). A more recent synthesis of Holocene alluvial chronologies considers both upland slackwater sites and lower elevation alluvial reaches of rivers (Harden et al. 2010). Pooled cumulative probabilities for over 700 ^{14}C dates suggest that whereas the period from 1300 B.C. to A.D. 1 experienced fewer large floods than from A.D. 1 to the present, only slight variability in flood regime is apparent during the past ca. 2000 years.

The degree to which these regional syntheses are applicable to Canal System 2 is uncertain. First, sediment storage in floodplains varies in time and space, and alluvial chronologies (and inferences of flooding) may differ not only between different rivers but also between upper and lower reaches of the same river (Harvey and Pederson 2011). Additionally, regional stratigraphic syntheses are affected by taphonomic processes and sample bias (Ballenger and Mabry 2011). The challenge is to disentangle climatic information from a complex physical system that is influenced by climatic and intrinsic geomorphological controls. Excavations of Hohokam canals next to Sky Harbor Airport provide new local stratigraphic palaeoflood information for the lower Salt River as well as direct evidence for flood damage to Canal System 2.

Methods

Recent excavations by Desert Archaeology, Inc., associated with development of land north of Phoenix Sky Harbor Airport, included segments of both Woodbury's North and Hagenstad canals ca. 500 m downstream from Park of Four Waters (FIGURE 2). The project area is bounded by the historical Grand Canal and Joint Head Canal to the north and south, respectively. The area was historically plowed, although a segment of Woodbury's North Canal was still extant at the surface in 1930 (FIGURE 4). All canals are therefore missing their upper dimensions. Backhoe trenches were used to expose canal segments in the subsurface and define cross-cutting stratigraphic relationships between canals. Sediment samples from within the canal channels were collected for particle-size analysis. Temporally diagnostic ceramics

were retrieved from canal channel fill and provide a terminus post quem. A lens of fine charcoal contained within channel fill of the Hagenstad Canal suggestive of in situ burning of weedy vegetation was sampled and submitted for AMS ^{14}C dating.

Numerical ages on canal channel fills were also obtained through optically stimulated luminescence (OSL), using the single-grain dating technique. The single-grain dating technique is employed to limit potential problems associated with incomplete exposure of grains to sunlight prior to their burial (Duller 2008; Olley et al. 2004). The OSL samples were collected by pounding metal tubes into exposed canal sediments and were processed at the University of Nebraska-Lincoln. Samples were wet-sieved to isolate 90–150 μm sand grains, treated in hydrochloric acid to remove carbonates, floated in 2.7 g/cm^3 sodium polytungstate to remove heavy minerals, and treated in 48% hydrofluoric acid for ca. 75 minutes to remove feldspars and etch quartz grains. Following this procedure, the remaining sample was treated in hydrochloric acid for ca. 30 minutes to remove any fluorides and then re-sieved to remove grains that were $< 90 \mu\text{m}$. The purity of the quartz separate was checked by both visual inspection and with exposure to infrared diodes on the luminescence reader.

OSL measurements were made on a Risø OSL/TL DA-20 luminescence reader equipped with a single-grain laser attachment (Bøtter-Jensen et al. 2000). Luminescence signals were measured with 1 s exposures with a green laser (532 nm) operating at 90% power (135 mW/cm^2) and signals were detected through a 7.5-mm UV filter (U-340). Preheat temperatures were determined by using preheat plateau tests (Wintle and Murray 2006), and based on these tests the samples were run with 10 second preheats of 200° C. Equivalent dose (D_e) values (FIGURE 5) were calculated using the Single Aliquot Regenerative (SAR) method (Murray and Wintle 2000). Individual grains were rejected if their recycling ratios were $> \pm 20\%$, their test dose errors were $> \pm 20\%$, D_e values exceeded 20% of the highest regenerative dose, or if the errors on the D_e values were $> \pm 30\%$. Given the relatively modest overdispersion values for each of our samples (TABLE 2), all age estimates were calculated using the Central Age Model (CAM) (Galbraith et al. 1999). One OSL sample from Woodbury's North Canal was interpreted using both the CAM and Minimum Age Model (MAM) (Galbraith et al. 1999), the latter best matching the age of temporally diagnostic polychrome ceramics in the deposit (see below). Each age was calculated using a minimum of 123 accepted grains. Environmental dose rate estimates were based on elemental concentrations of bulk sediments taken from a ca. 30 cm radius surrounding the OSL sample. Bulk sediment samples were milled and analyzed for concentrations of K, U, and Th using a high resolution gamma spectrometer. The cosmogenic component of the dose rate values were based on sample burial depth and calculated using equations from Prescott and Hutton (1994), and the final dose rates calculated following equations from Aitken (1998).

Results

Hagenstad Canal

The Hagenstad Canal was first identified and named by Bruce Masse (1976, 1981) during construction of the Hohokam

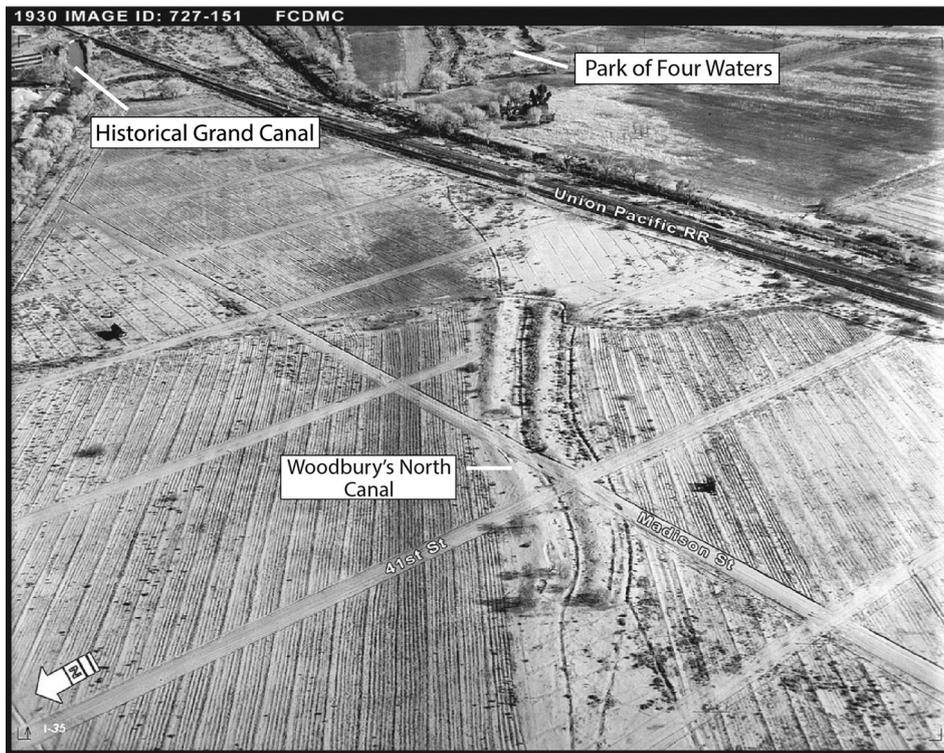


Figure 4. Oblique aerial photograph of a segment of Woodbury's North Canal in 1930 located north of the Union Pacific Railroad; view is to the southeast towards Park of Four Waters (at top of photo). Photo obtained from Flood Control District of Maricopa County (<http://www.fcd.maricopa.gov/business/maps.aspx>).

Expressway (FIGURE 2). Masse recognized that this was a major canal aligned southeast-northwest within System 2 that had experienced multiple episodes of remodeling, based on the presence of several nested channels within the alignment. A ca. 90 m long segment of the full canal

alignment was later exposed in a PHX Sky Train Project parcel to the northwest (Henderson 2017b). The alignment contains two nested, slightly meandering main channels. A distribution canal, Canal 303, extends at a right angle to the southwest (FIGURE 2) and was cut by the most recent

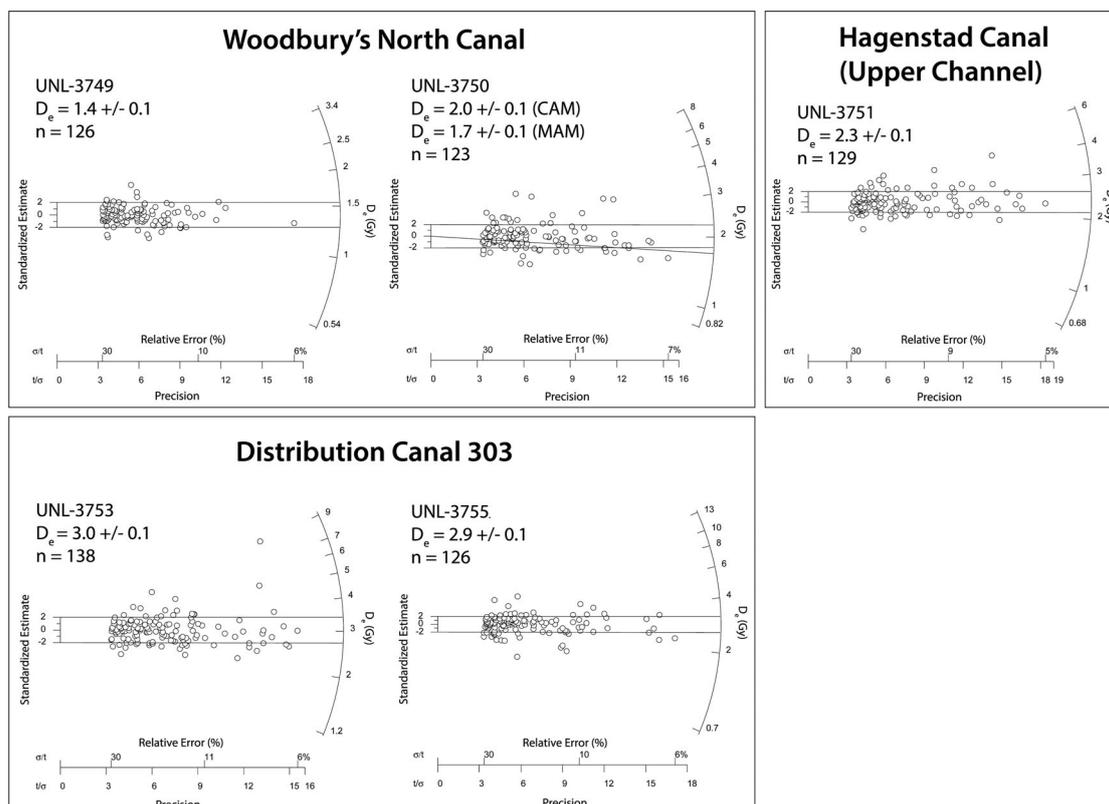


Figure 5. Radial plots showing distribution of equivalent dose (D_e) values for OSL samples; sample number (n) refers to accepted quartz sand grains used in the analysis. MAM D_e value is shown for UNL-3750, all other values were calculated using CAM. See Table 2 for details.

Table 2. Equivalent dose, dose rate data, and single-grain OSL age estimates for Woodbury’s North Canal, Hagenstad Canal, and Canal 303.

Canal	UNL Lab #	Depth (m)	U (ppm)	Th (ppm)	K ₂ O (wt %)	H ₂ O (%) ^a	Dose Rate (Gy/ka)	D _e (Gy) ^b	Grains (n) ^c	Age Model	OSL Age ^d ± 1 σ	O.D. % ^e	Calendar Age A.D. ^f
Woodbury’s N.	UNL-3749	1.8	2.1	7.5	2.0	5.0	2.68 ± 0.17	1.4 ± 0.1	126/4900	CAM	520 ± 50	16	1440–1540
Woodbury’s N.	UNL-3750	3.2	2.4	7.9	1.9	5.0	2.69 ± 0.17	2.0 ± 0.1 1.7 ± 0.1	123/4000	CAM MAM	740 ± 70 630 ± 60	29	1200–1340 1320–1440
Hagenstad	UNL-3751	2.1	2.1	6.6	2.2	5.0	2.71 ± 0.18	2.3 ± 0.1	129/3700	CAM	850 ± 80	25	1080–1240
Canal 303	UNL-3753	2.4	2.3	7.0	2.3	5.0	2.90 ± 0.19	3.0 ± 0.1	138/3800	CAM	1030 ± 90	25	890–1070
Canal 303	UNL-3755	2.2	2.5	7.8	2.0	5.0	2.78 ± 0.17	2.9 ± 0.1	126/4500	CAM	1040 ± 90	34	880–1060

^aEstimated water contents, assumes 100% variability in long-term moisture content

^bD_e values determined using Central Age Model (Galbraith et al. 1999)

^cAccepted grains/all grains run

^dOSL age estimate in calendar years before 2014

^eOverdispersion

^fCalendar age range based on 1 σ errors, rounded to nearest decade

Hagenstad Canal channel. Indeed, the most recent (upper) channel removed most of the earlier canal stratigraphy within the alignment. Nonetheless, portions of the older channel are preserved outside the most recent channel and contain alternating layers of sand, silt, and clay overlain by a sandy deposit that extends laterally several tens of meters away from the

canal alignment. The upper channel has distinct boundaries and an extant cross-sectional area of ca. 6 m³ that could have supported a discharge of up to ca. 4 m³/s (FIGURE 6; SUPPLEMENTAL MATERIAL 2). The base of this channel extends into Salt River cobbles cemented with iron and manganese oxyhydroxides indicative of periodic saturation. Deposits

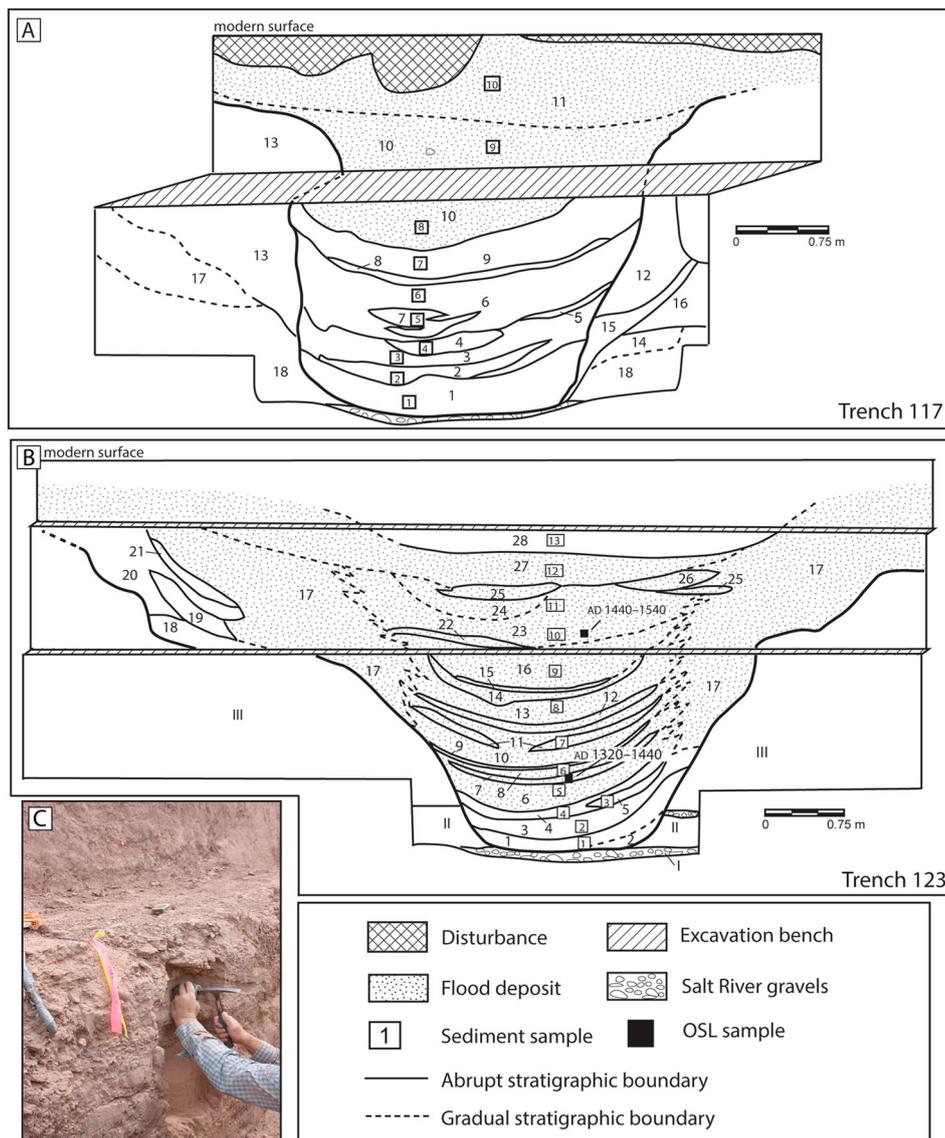


Figure 6. Hagenstad (A) and Woodbury’s North (B) canals excavated by Desert Archaeology downstream from Park of Four Waters. Luminescence samples collected from trench walls with metal cylinders (C). Numbered stratigraphic units are described in Supplemental Material 3. Profiles face southeast.

within the lower part of the most recent channel consist of alternating sand, silt, and clay (SUPPLEMENTAL MATERIALS 3–5) suggestive of regulated canal flow. However, the upper deposits in the most recent channel are dominated by thick loamy fine sand with subangular intraclasts of silt and silty clay that also extends laterally several tens of meters away from the canal. Masse (1988: 343) described these sand and clay intraclasts in the upper deposits of the Hagenstad Canal and interpreted them as probably relating to an uncontrolled Salt River flood. These deposits directly overlie bedded loamy fine sand and silty clay deposits that are interpreted as canal-use sediments suggesting the flood impacted the canal while it was still in use.

Masse (1981) hypothesized that the Hagenstad Canal dated to the Sedentary period (A.D. 950–1150) (SUPPLEMENTAL MATERIAL 1) based on ceramic typology and stratigraphic relationships with Woodbury's North and South canals (FIGURE 2). During our study, we sampled sands from an upper-middle stratum in the younger channel in Trench 121 for OSL dating. The single-grain OSL age was collected from a depth of 2.1 m below the present ground surface. The age indicates the sand was deposited around 850 ± 80 (1 σ) years ago or A.D. 1080–1240 (TABLE 2). Greater temporal precision is provided by an AMS ^{14}C date on *Phragmites* stems from an apparent in situ burned lens within the younger channel that dates 800 ± 30 B.P. (Beta-375256; A.D. 1190–1275 at 2 σ) (TABLE 3) indicating that the canal likely operated into the early Classic period (A.D. 1150–1300).

Two OSL ages were obtained from deposits within distribution Canal 303, supplied by the Hagenstad Canal (FIGURE 2). This distribution canal contained multiple channels within an 8–16 m wide alignment suggesting repeated channel repair and remodeling. The two OSL ages come from two distinct channels within the alignment at depths of 2.2 and 2.4 m and are temporally equivalent, yielding ages of A.D. 880–1060 and A.D. 890–1070 (TABLE 2).

Woodbury's North Canal

Woodbury's (1960) excavation of the North Canal at Park of Four Waters provided a look at the canal where the original berms are still preserved. The canal was later investigated during the Hohokam Expressway Project (Canal 11 in Masse [1981]) and more recently as part of Desert Archaeology's excavations north of Sky Harbor Airport (Canal 200 in Henderson [2015, 2017b]). The ca. 200 m segment that crossed the project area north of the airport originally had elevated berms whose crests were ca. 25 m (80 ft) apart (FIGURE 3), similar to that documented by Woodbury (1960) at Park of Four Waters. Woodbury's North Canal is one of the larger and later Hohokam canals within System 2. The truncated canal channel has a cross-sectional area of ca. 16 m² and a discharge capacity of up to ca. 17 m³/s (FIGURE 6; SUPPLEMENTAL MATERIAL 2) making it the largest canal within

System 2. Lower channel fill deposits are dominated by relatively well-sorted silt (SUPPLEMENTAL MATERIALS 3–5) consistent with multiple, controlled flow events. In contrast, the middle and upper parts of the channel are dominated by coarser, sandy bedded sediments with common angular to subangular silt intraclasts, some > 10 cm in diameter (FIGURE 7). These deposits correlate with stratigraphy previously described for this canal by Masse (1988). An important property of the upper fill is that it can be traced beyond the truncated channel berms, extending laterally for several tens of meters (Huckleberry 2015). The flood deposit is also traceable to several tens of meters down distribution Canal 306 (FIGURE 2) and over the headgate at the junction of the two canals (Henderson 2017a). The geometry and sedimentology of these upper deposits strongly suggest an uncontrolled Salt River flood (TABLE 1) that was channeled down the canal system, overflowed the berms, and extended across the floodplain. The change from moderately well-sorted alluvium at the base of Woodbury's North Canal (suggestive of regulated canal flow) to the overlying thick sandy deposit with silt intraclasts is abrupt, suggesting the flood impacted the canal while it was in operation, i.e., there are no intermediate slopewash deposits, suggesting a hiatus in use.

Temporally diagnostic ceramics and good preservation of channel and berms at Park of Four Waters have long suggested that Woodbury's North Canal was one of the younger canals within System 2 (Woodbury 1960). Attempts to date Woodbury's North Canal during the PHX Sky Train Project yielded mixed results. OSL samples from channel fill at 2.4 m and 1.8 m depths yielded one sigma ages of A.D. 720–980 and A.D. 1221–1341, respectively (Berger 2015). The older result seemed unlikely given stratigraphic evidence indicating the canal postdated the Hagenstad (Masse 1976) and the presence of Classic period (A.D. 1150–1450) (SUPPLEMENTAL MATERIAL 1) ceramics identified by Woodbury (1960). The younger result, which was obtained on the flood deposit, suggested the canal operated during the early Classic period. We performed a second round of OSL dating of Woodbury's North Canal that generated younger ages for the flood deposit. The lower sample was collected from 3.2 m deep and was dated to A.D. 1200–1340 based on the CAM (1 σ) (TABLE 2, FIGURE 5). The younger portion of this age range is compatible with the recovery of one large Gila Polychrome sherd and several other smaller polychrome sherds from the fill of the headgate structure at the junction of Woodbury's North Canal and distribution Canal 306 (Henderson 2017a) (FIGURE 2). These ceramics provide a terminus post quem of A.D. 1300. Consequently, we believe the MAM age for this sample, A.D. 1320–1440, more closely matches the true age of the deposit. The upper sample from 1.8 m deep generated an OSL age of A.D. 1440–1540 (one sigma). Given that System 2 was depopulated by approximately A.D. 1450, we believe that the upper OSL age is too young.

Table 3. Radiocarbon age information for the Hagenstad Canal.

Stratigraphic Context	Material	Beta #	$\delta^{13}\text{C}$ (‰)	Conventional Age (^{14}C yr B.P.)	Intercept with Calibration Curve ^a	2-sigma Calibration ^a	1-sigma Calibration ^a
Burned lens exposed above C303 junction; middle fill of youngest channel, possible channel cleaning prior to flood	Charred phragmites (common reed) stems	375256	-26.5	800 ± 30	A.D. 1250	A.D. 1190–1275	A.D. 1220–1265

^aINTCAL13 (Reimer et al. 2013).

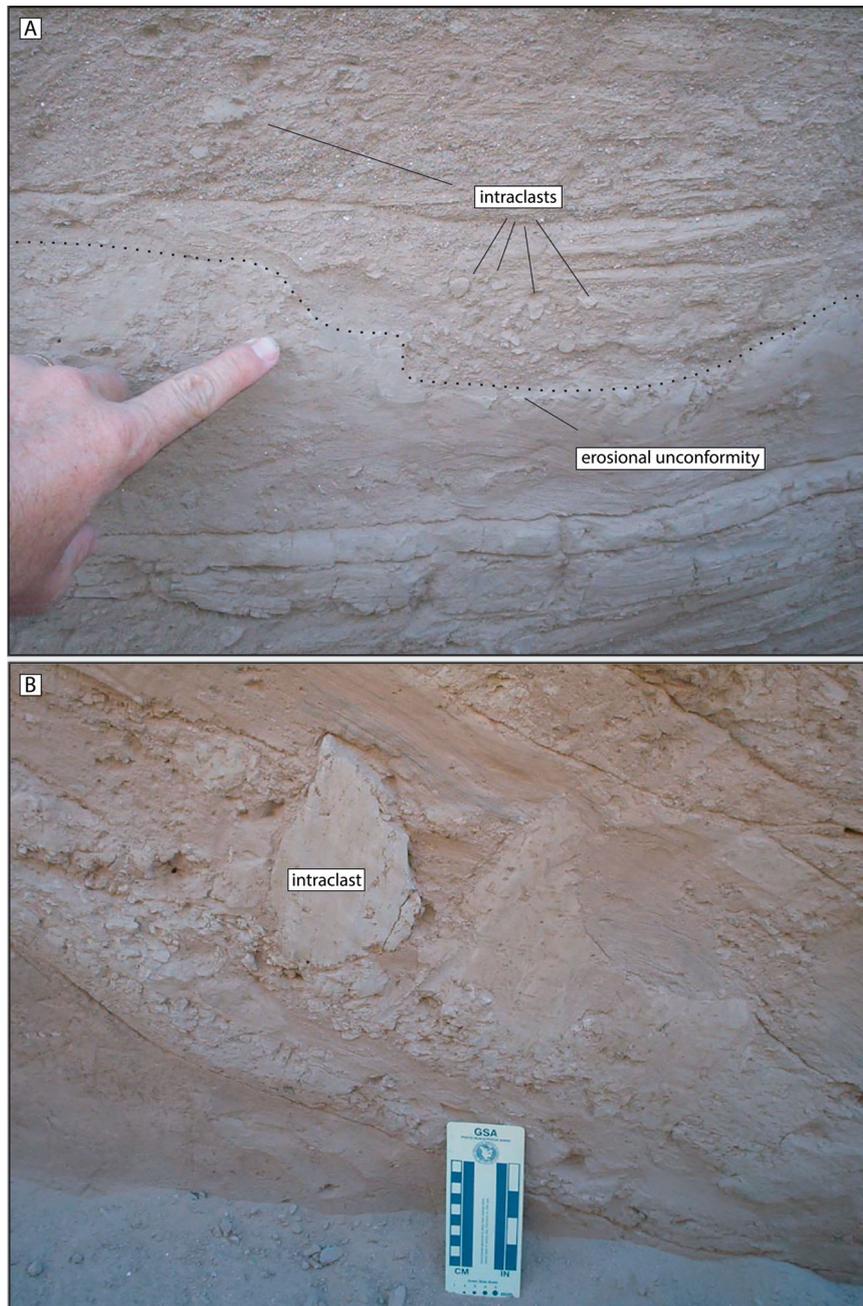


Figure 7. Canal fill and flood deposit stratigraphy in Woodbury's North Canal. A) Erosional unconformity separating canal fill (below) and overlying Salt River flood deposits with silt intraclasts. B) Large angular silt intraclast derived from bank or canal fill deposits entrained by a Salt River flood; GSA scale in centimeters (left) and inches (right).

Discussion

Dating canal stratigraphy

Hohokam canals regularly filled with sediment and required periodic cleaning and bank repair. Consequently, numerical ages from channel fills are biased toward the final episodes of use rather than their construction. Stratigraphic relationships confirm that Woodbury's North Canal is younger than the Hagenstad Canal and other parallel main canals as they are cut by distribution Canal 306 (FIGURE 2). This is supported by the OSL and ^{14}C ages from the upper Hagenstad Canal channel that predates OSL ages from Woodbury's North Canal (TABLES 2–3). Each dating method has its limitations: OSL ages may be affected by incomplete bleaching of sand grains and stratigraphic mixing whereas ^{14}C dating of detrital organic matter is prone to errors related to reworking of old carbon. We consider the ^{14}C age (A.D. 1190–1270) from

the upper Hagenstad channel to be the most accurate and precise of our chronology given that the dated context is a probable in situ burn that occurred between use events (FIGURE 8). This overlaps with the OSL age from the Hagenstad upper channel based on the CAM (A.D. 1080–1240). On the other hand, it is clear that the upper OSL age from Woodbury's North Canal is too young given the archaeological context. This sample may be adversely affected by mixing of younger sand grains from above through bioturbation or some other post-depositional process (Bateman et al. 2003; Hanson et al. 2015).

Whereas the upper Hagenstad channel is directly dated, the lower Hagenstad channel is indirectly dated through distribution Canal 303, which it supplied. OSL ages obtained from alluvial sands in Canal 303 generated one sigma ages of A.D. 880–1060 and A.D. 890–1070 (TABLE 2). We conclude that the Hagenstad Canal was first constructed in the late

Colonial period (SUPPLEMENTAL MATERIAL 1), operated into the early Classic period (i.e., ca. A.D. 850–1250) and was a long-lived canal alignment remodeled several times. Woodbury's North Canal was likely constructed after the Hagenstad Canal was abandoned. Based on the lower OSL sample, polychrome ceramics at the junction with distribution Canal 306, and archaeological context, we believe that Woodbury's North Canal functioned during the late Classic period (A.D. 1300–1400).

Canal repair and abandonment

The Hagenstad and Woodbury's North canals were major alignments within System 2. Woodbury's North Canal had the largest cross-sectional area and extended at least 34 km in length (Howard 1993); the length of the Hagenstad Canal is uncertain but likely exceeded 20 km during its later period of use. To excavate and maintain such large canals required considerable labor and coordination between communities supplied by the alignments (FIGURE 3). Whereas the level of coordination and type of political structures involved is debated, at a minimum there was some form of administrative control within these major canal alignments to implement their construction and operation (Howard 1993; Hunt et al. 2005; Masse 1981). When these canals were damaged by large floods that filled their channels with sediment, the mobilization of a large labor force involving multiple settlements would have been needed to perform repairs prior to the oncoming irrigation season.

The Hagenstad Canal is one of the older alignments within the area. Its earlier channels supplied water to villages in Canal System 2 approximately A.D. 850–1100. The Hagenstad Canal was damaged by an uncontrolled Salt River flood that penetrated the alignment and extended down distribution Canal 303 (FIGURE 8). The Hohokam had the labor capacity to reclaim the damaged Hagenstad Canal alignment by digging out flood deposits and excavating a new channel. This later phase of canal use dates to ca. A.D. 1070–1250 based on ¹⁴C and OSL ages (TABLES 2–3). Sometime during this period of use, another large Salt River flood broke through the intake and filled its upper channel with sandy alluvium. Following this flood, the Hohokam abandoned the alignment. It is unclear where the replacement canal was constructed, as there are multiple Classic period canals within System 2 (Bradley 1999; Masse 1981; Howard 1993). A smaller main canal, Canal 304, aligned southeast-northwest downslope from the Hagenstad Canal (FIGURE 2), appears to have been constructed during this time based on stratigraphic relationships: Canal 304 cuts through deposits of the second flood (FIGURE 8) but is cut by distribution Canal 306.

Sometime after the second flood, Woodbury's North Canal was constructed in a parallel alignment located ca. 50 m upslope from the Hagenstad Canal. Woodbury's North Canal, constructed at a higher elevation within System 2, was large enough to supply roughly three times that of its earlier counterparts. Construction was a major undertaking, and based on present evidence took place after A.D. 1300 in the late Classic period. In contrast to the Hagenstad Canal, there is little evidence for repeated remodeling within the Woodbury North Canal, suggesting that it was a relatively short-lived canal. As in the cases of its predecessors, a large Salt River flood penetrated the alignment and filled the channel with sandy alluvium. Within the current project area, the

flood waters entrained aggregates of earlier channel fill and bank material (FIGURE 7) and damaged Canal 306's adobe and cobble headgate structure filling the distribution canal with sandy alluvium. Woodbury's North Canal was thereafter abandoned. Destruction of Woodbury's North Canal removed the primary source of water for late Classic period communities located away from the Salt River within Canal System 2 (FIGURE 3). No subsequent canal of similar size was constructed that supplied this portion of the system. It is unlikely these communities could have persisted without a functioning main canal.

Relation to palaeoflood records

The plexus of Hohokam canals downstream from Park of Four Waters provides insight into the timing of three large Salt River floods (FIGURE 8). The first flood occurred during an early phase of the Hagenstad Canal dated to ca. A.D. 850–1100. Given that most canals contain deposits from their later episodes of use, we estimate the flood to date to the latter part of this age range, i.e., A.D. 1000–1100. The second flood separates the last use of the Hagenstad Canal and construction of Woodbury's North Canal. The upper Hagenstad Canal channel dates to approximately A.D. 1070–1250, and we estimate that the second flood likely occurred in the A.D. 1200s. The third flood that terminated Woodbury's North Canal clearly postdates A.D. 1300 based on ceramic evidence. There is the possibility that the flood occurred as late as A.D. 1450 given that Salado Polychrome (A.D. 1300–1450) retrieved from the channel fill only provides a limiting age. However, most Hohokam settlements were abandoned within Canal System 2 by the early A.D. 1400s (Abbott 2003; Henderson and Clark 2004). A large coordinated effort involving many people would have been required to maintain a canal as large as Woodbury's North. We think it is likely that Woodbury's North Canal stopped functioning in the late A.D. 1300s and that the third flood dates to A.D. 1300–1400.

The occurrence of three large floods on the Salt River over the course of 400 years is not particularly surprising. Multiple large floods occurred in the late 1800s and early 1900s prior to the construction of dams (Ackerly et al. 1987; Zarbin 1997). Stratigraphic palaeoflood records in the Southwest suggest that the earliest canals developed during a period of relatively low flood frequency (Ely 1997; Harden et al. 2010) (FIGURE 9). In contrast, the Hohokam appear to have practiced canal irrigation during a period of greater flood frequency—and by extension, greater floodplain instability—relative to what their predecessors experienced during the Early Agricultural period (SUPPLEMENTAL MATERIAL 1). Identifying changes in flood frequency during the Hohokam Millennium based on the stratigraphic palaeoflood record is somewhat problematic due to low variability within this period and the fact that younger deposits are subject to greater preservation and sample bias (Ballenger and Mabry 2011). Overall, the three floods associated with the Hagenstad and Woodbury's North canals fall between peaks in flood frequency identified by Harden and colleagues (2010) at approximately A.D. 700 and 1700 but still occur during a period of apparent enhanced flooding that began ca. 2000 years ago.

Most assessments of past flooding and floodplain dynamics for the Salt River coeval with Hohokam canal irrigation have been based on dendrohydrological

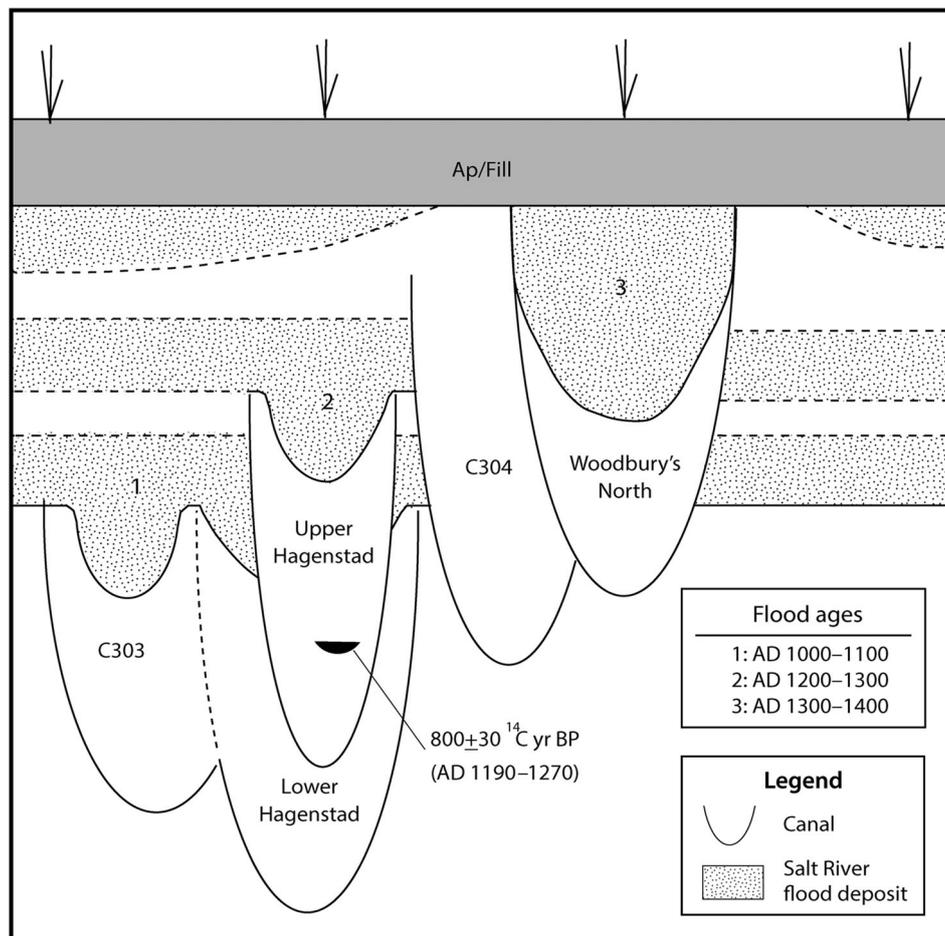


Figure 8. Schematic stratigraphic diagram of Salt River floods and selected canals west of Park of Four Waters (FIGURE 2). Flood ages based on combined ^{14}C , OSL, and ceramic evidence.

reconstructions (Graybill et al. 2006) (SUPPLEMENTAL MATERIAL 6). As noted, reconstructed Salt River annual discharges for a 480-year period (A.D. 900–1380) display relatively average values with low variability. This has been interpreted to indicate a period favorable for expansion of canal systems and settlements that correlated with overall population growth (Howard 1993; Nials et al. 1989; Redman 1999: 154). The two floods that damaged the Hagenstad Canal occurred during this period. Dendrohydrological reconstruction indicate that flow variability increased beginning A.D. 1381, a year that marked the largest flow in 480 years (Graybill et al. 2006). Whether or not the extensive flood deposit within Woodbury's North Canal dates to A.D. 1381 cannot be ascertained given resolution limits of our chronometry. We can only state that the flood likely occurred in the A.D. 1300s and may be linked to this increase in annual runoff. Given that the two floods in the Hagenstad Canal occurred during a period of inferred low flood frequency (SUPPLEMENTAL MATERIAL 6), one should exercise caution in correlating specific floods (instantaneous discharge) to annual or seasonal discharge reconstructed from tree rings. Large floods correlate with large annual discharge but can occur during average or dry years (Graybill et al. 2006: 86; Woodson 2015).

Changes in resilience?

Resilient human adaptive systems are able to absorb social and environmental perturbations through a variety of cultural

responses. Large floods that destroy intakes and fill main canal alignments with sediment were important environmental perturbations for the Hohokam. By A.D. 1400, agriculturalists in the Southwest had ca. 3000 years of cumulative experience with water control, floods, and drought. For most of the Hohokam Millennium, they had the labor and organization to either repair damaged canals or to engineer and build new alignments (Ravesloot et al. 2009; Woodson 2015). The question arises as to whether or not something had changed in the A.D. 1300s such that the Hohokam became less resilient to these disturbances.

Excavations at Pueblo Grande (FIGURES 2, 3) identified ecological and osteological evidence of over-exploitation of natural resources and increased biological stress and mortality in the Classic period (Abbott 2003) (although McClelland [2015] disagrees). This was a time when settlements became more aggregated throughout the lower Salt River Valley and social organization became more fragmented (Hill et al. 2015; Redman et al. 2009). Reduced subsistence diversity in general and over-reliance on canal irrigation in particular may have made the Hohokam more vulnerable to floods and floodplain changes (Abbott 2003; Hegmon et al. 2008; Nelson et al. 2010).

It is also possible that the flood that damaged Woodbury's North Canal was different from previous inundations. For example, if the third flood was accompanied by significant channel incision preventing diversion of gravitational water from the Salt River into canal intakes, the effort to repair Woodbury's North Canal becomes much greater. Whereas

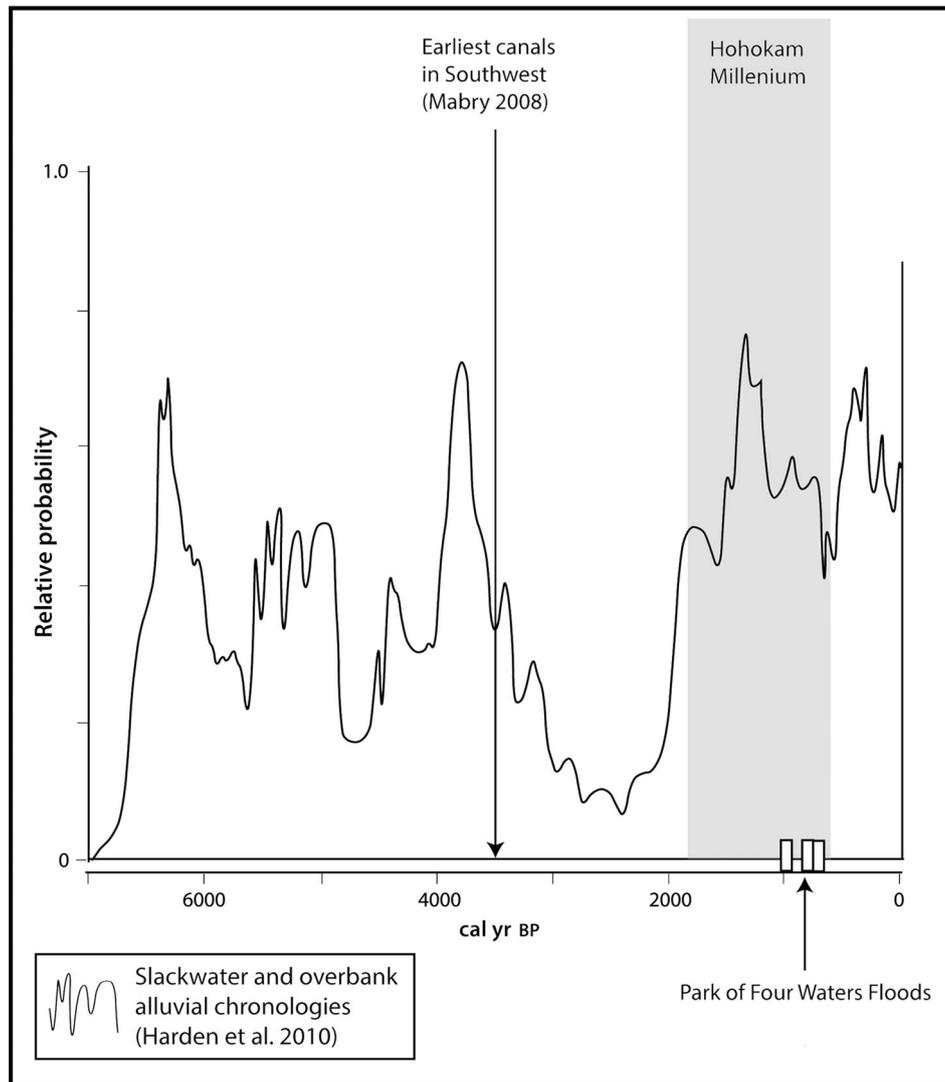


Figure 9. Comparison of Salt River palaeofloods at Park of Four Waters and regional stratigraphic palaeoflood synthesis (Harden et al. 2010; Mabry 2008).

channel changes on large dryland rivers correlate with increases in flood frequency and include major channel avulsions and/or downcutting (Graf 1983; Graybill et al. 2006; Huckleberry et al. 2013; Waters and Ravesloot 2001), we have no evidence for major floodplain changes at Park of Four Waters during Hohokam time (Birnie 1994). The lower Salt River appears to have downcut sometime after A.D. 1100 approximately 25 km downstream from Park of Four Waters (Huckleberry et al. 2013), an event that may correlate with the flood that damaged Woodbury's North Canal. However, floodplain dynamics on large fluvial systems are more likely to catalyze settlement changes within a river valley than force large-scale depopulation. For example, changes in floodplain morphology along the middle Gila River south of Phoenix (FIGURE 1) around A.D. 1000–1100 correlate with canal system and village reorganization but not valley-wide abandonment (Loendorf and Lewis 2017; Waters and Ravesloot 2001; Woodson 2016). One can envision local abandonment of major canal alignments due to channel entrenchment, but valley-wide abandonment of canal alignments during the late Classic period seems unlikely.

We consider large floods, whether or not accompanied by unfavorable geomorphic changes to the Salt River floodplain, as a contributing factor rather than a primary driver of social stress in the late Classic. Other factors somehow reduced the

capacity of the Hohokam to rebuild Woodbury's North Canal after it was flood-damaged in the A.D. 1300s. These may include population decline due to increased mortality and/or reduced fertility, or a lack of administrative control and social cohesion within System 2 to mobilize sufficient labor for canal repair. Scattered small settlements within System 2 persisted into the early 1400s, likely supplied by smaller canals that required less population and/or labor to maintain. By A.D. 1500, those settlements were abandoned, and the lower Salt River Valley was depopulated to the point of archaeological invisibility.

Summary and Conclusions

Archaeological excavations of early historical canals destroyed by large floods in south-central Arizona provide stratigraphic analogs for identifying flood deposits in Hohokam canals. Flood sediments in the upper reaches of main canals close to their intakes are characterized by thick, sandy deposits with matrix-supported, angular-to-subangular intraclasts of finer sediment. Three alluvial deposits containing these stratigraphic properties and dated A.D. 1000–1400 by a combination of ^{14}C , OSL, and ceramics are contained within two Hohokam main canal alignments at Park of Four Waters. The Hagenstad Canal was the primary main

canal alignment within Canal System 2 during the late Colonial, Sedentary, and early Classic period, servicing the greater La Ciudad vicinity. Remodeled several times, this canal experienced repeated flood damage near its intakes over the course of at least 300 years. Multiple channels associated with this alignment indicate that sufficient labor was available to clean-out and repair the alignment multiple times. Sometime between A.D. 1000–1100, one large flood penetrated the main canal alignment. The Hagenstad Canal was cleaned out and used again. Another large flood penetrated the Hagenstad Canal sometime in the A.D. 1200s, after which the alignment was abandoned.

Woodbury's North Canal was subsequently constructed and became the largest main canal within System 2 during the late Classic period servicing nearly all locations within the central occupation zone comprised by La Ciudad, Casa Buena, and Grand Canal Ruins settlements. Woodbury's North Canal lacks multiple channels, suggesting that it had a shorter lifespan. Its operation coincides with a period when Hohokam settlements were more aggregated within Canal System 2, and people were heavily reliant on fewer, larger canals. A substantial Salt River flood destroyed the intake for this canal sometime in the A.D. 1300s and deposited sandy sediment several kilometers down its alignment and through the upper part of at least one distribution canal (Canal 306). Woodbury's North canal was then abandoned and no canal of similar size was constructed in the area until the settlement of Euro-American farmers in the late 1800s.

Our study adds further evidence that large floods were a recurrent problem for Hohokam farmers. In most cases, the Hohokam had the capacity to repair canal alignments or construct new ones in the same area. Knowing when large floods impacted Hohokam settlements helps to define the environmental context of this long-lived culture. The timing of large floods need not coincide with regional proxy climate records. The two Hagenstad Canal flood deposits indicate the Salt River had large floods during a period of diminished flood regime based on dendrohydrological reconstructions. However, the flood that destroyed Woodbury's North Canal partly overlaps in time with a period of greater large flood frequency (A.D. 1381–1746). Whereas regional palaeoflood records and dendrohydrological reconstructions provide insight into changes in climate and flood regime, they are insufficient for reconstructing individual floods in particular locations. Inferences of flood impacts on past agricultural settlements are best made with local stratigraphic evidence. The best opportunity for identifying such evidence is in the larger main canals near their intakes.

The Hohokam devised different strategies for dealing with large floods. Our study provides evidence for three different Hohokam responses to canal damage. After the first flood, they responded by rebuilding the intake and digging out a new channel within the Hagenstad Canal alignment. After the second flood, the Hohokam abandoned the Hagenstad Canal alignment and later constructed a larger canal (Woodbury's North). This canal likewise experienced a large Salt River flood, but the Hohokam abandoned the alignment and no other canal of comparable size was again constructed in System 2.

To what degree floodplain changes played a role in these variable Hohokam responses to flooding is unclear and awaits further study. Of significance here is that archaeologists now have for the first time evidence for a destructive flood along a

major canal alignment during the late Classic period. The societal impact of flooding, with or without major geomorphic change, would have varied depending on political and economic conditions, i.e., the human dimension to natural hazards (Oliver-Smith and Hoffman 2002). The ability of the Hohokam to repair such large canals required some form of administrative oversight that may have no longer been present when Woodbury's North Canal was damaged. For reasons yet defined, the Hohokam did not replace this major canal alignment. The fact that they did not rebuild may indicate reduced Hohokam resilience to environmental disturbance in the A.D. 1300s. Conflicts, settlement changes, and population decline are evident across much of the Southwest during this time, including areas where people were not reliant on large earthen canals. A convergence of social and environmental factors is likely responsible.

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