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Journal of South American Earth Sciences 14 (2001) 541–555

Journal of
South American
Earth Sciences

www.elsevier.com/locate/jsames

Early irrigation systems in southeastern Arizona: the ostracode perspective

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Received 1 March 2000; revised 1 August 2000; accepted 1 May 2001

Abstract

For the first time, the Early Agricultural Period (1200 BC–150 AD) canal irrigation in the Santa Cruz River Valley, southeastern Arizona, is documented through ostracode paleoecology. Interpretations based on ostracode paleoecology and taphonomy are supported by anthropological, sedimentological, geomorphological, and palynological information, and were used to determine the environmental history of the northern Tucson Basin during the time span represented by the sequence of canals at Las Capas (site AZ AA:12:753 ASM). We also attempt to elucidate based on archaeological artifacts if the Hohokam or a previous civilization built the canals.

Between 3000 and 2400 radiocarbon years BP, at least three episodes of canal operation are defined by ostracode assemblages and pollen records. Modern (mid–late 20th century) canals supported no ostracodes, probably because of temporally brief canal operation from local wells. Three stages of water management are well defined during prehistoric canal operation. Ostracode faunal associations indicate that prehistoric peoples first operated their irrigation systems in a simple, 'opportunistic' mode (diversion of ephemeral flows following storms), and later in a complex, 'functional' mode (carefully timed diversions of perennial flows).

The geomorphological reconstruction indicates that these canals had a minimum length of 1.1 km, and were possibly twice as long. The hydraulic reconstruction of these canals suggests that they had similar gradients (0.05–0.1%) to later prehistoric canals in the same valley. Discharges were also respectable. When flowing at bank-full, the largest canal provided an acre-foot of water in about 2.3 h; when flowing half-full (probably a more realistic assumption), it produced an acre-foot of water in about 8.6 h.

Palynological records of the oldest canals (here identified as Features 3 and 4; 3000–2500 years BP) indicate they were used temporarily, since riparian vegetation did not grow consistently in the area. The presence of maize (*Zea* sp.) pollen in the canals confirms agricultural use of the canal water. However, a low percentage of maize and weed pollen suggests limited agricultural activity in this location, consistent with the lithostratigraphy, granulometry, and ostracode paleoecology. Agricultural fields were probably located downstream of this site.

Ostracode assemblages show patterns consistent with the opportunistic or functional water control method, hence proving their value as indicators of human activity and environmental change. The transition from opportunistic to functional modes of canal operation indicates the increasing complexity of the social structure in the Santa Cruz Valley during the San Pedro Phase (1200–800 BC) of the Early Agricultural Period.

Keywords: Early agricultural period; Ostracodes; Pollen; Geomorphology; Water control; Opportunistic mode; Functional mode

1. Introduction

Ostracodes have been used to reconstruct the history of operation of several prehistoric canal systems in the Phoenix Basin of central Arizona (Palacios-Fest, 1989, 1994, 1997). Prior to these studies, Bradbury et al. (1987) used nonmarine ostracodes as indicators of agricultural activity by the prehistoric Maya in Belize. Other studies have also shown the relation between ostracodes and agricultural activities over long intervals of prehistory (Curtis et al., 1995; Goman and Byrne, 1998). However, these latter studies relate ostracodes from lake deposits with pollen grains of cultigens to infer environmental changes. None of these studies established a direct connection between canal operation and ostracode populations. In this study, ostracode assemblages are used as indicators of modes of water control for agriculture in the middle Santa Cruz Valley of southern Arizona. Also, environmental

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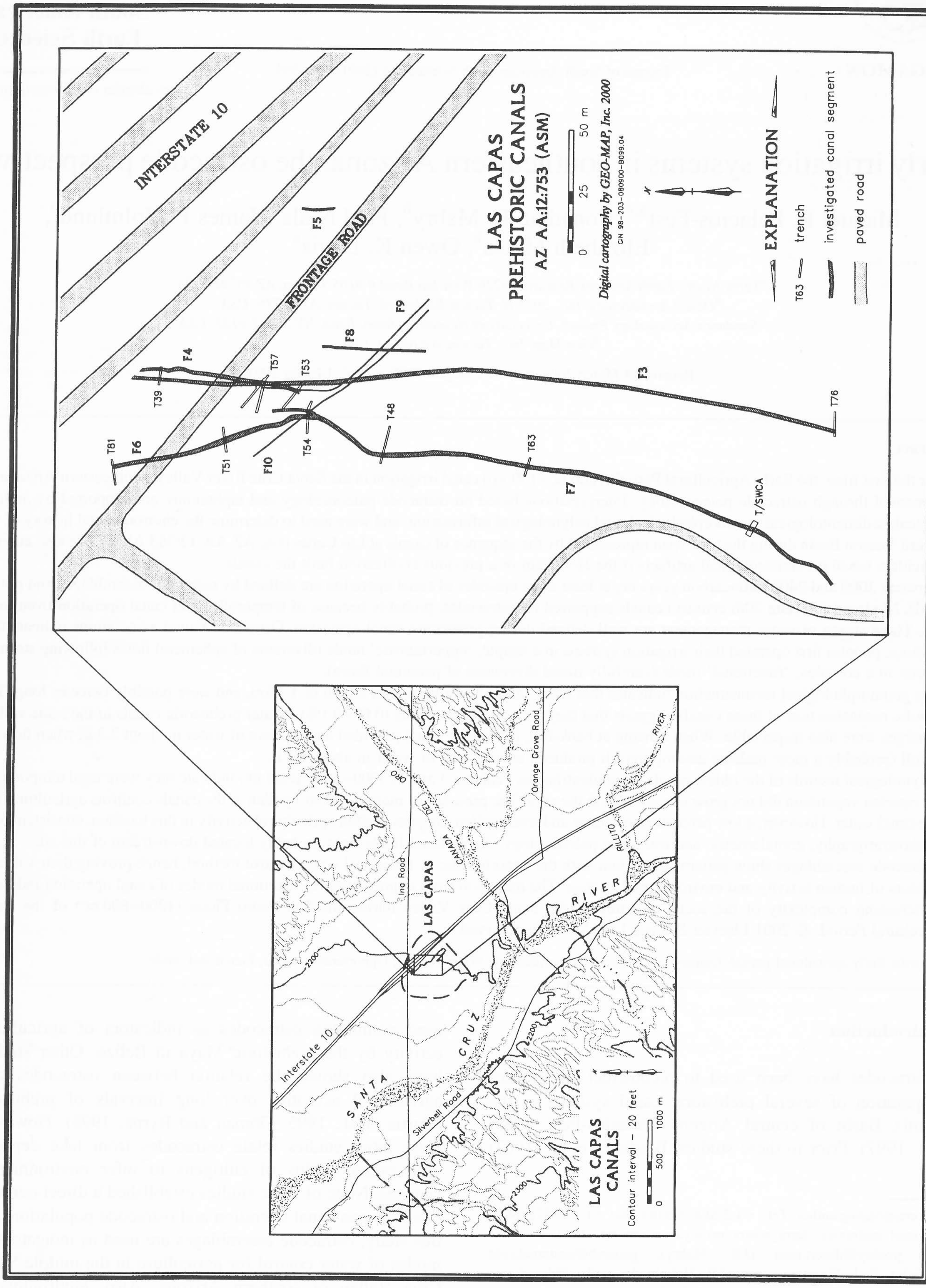
0895-9811/01/$ - see front matter
PII: S0895-9811(01)00047-5



LAS CAPAS
PREHISTORIC CANALS
AZ AA:12:753 (ASM)
0 25 50 m
Digital cartography by GEO-MAP, Inc. 2000
EXPLANATION
trench
investigated canal segment
paved road
INTERSTATE 10
FRONTAGE ROAD
F3
F4
F5
F6
F7
F8
F9
F10
T39
T48
T51
T53
T54
T57
T63
T76
T81
T/SWCA
LAS CAPAS
CANALS
Contour interval - 20 feet
0 500 1000 m
Interstate 10
Ina Road
Orange Grove Road
Silverbell Road
SANTA CRUZ RIVER
RILLITO RIVER
CANADA DEL ORO
LAS CAPAS
2200
2300

changes that affected prehistoric human populations in the region are identified.

A close relation between human activity and environment in semiarid regions has existed since the end of the Pleistocene in southwestern North America. After Paleoindians hunted megafauna in the terminal Pleistocene, hunter-gatherers inhabited this area through most of the Holocene (Huckell, 1996; Mabry, 1998). During the past two millennia, agricultural groups (cultures) irrigated fluvial terraces along riverine systems (Haury, 1976; Masse, 1981). It is necessary to understand how these prehistoric farmers used riverine resources to exploit domesticated plants in order to understand cultural development in the Southwest.

Pre-Hohokam irrigation canals as old as ~3000 radiocarbon years BP (ca. 1000 BC) have been discovered in the Tucson Basin reach of the Santa Cruz River Valley. Previous studies of irrigation systems in the Southwest were limited to large Hohokam systems in the Phoenix Basin and a few smaller canals in the Tucson Basin (Masse, 1981; Ackerly and Henderson, 1989; Fish et al., 1992; Ezzo and Deaver, 1996; Mabry and Holmlund, 1998). Fish et al. (1992) recognized two types of canal operation: opportunistic and functional. Opportunistic canals are defined as those diverted from ephemeral storm flows, whereas the functional operation implies the periodic opening of the canal headgate to flood the canals and fields during the agricultural season. Based on the small sizes and flow directions of prehistoric canals in the Tucson Basin, it was suggested that the Hohokam opportunistically diverted ephemeral drainages after storms (Fish et al., 1992). Was this the case? It is unknown when the transition from opportunistic to functional operation by the Native Americans occurred. Did the Hohokam build the irrigation canals in the Tucson Basin during the late San Pedro Phase of the Early Agricultural Period? Or are we dealing with a different culture? Did this people use opportunistic diversion for irrigated agriculture? Or were they able to develop more complex strategies after several centuries of using an opportunistic approach? With paleoecological (ostracodes), geomorphological, sedimentological, and palynological data, we document the evolution of canal operations in the middle Santa Cruz Valley during the San Pedro Phase (1200–800 BC) of the Early Agricultural Period and its implications for social structure.

2. Study area

Las Capas (site AZ AA:12:111 ASM) is located at the eastern edge of the Santa Cruz River floodplain, below (north of) its confluences with the Cañada del Oro (CDO) and Rillito Rivers in the western Tucson Basin. Sediments at the site are likely derived from all three drainages. The site is bisected by an interstate highway in northwest Tucson, Arizona (111°3′W, 32°20′N), at an elevation of about 666 m above sea level (Fig. 1).

Natural riparian vegetation of the Santa Cruz River included trees such as cottonwood (*Populus*), ash (*Fraxinus*), willow (*Salix*), sycamore (*Platinus*), and walnut (*Juglans*) (Brown, 1982). Now, however, the floodplain of the Santa Cruz contains conspicuous members of the Chenopodiaceae family — including saltbush (*Atriplex canescens*, *A. polycarpa*), pigweed (*Chenopodium album*), and carelessweed (*Amaranthus palmeri*). Upland vegetation of the Tucson Basin is classified as the Arizona Upland division of the Sonoran Desert (Brown, 1982). Triangle-leaf bursage (*Ambrosia deltoidea*) is common on the lower slopes of the mountains surrounding the basin. Club-moss (*Selaginella eremophyla*) is common on steep, north-facing slopes below 1000 m elevation.

3. Stratigraphic sequence

A total of 38 AMS dates were obtained through Beta Analytical, Inc. Detailed information is available upon request to Desert Archaeology, Inc. Here we summarize the data. Samples used proceed from cultural contexts, which include pits, canals, and midden deposits. These dates range from 2970 to 2430 BP (uncalibrated), that is, around 1200–600 BC (calibrated). Thirty-two dates are directly on cultigens (all are on maize except one on a bean); these range from 2960 to 2500 BP (ca. 1200–700 BC). A domesticated common bean dated 2960 bp, which is about 500 radiocarbon years older than the previously oldest date on a bean in the Southwest.

The sequence of canals is contained in seven alluvial strata labeled Units 1–7 (top to bottom) (Fig. 2). The uppermost stratum (Unit 1) consists of a sandy loam, gravelly at the base, about 35 cm thick (historic plow zone). Two historic canals (Features 9 and 10) are identified at the modern ground level. Unit 2 (2500–600 radiocarbon years BP) consists of a silty-to-fine sandy loam coarsening upward, about 50 cm thick. Two prehistoric canals (Features 1 and 2) are identified in this stratum. Unit 3 (2500 radiocarbon years BP) consists of a medium-to-coarse sandy loam representing a flood originating in the CDO watershed; although variable in thickness, it averages about 15 cm in depth across the site.

Unit 4 (2800–2500 radiocarbon years BP) consists of alternate layers of silt and clay occasionally intercalated by sandy loam; it is about 40 cm thick. Evidence of soil development is present at the top of the unit. Pit structures, storage pits, hearths, human burials, and artifacts are

Fig. 1. Location map of Las Capas (sites AZ AA:12:111 ASM and AZ AA:12:753 ASM, the latter assigned only to canals), Tucson, Arizona, along the east floodplain terrace of the Santa Cruz River. Trenches (T) selected for this study from four canals or features (F) are marked by □. In subsequent figures, trenches are arranged from upstream to downstream and identified by a number (e.g. T76). (Modified from Geo-Map, Inc).

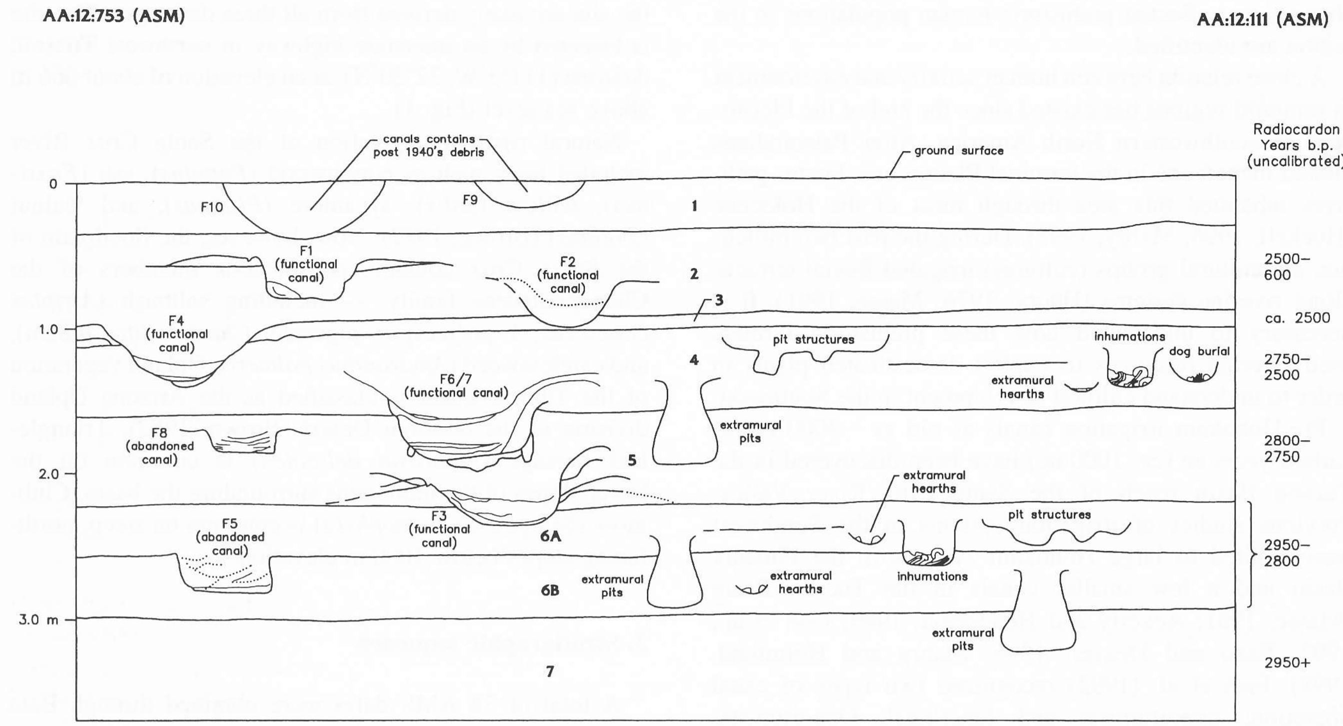


Fig. 2. Composite stratigraphic sequence of prehistoric irrigation canals at Las Capas [site AA:12:111 (ASM)] showing floodplain strata, archaeological features, and radiocarbon dates. Most canals [sites AA:12:753 (ASM)] fall within the San Pedro Phase of the Early Agricultural Period. Historic canals postdate World War II. (Modified from Mabry (1999)).

common in Unit 4. Three canals (Features 4, 6, and 7) were excavated in this stratum. Unit 5 (2900–2800 radiocarbon years BP) consists of a clayey loam, occasionally intercalated with silty sand, about 60 cm thick. One aborted canal (Feature 8, not discussed in this paper) is recorded in this layer.

Unit 6 (3000–2900 radiocarbon years BP) is divided into two subunits (6a and 6b) based on their lithologic compositions. Subunit 6a consists of loamy sand characterized by a flood incursion, while Subunit 6b below is composed of a homogeneous layer of sandy loam. At the top of Subunit 6a, paleosol formation is evident. Abundant evidence of human activity is common (e.g. pit structures, hearths, burials, and artifacts). One canal (Feature 3) was excavated in this surface. In contrast, Subunit 6b shows limited human activity; a few pits and an aborted canal (Feature 5) were excavated in this earliest cultural stratum. Unit 7 (pre-3000 radiocarbon years BP) consists of mid to late Holocene channel sands devoid of cultural materials.

4. Materials and methods

One hundred and seventy-three sediment samples were collected from eight canal features exposed in 12 trenches at site AZ AA:12:753 (the unique site number assigned to the canals). Each sample consisted of approximately 30 g of sediments that were collected as a rectanguloid excavation (1 cm thick × 2 cm long × 2 cm deep) at microstratigraphic intervals of 2–10 cm depending on strata thickness and availability. Samples were collected in plastic zip-lock bags, which were labeled, dated, and sealed. Stratigraphic contexts were marked in feature profiles. Of these 173 samples, 73 contained enough ostracodes for paleoecological analysis. Sixteen samples from the older canals (Features 3 and 4) were analyzed for pollen. Ostracode samples were selected to reconstruct individual canal histories, to potentially correlate equivalent strata between different trenches, and to attempt to define periodicity (seasonality) of canal operations. Pollen records, sedimentology, and hydraulic characteristics were used to test ostracode paleoenvironmental interpretations and establish an integrated model of canal operation.

Samples were prepared using a modified version of the protocol described by Forester (1988). Sediment residuals were analyzed under a low-power stereoscopic microscope. All 73 fossiliferous samples were examined to identify fossil contents and faunal assemblages. Total and relative abundances were recorded. Taphonomic features were used to determine origins of specimens (Delorme, 1989; Taylor, 1991). Degrees of fragmentation were used as indices of post-burial desiccation and sediment compaction. Abrasion was used as an index of transport. Encrustation and coating were interpreted as

Table 1
Environmental conditions in which continental water ostracodes grow. Some eurytopic species occur under a combination of water factors shown in this chart. Stenotopic organisms are restricted to one or two water chemistry conditions. A combination of factors (e.g. temperature, salinity) also limit ostracode development

Habitat	Permanence	Temperature	Salinity	Chemistry
Stream: channeled flow	Permanent: perennial	Eurythermic: organisms adapted to a wide range of temperature	Euryhaline: organisms adapted to a wide range of salinity	Type I: Ca^{2+}, Mg^{2+}, $HCO3^-$ dominated (freshwater)
Standing: low or no flow	Ephemeral: periodical dry-out	Stenothermic: organisms constrained to a narrow temperature range	Stenohaline: organisms constrained to a narrow salinity range	Type II: Ca^{2+}-rich/HCO_3^--depleted, Na^+, Mg^{2+}, SO_4^{2-} or Na^+, Mg^{2+}, Cl^--dominated (hardwater)
		Thermobiont: 20–25°C		
		Thermobiont: 20–25°C; thermophillic: ~20°C; criobiont: $<$10°C; cryophillic: 10–15°C		Type III: alkali-rich/Ca^{2+}-depleted, Na^+, Mg^{2+}, Cl^- or HCO_3^- or SO_4^{2-}

indicators of authigenic mineralization or stream action, respectively. The redox index and color of each valve reflected burial conditions. The carapace/valve (C/V) and adult/juvenile (A/J) ratios were used as indicators of biocenosis. The latter parameter is commonly related to diagenetic effects. However, based on the relatively young stage of the canal sediments, we consider that the A/J ratios are a good indicator of in-place or untransported local development of populations. In addition, comparisons with the granulometric analysis and lithostratigraphy of the canals were critical to determine ostracode origins and energy of transport. Commonly, coarse-grained sediments are deprived of ostracodes or support only adult forms since these are more resistant to transport. Fine-grained sediments instead allow establishment of local populations where low-energy and nutrient-rich waters favor faunal settlement. Canal geomorphology and gradients were used to verify transport likelihood of ostracode valves.

Table 1 presents the environmental characteristics where continental ostracodes grow, and Table 2 documents the generalized conditions controlling the species present at Las Capas (site AZ AA:12:753). Based on species abundance, a paleosalinity index was used to establish the canal operation history (Palacios-Fest, 1994). The paleosalinity index was derived from the information in Tables 1 and 2 to generate the equation

$$\begin{aligned} SI = {} & [4(\%\ \textit{Limnocythere n.}\ \text{sp., cf.}\ \textit{L. paraornata}) \\ & + 3(\%\ \textit{C. vidua}) + 2(\%\ \textit{C. glaucus}) \\ & + (\%\ \textit{C. patzcuaro})] - [(\%\ \textit{H. brevicaudata}) \\ & + 2(\%\ \textit{Potamocypris unicaudata}) + 3(\%\ \textit{I. bradyi}) \\ & + 4(\%\ \textit{C. arcuata})] \end{aligned}$$

The index weights species with incrementally higher salinity tolerances positively, and species with incrementally lower salinity tolerances negatively. *Limnocythere* n. sp., cf. *L. paraornata* is assumed to be a salinity tolerant species because it occurs in the cienega-like phases in these canals and not during the freshwater input stages.

Table 2
Generalized environmental conditions controlling continental water ostracode assemblages from Las Capas irrigation canals [sites AA:12:111 (ASM) and AA:12:753 (ASM)] in Tucson, Arizona

Species	Habitat	Permanence	Temperature[a]	Salinity[a] (ppm)	Chemistry[a]
Limnocythere n. sp. cf. *L. paraornata*	Lake, pond or stream	Ephemeral or permanent	Eurythermic	500–75,000	Type I and II
C. vidua	Lake, pond or stream	Ephemeral or permanent	Eurythermic	100–4000	Types I and II
C. glaucus	Lake, pond or stream	Ephemeral or permanent	Eurythermic	10–10,000	Type I and II
C. patzcuaro	Lake or pond	Ephemeral or permanent	Eurythermic	200–5000	Type II (eventuall type III)
H. brevicaudata	Stream, lake or spring	Ephemeral or permanent	Eurythermic	200–3000	Type II
P. unicaudata	Pond, stream and lake	Ephemeral or permanent	Eurythermic	100–3000	Types I and II
I. bradyi	Stream, lake or spring	Permanent	Eurythermic	100–4000	Types I and II
C. arcuata	Spring, stream, cienega, pond	Permanent	Thermobiont	100–4000	Types I and II

[a] Source of data: Delorme (1989), Forester (1991) and Palacios-Fest (1994).

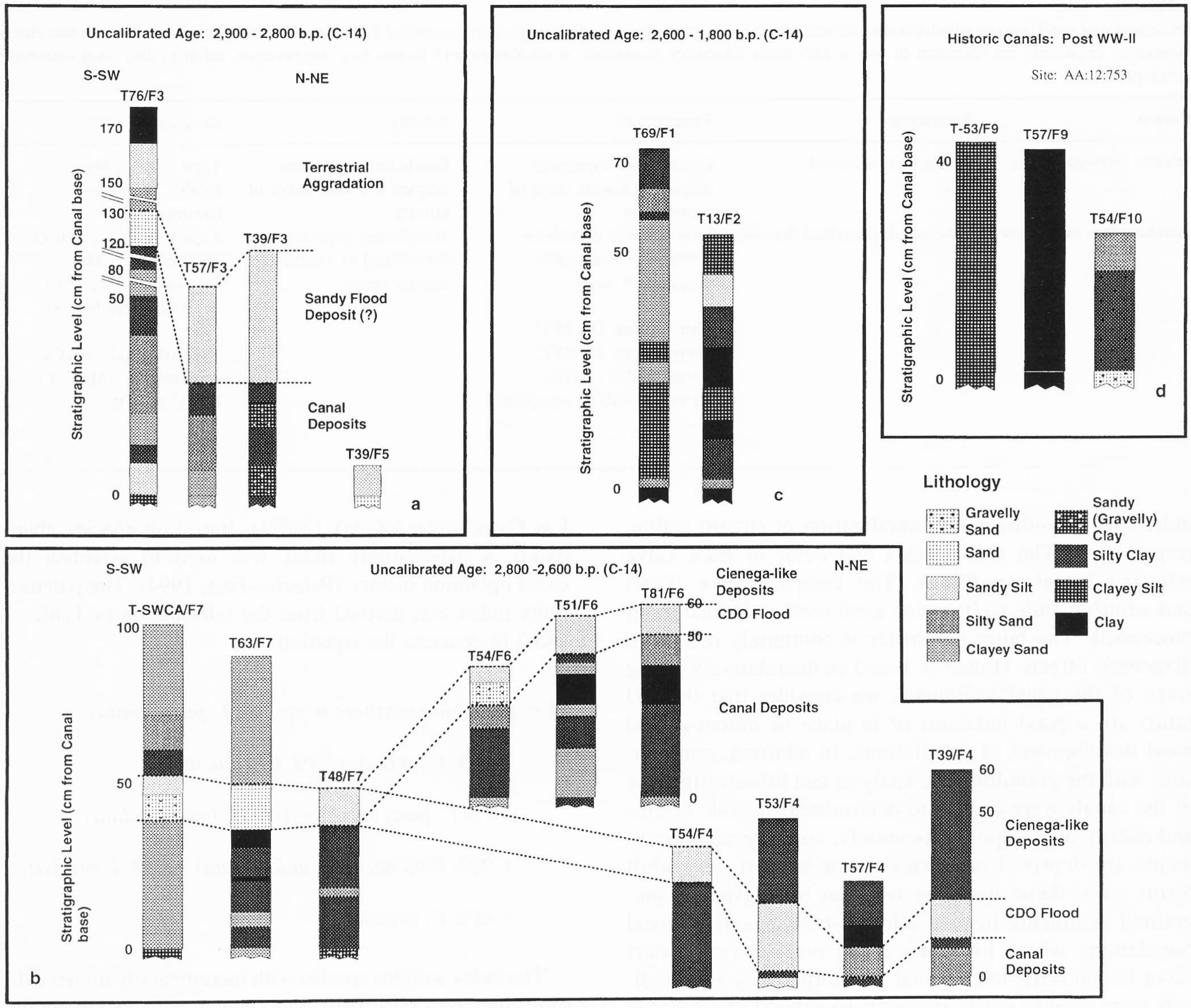


Fig. 3. Lithostratigraphy of canals by trench arranged from south-southwest to north-northeast, including uncalibrated age and main sedimentological events: (a) Features 3 and 5; (b) Features 7, 4, and 6; (c) Features 1 and 2; and (d) Features 9 and 10.

5. Results

5.1. Stratigraphy and sedimentology

Fig. 3 summarizes the canal stratigraphy by time interval and correlates them across the area of study; they are shown from south-southwest to north-northeast (upstream to downstream). Canal microstratigraphy shows several strata of variable shapes and thicknesses. Fig. 4 shows the grain-size frequency by canal through time. Lithologically, the sediments are strongly dominated by silt and clay, except the CDO flood deposit (Unit 3) consisting of sand. Sediments range in texture from clay to sand and vary in color from dusky brown (5 YR 2/2) to moderate yellowish brown (10 YR 5/4).

5.2. Ostracode record

Table 1 shows the number of organisms recovered from each sample, including major groups — mollusks, oogonia of charophytes (calcareous algae reproductive structures), vertebrate bone fragments, plant debris, and ostracode species. Nine ostracode species were identified. *Ilyocypris bradyi* was the most common and abundant throughout the set of samples. *Cypridopsis vidua* was second. *Limnocythere* n. sp., cf. *L. paraornata* occurred in several canals. Other species (*Cyprinotus glaucus*, *Herpetocypris brevicaudata*, *Candona patzcuaro*, *Chlamydotheca arcuata*, *Potamocypris unicaudata*, and *Cypridopsis* sp.?) occurred occasionally. Some specimens are listed as unidentified in the table, occurring sporadically in the canals. Based on occurrence and relative abundance, the assemblage is

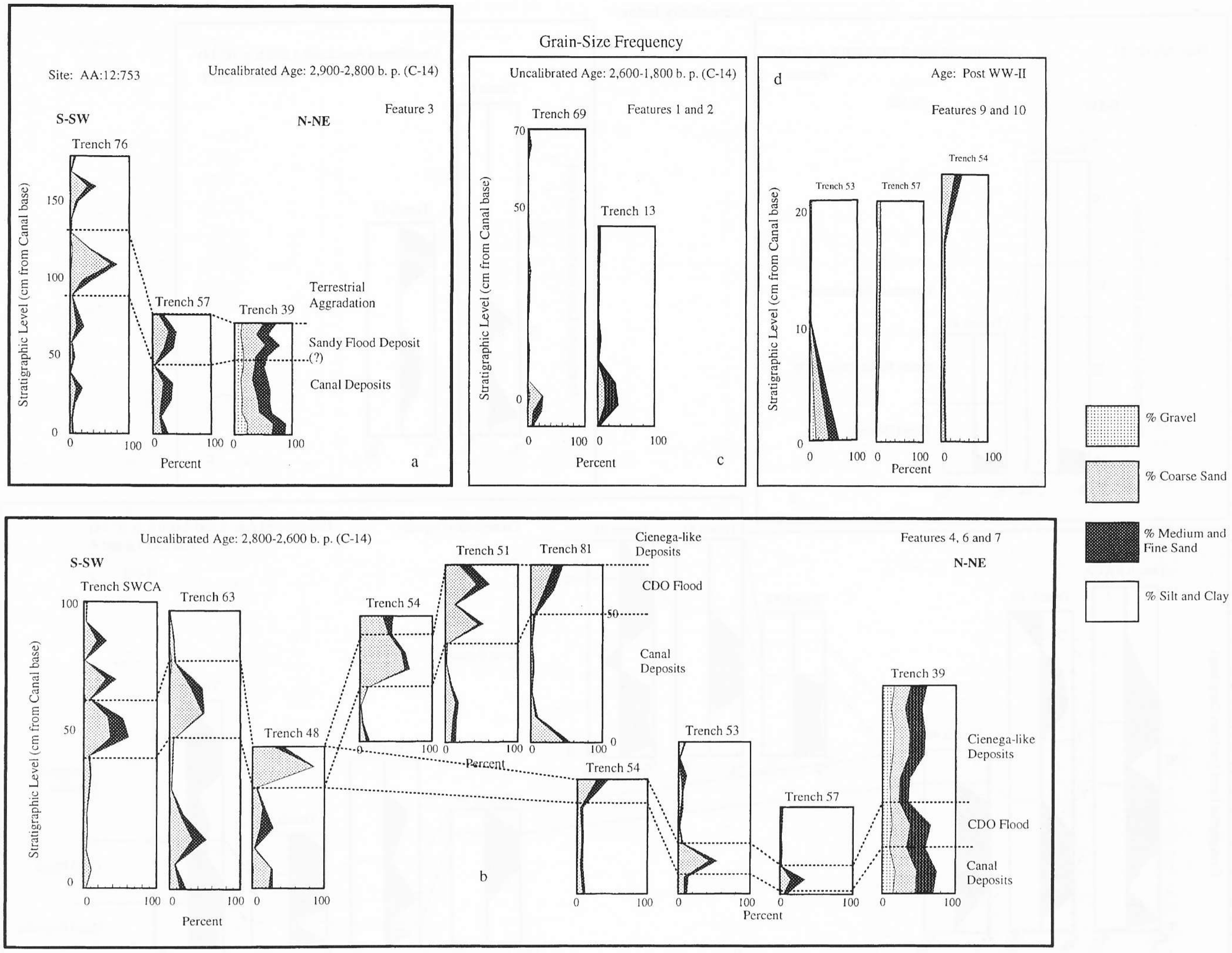


Fig. 4. Granulometric frequency of sediments by canal and trench, arranged from west to east, including grain size and spatial correlation among trenches by canal: (a) Feature 3; (b) Features 7, 6, and 4; (c) Features 1 and 2; and (d) Features 9 and 10.

dominated by *I. bradyi*, a stream-flow indicator. The faunal association is consistent with the water chemistry type I (dilute) and type II (Ca-enriched waters, dominated additionally by Na^+, Mg^{2+}, and SO_4^{2-}) of Eugster and Hardie (1978).

Tadayon and Smith's (1994) and Tadayon's (1995) surface- and groundwater analyses of the modern Rillito Creek (sampled from August 1987 to August 1993) showed near equivalent proportions of bicarbonate and Ca, with the latter slightly dominant. The paleoecologic inference of the area's water chemistry based on ostracodes is consistent with modern water analyses. The main canal waters evolved from type I to type II as they reached the distal ends of minor canals and were subject to salinization. The increasing diversity and occurrence of *Limnocythere* n. sp., cf. *L. paraornata* that indicates warm, more saline conditions, suggests this trend.

For each canal, the sequence of species distribution and inferred paleoecology is used to interpret environmental transitions through time in the canals. The paleosalinity index developed for each canal is documented in Fig. 5 to correlate canals among trenches. All fossil samples are characterized by a small population (1–504 individuals per sample) and low diversity (one–nine species). Based on Delorme (1969, 1989), taphonomic characteristics (listed above) are used to distinguish allochthonous (transported) from autochthonous (local) populations.

Two canals (Features 3 and 5) represent the oldest record of irrigation agriculture (3000–2900 BP) at site AZ AA:12:753 (Fig. 3(a)). Feature 5 (Trench 15) is an aborted canal and, therefore, unfossiliferous; it is not discussed further in this report. In contrast, Feature 3 is an opportunistic canal and was sampled from three trenches (76, 57, and 39). The samples from Trench 57 are unfossiliferous. Four samples contain ostracodes at the base of this canal in Trenches 76 (upstream) and 39 (downstream). Based on granulometric analysis, Fig. 4(a) shows the accumulation of fine sediments associated with *I. bradyi* and *C. vidua*, the only two species recorded. The former is the dominant species. Relatively high fragmentation, high abrasion, and

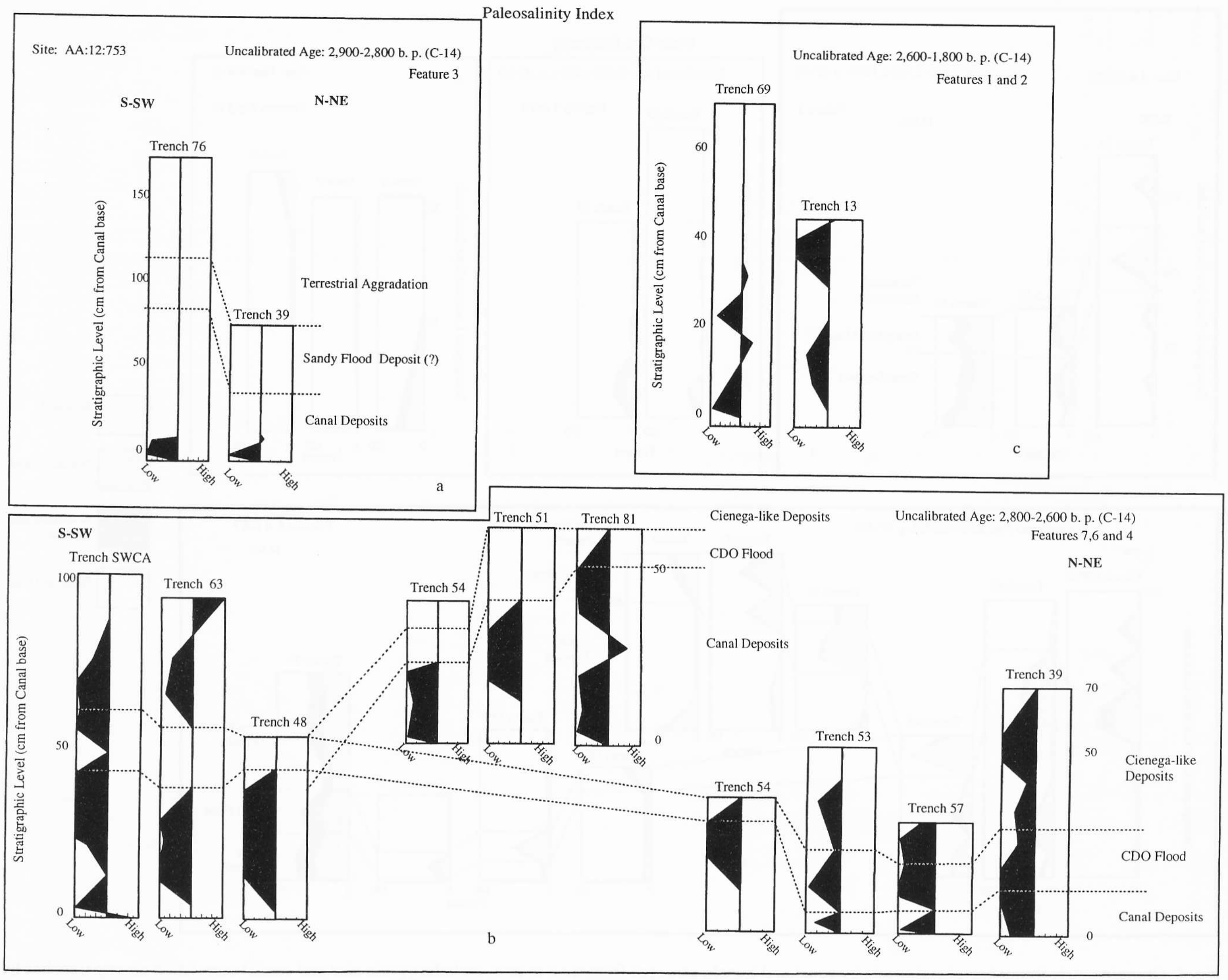


Fig. 5. Paleosalinity index derived from ostracode relative abundance (see text for explanation) by canal and trench, including spatial correlation among trenches: (a) Feature 3; (b) Features 7, 6, and 4; and (c) Features 1 and 2.

slight oxidation are observed in these specimens. Encrustation or light coating was noticed in the samples from Trench 39, where the redox index switches from low oxidizing to reducing conditions. In addition, Feature 3 contains a high percentage (>50%) of *Chenopodiaceae-Amaranthus* but a low percentage (<20%) of *Ambrosia* and other *Asteraceae*. Feature 3 also contains a low percentage of charcoal and corn (*Zea*) (<1%). The content of riparian plants, such as *Cyperaceae*, *Alnus*, *Fraxinus*, *Juglans*, *Populus*, and *Salix* at the base of the canal are low (<2%), and are lacking upward in the stratigraphic sequence.

Three canals (Features 4, 6, and 7) represent the next generation of irrigation agriculture (2800–2500 BP) at the site (Fig. 3(b)). Fine sediments are associated with fossiliferous samples (Fig. 4(b)). Feature 7 is a functional canal and was sampled from three trenches (SWCA Trench, 63, and 48). SWCA Trench, the trench farthest upstream, provided 13 fossiliferous samples. Samples SWCA-7-1–SWCA-7-9 represent canal use. The reference sample (SWCA-7-16) collected 2 cm beneath the canal surface contains a small assemblage of ostracodes consisting of *I. bradyi*, *C. vidua*, and *Limnocythere* n. sp., cf. *L. paraornata*, suggesting a cienega-like deposit. Samples SWCA-7-10–SWCA-7-15 suggest post-use cienega-like deposits (Table 3). SWCA Trench provides the richest and most diverse assemblage from Feature 7, including *I. bradyi*, *C. vidua*, *Cypridopsis* sp.(?), *Limnocythere* n. sp., cf. *L. paraornata*, *C. glaucus*, *P. unicaudata*, and *C. arcuata* throughout the stratigraphic sequence. Fragmentation and abrasion of specimens is low. Encrustation and coating are absent in the lower portion, but they increase toward the top of the section, whereas the redox index shows low oxidation throughout. In general, the palynological content of Feature 4 in this stratigraphic sequence is representative of Unit 4. Corn (*Zea*) pollen is present in low percentages (~2%), but *Chenopodiaceae-Amaranthus* occurs in high percentages

Table 3

Fossiliferous samples containing ostracodes. Samples are arranged from source of water (south-southwest) to distal fields (north-northeast). Initial number indicates trench, then feature, and finally sample number from base of canal. Stratigraphic level indicates distance from base of canal to datum. Relative abundances of the ostracode species were used to calculate the paleosalinity index (see text for details)

	Total populations							Ostracode species									
Sample ID #	Stratigraphic level (cm)	Uncalibrated age (yrs. BP)	Ostracodes	Molluscs	Oogonia (*Chara*)	Vertebrate bones	Plant debris	# *I. bradyi*	# *C. vidua*	# *Cypridopsis* sp. ?	# *H. brevicaudata*	# *Limnocythere* n. sp. cf. *L. paraornata*	# *C. glaucus*	# *P. unicaudata*	# *C. patzcuaro*	# *C. arcuata*	# *Unidentified*
76-3-1	1	2900–2800	3	11			13	3									
76-3-2	9		17				18	15	1								1
39-3-1	1	2900–2800	2	1				2	5								
39-3-3	9		9	4	3			4									
54-4-3	20	2800–2600	6	1			9	6									
54-4-4	29		3	5			16	3									
53-4-1	1	2800–2600	25	10				22				3					
53-4-3	11		81	11			21	78				3					
53-4-4	21		29	14			34	17	12								
53-4-5	35		17	4			13	14	2				1				
57-4-1	1	2800–2600	49	4		2		47	2								
57-4-3	9		27	13				26	1								
57-4-4	11		4	19				4									
57-4-5	17		23	28				21	2								
57-4-6	23		40	14				39	1								
57-4-7	27		8	2				5	2								1
39-4-1	1	2800–2600	37	4				32	1			4					
39-4-2	10		2			1		2									
39-4-3	11		1					1									
39-4-4	18		6					6									
39-4-5	25		32	67				24	6			2					
39-4-6	34		118	7	3	1		94	24								
39-4-7	42		8	1				5	3								
39-4-8	48		1	2				1									
39-4-9	55		2	2				2									
54-6-1	1	2800–2600	371	20			34	361	6			4					
54-6-2	11		38	11			29	34	2			2					
54-6-3	20		10	19			21	10									
51-6-3	17	2800–2600	71	39			35	70									1
51-6-4	26		12	2			19	12									
51-6-5	31		64	21			39	64									
81-6-1	1	2800–2600	53	12			26	51				1					1
81-6-2	7		28	4			38	25	3								
81-6-3	17		79	21			46	76				3					
81-6-4	25		3	1			21	1				2					
81-6-5	35		81	9			65	76	1			2					2
81-6-6	47		4	2			31	4									
SWCA-7-16	− 2	2800–2600	7					2	2			4					
SWCA-7-1	1		115	34				113				1					1
SWCA-7-3	19		38	9			23	31	6			1					
SWCA-7-4	21		4	3			17	4									
SWCA-7-5	24		5	3			12	5									
SWCA-7-6	31		18	5			6	18									
SWCA-7-7	40		1					1									
SWCA-7-9	53		1					1									
SWCA-7-10	59		18	57			8	17	1								
SWCA-7-11	67		8	8			11	8									
SWCA-7-12	73		158	8			34	120	30			4					4
SWCA-7-13	74		336	115		1	46	245	80	1			7	3			
SWCA-7-15	98		504	23	40	1	69	232	165	22		12	68			4	1
63-7-2	8		4	3			13	4									
63-7-3	13		17	5			19	17									
63-7-4	20		17	9			28	16				1					

Table 3 (*continued*)

	Total populations							Ostracode species						
63-7-5	26		17	24			33	17						
63-7-9	64		151	1			39	140	9		2			
63-7-10	75		17	17			27	14	3					
63-7-11	93		3	1			18		3					
48-7-2	11		44	66			32	44						
48-7-3	16		35	3			21	35						
48-7-4	21		88	15			26	88						
48-7-5	35		4	6			14	4						
69-1-20	− 3	2600–1800	252	43	2	1		125	107	1	17	1	1	
69-1-1	1		37	74	2			34	1	2				
69-1-2	11		11	16				5	5	1				
69-1-3	16		11	9				3	6	1	1			
69-1-4	22		5					4						
69-1-5	27		28	2				13	2		9	3		1
69-1-6	31		32	9				12	9		8	3		
13-2-2	7	2600–1800	11	3			45	8	3					
13-2-3	14		100	10			52	80	16					4
13-2-6	37		2	1			94	2						
13-2-7	41		1	1		1	16	1						
13-2-8	46		8	17			21	4			4			

(up to 90%). *Ambrosia* and other *Asteraceae* pollen are relatively abundant (up to 25 and 7%, respectively).

From Trench 63, Feature 7 contains seven fossiliferous samples, and species diversity declines substantially to three species: *I. bradyi*, *C. vidua*, and *Limnocythere* n. sp., cf. *L. paraornata*. Samples 63-7-2–63-7-5 represent canal operation. Samples 63-7-9–63-7-11 represent sediments that accumulated ostracodes after the CDO flood. The taphonomic characteristics included moderate fragmentation, abrasion and encrustation, and low oxidation of valves. The downstream trench (48), where Feature 7 is exposed, is monospecific, with *I. bradyi* present in four samples. All four samples were collected from strata representing canal operation. Specimens are moderately fragmented, and abrasion and encrustation of valves are low. The redox index suggests low-oxidation conditions.

Farther downstream, Feature 7 branches into Features 4 and 6, both of which were functional canals. Feature 6, branching to the north, is exposed in Trenches 54, 51, and 81. In Trench 54, three samples are fossiliferous, with *I. bradyi*, *C. vidua* and *Limnocythere* n. sp., cf. *L. paraornata* represented. All three samples contain ostracodes that indicate canal operation. Moderate to low fragmentation, abrasion, and encrustation characterize the assemblage. Low-valve coating occurs only in the uppermost fossiliferous sample. The redox index suggests low-oxidized valves.

To the northeast, Trench 51 contains three fossiliferous samples. All three samples indicate canal operation. The assemblage from Feature 6 is mostly monospecific (an unidentified species was collected at the base of the canal), consisting of *I. bradyi*. Fragmentation is moderate, but abrasion is low. Encrustation and coating are also low, whereas the redox index increases from low to moderately oxidized valves.

The downstream Trench 81 contains six fossiliferous samples with four species: *I. bradyi*, *C. vidua*, *Limnocythere* n. sp., cf. *L. paraornata,* and an unidentified species. *I. bradyi* is the dominant species; all other species occur sporadically throughout the sequence. All six samples were collected underneath the CDO flood deposits and represent canal operation. Fragmentation ranges from moderate to high, but abrasion is moderately low. Encrustation is low. Coating is low except in a sample about 7 cm from the base of the canal, where it is high (95%). The redox index shows low oxidation of valves.

Feature 4, the northeast fork of Feature 7, is exposed in four trenches. Upstream, Trench 54 provides two fossiliferous, but monospecific, samples — only *I. bradyi* is present. Both samples are obtained from strata below the CDO flood deposit. Moderate to low fragmentation, low abrasion, and low encrustation characterize the assemblage. The redox index shows low oxidation of valves. Downstream, Trench 53 provides four fossiliferous samples. Sample 53-4-1 is the only one collected from below the CDO flood deposit and represents canal operation; all other sampled sediments represent post-use accumulation. Fragmentation is moderate, but abrasion and encrustation are low. The redox index shows low oxidation of valves.

Trench 57 contains six fossiliferous samples from farther downstream in Feature 4. Sample 57-4-1 is also the only sample collected from beneath the CDO flood deposit and represents canal operation; the remaining five samples are from sediments that accumulated after the flood. Three species are present: *I. bradyi*, *C. vidua*, and an unidentified species. Fragmentation and abrasion range from moderate to low. Encrustation is low, and the redox index shows fluctuating oxidizing conditions. Finally, the farthest downstream trench (39) provides nine fossiliferous samples. Samples 39-4-1–39-4-4 were collected from below the CDO flood deposit (sample 39-4-5), while the rest (39-4-6–39-4-9) were collected from sediments that accumulated after the CDO flood. Fragmentation fluctuates from low to high. Abrasion ranges from moderate to low. Encrustation, coating, and the redox index are high in only the lower portion of the record.

Two canals (Features 1 and 2) represent the last interval of irrigation agriculture (2500–2400 BP) at site AZ AA:12:753 (Fig. 3(c)). Fine-grained sediments accumulated throughout most of the stratigraphic sequences in both canals (Fig. 4(c)). Features 1 and 2 are not directly connected but correlate in time; therefore, they are discussed as a group. Feature 1 (Trench 69) contains six fossiliferous samples, with *I. bradyi*, *C. vidua*, *H. brevicaudata*, *Limnocythere* n. sp., cf. *L. paraornata*, *Potamocypris* sp., *C. patzcuaro*, and an unidentified species. Fragmentation is moderate, but abrasion is low. Encrustation is not significant except in one sample (69-1-3). The redox index shows low to moderate oxidation of valves. Feature 2 (Trench 13) provides five fossiliferous samples, including *I. bradyi*, *C. vidua*, *Limnocythere* n. sp., cf. *L. paraornata*, and an unidentified species. Fragmentation is moderate to high, abrasion is low, and the redox index shows low-oxidizing conditions. No palynological data are available from these canals.

Samples from the modern canals (Features 9 and 10) exposed in Trenches 53, 54, and 57 are unfossiliferous. Homogeneous sedimentation rates are inferred from Figs. 3(d) and 4(d). Apparently, these canals were fed by wells for short periods of time, preventing them from supporting ostracodes.

6. Interpretation

Based upon the combined faunal, palynological, and sedimentological compositions of the canal sediments, we made the following interpretations. Canal irrigation at Las Capas (site AZ AA:12:753) was conducted in a stable floodplain with a high water table, as Mabry (1999) proposed. The ostracode fauna suggests pulses of water input from the Santa Cruz River. The 35 intervals sampled in Feature 3 from Trenches 76, 57, and 39 show fast stream-flow conditions at the base that supported *I. bradyi* and *C. vidua*, then canal operation stopped abruptly and fine sediments accumulated but did not support ostracodes (from base to 10 cm of canal deposits). The occurrence of a mainly adult population of these two species, indicative of stream flow, suggests reworking of valves from the Santa Cruz River as shown by fragmentation, abrasion, and the C/V and A/J ratios. However, it is also possible that juveniles did not preserve in the deposit. Post-canal-use deposits consisting of silt and clay with lenses of sand lack ostracodes, implying terrestrial (alluvial) aggradation with eventual transport of channelized sands (e.g. 105–125 cm) in some areas (Trench 76). In addition, the palynologic record is also indicative of short-term stream flow. The low values of riparian vegetation in the canal samples suggest that this canal did not retain water long enough to support its growth in or near the canal. However, evidence of agriculture is clear as shown by the low percentage (<1%) of corn (*Zea*), but it was probably limited since weed pollen is also low in concentration (<2%).

Feature 3 suggests that, between 3000 and 2900 BP (Unit 6a), it was an opportunistic canal used by occasionally diverting flows from permanent or intermittent streams during the irrigation season, but water did not stand in the canal throughout the year. This interpretation is supported by the adult-dominated, almost monospecific, assemblage of *I. bradyi* and *C. vidua* (rare), also characterized by high fragmentation and abrasion. The paleosalinity index shows dilute water input into the canals during operation. In Trench 39 (downstream end of canal; 280 m from Trench 76), slow-moving to standing water in this canal supported aquatic gastropods (e.g. *Physa virgata*) and calcareous algae (gyrogonites of *Chara*). Increasing salinity is shown by the paleosalinity index (Fig. 5(a)). Waters (1988) proposes that the interval between 4000 and 2500 BP was more mesic than today, with frequent channelization and cienega deposition. Effective moisture was high at this time, increasing lake level as well as river and stream flows (Mabry, 1998, 1999). Mabry (1998, 1999) suggests that during this wet interval fine-grained alluvial sediments accumulated across the Southwest, but in some areas deposition was interrupted by erosional episodes (e.g. 2900–2600 BP).

A subsequent interval of canal irrigation at site AZ AA:12:753 occurs between 2800 and 2600 BP (Unit 4). The 87 intervals sampled from three interconnected canal features (7, 6, and 4) show a consistent pattern of water pulses before the CDO flood. In contrast to Feature 3 where canal operation appears to be opportunistic, Features 7, 6, and 4 show evidence of controlled flow or what we identify as functional canal operation (Fig. 5(b)). Again, generalizing the palynological record for this stratigraphic unit (4), it is evident that agricultural activity occurred in the location. A slightly higher percentage (~2%) of corn (*Zea*) in Trench 57 than in Feature 3 is apparent. However, it is unclear to what extent it is representative of increasing agriculture. What makes a difference with respect to Feature 3 is the higher content of weeds and riparian vegetation consistent with longer periods of water flow in the canals. Charcoal is also more abundant.

Feature 7 (at Trench SWCA) supported *Limnocythere* n. sp., cf. *L. paraornata* and *C. vidua* at the base of the canal, probably because the canal was dug in cienega-like deposits. Fragmentation and abrasion are low in this site, suggesting an in situ population. The canal history at this trench indicates that during canal operation, two cycles of water input separated by a period of salinization are evident (Fig. 5(b)). The same pattern, although not as marked, is observed in Trench 63 about 70 m downstream. One explanation for the apparent short salinization event is that the freshwater input actually represents the upper event recorded at the SWCA Trench with two pulses. Then, at Trench 48 about 120 m downstream from the SWCA Trench, only one cycle of water input is recorded that correlates well with the upper event observed at the SWCA Trench and Trench 63. If water flow is sustained for several weeks, freshwater reaches the end of the canals and supports ostracode populations.

Where Feature 7 forks into Features 6 and 4, it is possible to recognize one or two freshwater pulses into the canals. Low to moderate fragmentation and abrasion, and low A/J ratios, suggest in situ populations. For example, in Trench 54, Feature 6 (160 m downstream from the SWCA Trench) shows two cycles of water input with a minor cycle of salinization in between. At Trench 51 (200 m downstream from SWCA Trench), only one cycle of freshwater input is detected. In contrast, in Trench 81 (240 m downstream from the SWCA Trench), two cycles are well defined. A sharp episode of salinization is marked between the two freshwater pulses at this location. Two possible reasons contributed to increasing salinity in Feature 6: one is an evaporitic episode associated with headgate operation, the second is backflow from the agricultural fields. Either one of these two alternatives would increase the amount of salts in solute composition. However, for ostracodes to record this change a prolonged exposure to high salinity would be necessary. Backflow will increase salinity temporarily, but the salts would dilute shortly as freshwater continues flowing into the system.

Feature 4, the south fork of Feature 7, also shows evidence of canal water management as suggested by the paleosalinity index and the taphonomic features. Trench 54 (160 m downstream from the SWCA Trench) shows only one episode of freshwater input. Moderate fragmentation and abrasion of *I. bradyi* indicate the species was introduced with the flow. The same pattern is obvious 10 m downstream in Trench 53. Then, in Trench 57 (185 m downstream from the SWCA Trench), the canal shows two or three freshwater pulses as suggested by the paleosalinity index. The first pulse was followed by a severe salinization event, suggesting that water input was brief, thus preventing ostracodes from settling and growing. *I. bradyi* and *C. vidua* were introduced by water flow. The second pulse includes a minor salinization episode or slower flow, which allowed

C. vidua to increase in population. Trench 39 (230 m downstream from the SWCA Trench) shows a flooding episode. The occurrence of *Limnocythere* n. sp., cf. *L. paraornata*, a species characteristic of high temperature and salinity, at the base of Feature 4 suggests that canal operation was conducted during late spring-summer, through the monsoon season. Subsequent freshwater input decreased the salinity to below *Limnocythere* n. sp., cf. *L. paraornata*'s tolerance (1000 ppm; Forester, 1985), thereby preventing it from growing in this canal.

Two possible explanations may be issued in regard to the alternate occurrence of water pulses along the canals. It is possible that canals were cleaned out occasionally in some sections, destroying evidence of sediment accumulation. Therefore, only one cycle of water input is recorded (e.g. Trenches 48, 51, and 54). The other possibility is that these pulses show the progress of excavation of canals upstream and downstream as the native people increased in population and their subsistence needs increased. The first hypothesis is the most likely because it explains why some distal intervals hold two cycles of water pulses. In addition, assuming that these sediments represent the last canal operation, it is reasonable to conclude that the inhabitants did not have to clean out every section of the canals. Only silted sections would have been cleaned. Sediments suggestive of such clean-cuts are visible in canal cross sections that imply systematic and repeated cleanings of certain canal segments. The second hypothesis, although intriguing, does not explain why distal trenches show two cycles while intermediate ones do not. More detailed sampling in the future at Trenches 48, 51, and 54 will allow a better interpretation.

Across the area covered by this study, the CDO flood deposit caps canal deposits in Features 4, 6, and 7. In most areas, the flood sands lack ostracodes, except in the SWCA Trench and Trench 39, where ostracode populations were low and consisted of two species (*I. bradyi* and *C. vidua*). Following the flood, and as a result of it, a cienega formed. The cienega deposit is visible in several trenches (SWCA Trench, 63, 53, and 39). Based on the ecology of the ostracode species (cf. Palacios-Fest, 1994, 1997) recovered from site AZ AA:12:753, it is inferred that the cienega lasted for at least several weeks to allow *C. arcuata* and *C. glaucus* to become established. However, the absence of *Limnocythere* n. sp., cf. *L. paraornata* cannot be explained, as this species would be expected as salinity increases. Salinity certainly increased, as shown in Trench 63, where *C. vidua* flourished and replaced *I. bradyi*.

Two canals (Features 1 and 2 in Trenches 69 and 13, respectively) show similar trends (Figs. 4(c) and 5(c)), raising the possibility that they were operated contemporaneously sometime between 2500–2400 BP (Unit 2). The 26 intervals sampled within canal deposits show that, as in Features 7, 6, and 4, water management was conducted. Feature 1 accumulated a more diverse assemblage than Feature 2, which included *C. patzcuaro*, a species requiring over three months to reach maturity (Forester, 1987; Palacios-Fest, 1994, 1997). The occurrence of *Limnocythere* n. sp., cf. *L. paraornata* and *Potamocypris* sp.(?) at the top of the sequences suggests standing water and increasing salinization. However, the freshwater pulses and salinization cycles are consistent between the two canals. The moderate fragmentation of *I. bradyi* and the low fragmentation, abrasion, and low A/J ratio of most other species suggest that the specimens preserved in these canals grew in situ following episodes of freshwater input.

The modern (post-WWII) Features 9 (Trenches 53 and 57) and 10 (Trench 54) contain no ostracodes (Figs. 3(d) and 4(d)). The mostly fine-grained sediments accumulated through the 11 intervals sampled suggest poor conditions for ostracode growth, perhaps due to short-term water input from artificial wells.

7. Discussion

The data presented in this study are derived from the first ostracode assemblages from pre-Hohokam irrigation canals in the Sonoran Desert (Palacios-Fest, 1989, 1994, 1997). The ostracode fauna seems to support Mabry's (1999) interpretation that irrigation was conducted in a stable floodplain with a high water table. Stream assemblages alternate with cienega-like faunal associations in a manner that indicates episodes of riverine input and high-water-table stands.

Based on the ostracode record, two recognizable stages of canal operation allow us to distinguish opportunistic from functional modes of canal operation. Opportunistic operation of prehistoric canals has been previously reported by Fish et al. (1992) in the Marana area. It involves opening of the canal headgate as ephemeral drainages flow during storms. However, the record at Las Capas (site AZ AA:12:753) may suggest a variant of this interpretation since ostracodes are unlikely to have been supported by storm flows from ephemeral channels. At that time, the Santa Cruz was not an ephemeral source of water but probably an intermittent one. Therefore, opportunistic canals probably operated during years or seasons of flow, providing a prolonged supply of water that supported the fauna introduced by the same flow. In contrast, functional canal operation implies human control of water flow into the canal over a long-term basis, but not necessarily year-round. We speculate that the paleosalinity indices constitute the distinctive argument to recognize opportunistic from functional operation. We are aware of the potential limitations of this analytical instrument. For example, Palacios-Fest (1997) demonstrated that, during the Classic Period, the Hohokam at Pueblo Blanco in the Phoenix Basin mastered functional canal operation. Feature 3 of Las Capas canals represents the first record of an opportunistic canal to be compared with known functional canals of Hohokam age. Therefore, we will leave our interpretation as a tentative one, until further research on prehistoric canals is available.

At site AZ AA:12:753 the transition from opportunistic to functional canal operation can be identified among two sets of canals. Feature 3, the oldest canal (3000–2900 BP), shows evidence of a brief flooding event. The poor, adult-dominated, faunal composition advocates for one episode of water input. Ostracode records are consistent with our pollen data, showing the occurrence of corn (*Zea*) and low percentages of riparian plants (<2%) such as *Cyperaceae*, *Alnus*, *Fraxinus*, *Juglans*, *Populus*, and *Salix*. These low values in the canal samples suggest that Feature 3 did not retain water long enough to permit the growth of riparian vegetation in or near the canal.

Feature 3, dated 3000–2900 BP (1000–800 BC), is the earliest irrigation canal reported from the Southwest to date. Previous environmental studies of the Southwest suggest that between 4000–2500 years BP, warm/wet conditions characterized the area (Waters, 1988a,b; Mabry, 1998). Current ostracode data are not enough to confirm this. However, future planned analyses of shell chemistry (both stable isotopes and trace elements) of *I. bradyi* valves will provide critical information about water temperature, salinity, and effective moisture at the time of shell formation.

During the late San Pedro Phase (Unit 4; 2800–2500 BP), new canals (Features 7, 6, and 4) were constructed at this site. Two main differences between Feature 3 and Features 7, 6, and 4 are evident. First, the younger canals (Features 7, 6, and 4) were used for a prolonged period of time, and they accumulated thick sequences of water-lain sediments; this contrasts with the thin accumulation in Feature 3. Second, the faunal association is richer and more diverse in Features 7, 6, and 4 than in Feature 3, suggesting two situations.

During the interval in which Features 7, 6, and 4 were operated, the climate was probably warmer and drier than the previous 200–300 years, allowing the occurrence of more saline-tolerant species. In some trenches, *Limnocythere* n. sp., cf. *L. paraornata* occurs at the base of the canal. The other pattern recorded by canal ostracodes is that episodes of water input alternated with intervals of salinization, some of which included canal desiccation while others included increasing salinity followed by a return to dilute water conditions. These pulses of water input appear to have been of human rather than climatic origin. This pattern is not recorded after the CDO flood except in Trench 39, where cienega-like deposits show a slight salinity fluctuation, then a drastic dilution effect (probably due to a water table rise), followed by the disappearance of fauna at the top of the sequence.

In consequence, the ostracode paleoecology preserved at site AZ AA:12:753 generates an identifiable human-impact signal, while the climatic record is somewhat masked. Three characteristics observed in this study support this hypothesis: (1) As shown above, canal waters evolved from type I (dilute) to type II (Ca-enriched waters, dominated additionally by Na^+, Mg^{2+}, and SO_4^{2-}). Pathway variation was more significant as canal headgates were closed and water evaporated within some segments of the canal; (2) no evidence of severe salinization was recorded by ostracodes except in Trench 81 (end of Feature 6); and (3) Mabry and Holmlund (1998) inferred that Hohokam irrigators in the Santa Cruz Valley used fallow cycles; salts did not accumulate in prehistoric irrigated soils because the irrigators flushed the soils periodically with heavy irrigation; however, it is difficult to support this argument because canal or field flushing would imply accumulation of salts somewhere else and no evidence of that was found in the location.

Currently, local tree ring records do not extend back to this time interval (Adams, 1999). Also, available tree ring information is not strictly representative of the Tucson Basin, but rather reflects conditions on the Mogollon Rim and Colorado Plateau (Meko and Graybill, 1995; Meko et al., 1995). Therefore, a correlation between ostracode and other biological records of paleoclimatic changes is not currently possible.

8. Conclusions

Site AZ AA:12:753 provides important paleoecological information for understanding early prehistoric agricultural techniques in southeastern Arizona. Ostracode paleoecology shows the transition from opportunistic to functional canal operation between 3000 and 2400 radiocarbon years BP (1200–600 BC). Multitrench sampling and analysis proved a feasible technique to reconstruct canal history. Dominance of *I. bradyi* in all canals suggests input from the Santa Cruz River. Feature 3 represents a one-time, opportunistic canal operation that allowed the growth of *Limnocythere* n. sp., cf. *L. paraornata* in a downstream trench (39) with increasing salinization. However, evidence of multiple cleanout episodes (layers of blocky clay) in this canal, implying a longer use life, conflicts with this interpretation. More detailed analysis may clarify this matter.

Sometime between 2800 and 2500 years BP (ca. 1000–800 BC), San Pedro Phase farmers began to control water input into canals. Variations in the ostracode population still dominated by *I. bradyi* suggest alternating intervals of salinization and water input consistent with episodes of headgate opening. Features 7, 6, and 4 show a variable ostracode composition, but the climatic signal is not evident in this record. Finally, during late San Pedro Phase (2600–1800 BP), once again cultural impacts (e.g. pit structures, storage pits, hearths, human burials, and artifacts) affected the area (Features 1 and 2). Ostracode paleoecology suggests that the Santa Cruz River floodplain was subject to human impact (e.g. cycles of water input and dominance of *I. bradyi*) as proposed by Waters (1988a).

To date, these are the first canals to show change in technology from simple opportunistic diversion of flows to a long-term, functional mode of canal operation. It is now critical to conduct similar analyses in canals of equivalent age elsewhere (e.g. central Mexico), which would help to identify a pattern in how irrigation technologies evolved.

Lack of a well-defined climatic signature from ostracode paleoecology suggests that shell chemistry will provide the data to test our hypothesis of human versus climatic impact in the Las Capas site. Stable isotopes (^{18}O) and trace elements (Mg/Ca and Sr/Ca ratios) will allow identification of water sources, salinization trends, and temperature and salinity at the time the shells formed.

Acknowledgements

This study was conducted under the support of Desert Archaeology, Inc. The authors recognize the invaluable comments and suggestions made by our two reviewers, Dr Elizabeth Brouwers and Dr Rick Forester.

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Lastly, a well-dated climatic sequence from [illegible] paleoecology suggests that shell chemistry will provide the [illegible] of the importance of [illegible] climatic impacts in the Las Capas site. Stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) [illegible] along with Mg/Ca and Sr/Ca ratios will allow identification of [illegible] water and [illegible] [illegible] through the shells [illegible].

Acknowledgements

This study was conducted under the auspices of Desert Archaeology, Inc. The authors recognize the invaluable [illegible] and suggestions made by our [illegible] reviewers, Dr. Elizabeth [illegible] and Dr. [illegible].

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