Nonmarine Ostracode Shell Chemistry from Ancient Hohokam Irrigation Canals in Central Arizona: A Paleohydrochemical Tool for the Interpretation of Prehistoric Human Occupation in the North American Southwest

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Environmental archaeology studies on samples from an agricultural context provide information that may be used to answer questions of climatic vs. human impact on Hohokam prehistory. Hohokam irrigation systems were fragile and subject to episodic damage and destruction. Ostracodes are sensitive to hydrochemical changes. Their fossil record in Hohokam canals can provide useful data to understand human/environment relationships in the past. Low-Mg calcite ostracode carapaces form in thermal and chemical equilibrium with the host water. Magnesium and strontium are commonly incorporated into the shell as trace elements, which can be used to track paleotemperature and paleosalinity variations. Thus, fossil ostracodes reflect the water chemistry in which the valves were precipitated. Valves of *Limnocythere staplini, Candona patzcuaro,* and *Cypridopsis vidua* were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) to determine the Mg/Ca and Sr/Ca ratios. Trace element data were used to reconstruct the canal water chemistry and to propose paleoclimatic and human-impact hypotheses for environmental change. The ostracode record shows some evidence of a progressive salinization process between A.D. 1025 and 1425 that may be the result of human disturbance; this inference is supported by independent evidence from geographic, palynologic, and dendroclimatologic data. In addition, two major climatic events, large enough not to be masked by human activity, were also recorded by ostracode geochemistry: a flood between A.D. 855 and 910, another flood prior to A.D. 1350, and a drought between A.D. 1365 and 1425.

INTRODUCTION

In recent years geoarchaeologists have demonstrated methods for distinguishing between climatic and anthropogenic agents of environmental change (Petersen, 1987; Waters, 1988; Ackerly, 1989a; Katzer, 1989a). Hohokam culture created the only known large-scale pre-Columbian irrigation systems in the United States (Ackerly, 1989a). However, these irrigation systems were fragile and subject to episodic damage and destruction (Graybill, 1985). Climate

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appears to have affected Hohokam agriculture in several ways, including the timing and magnitude of floods and drought, but Hohokam agriculture also induced waterlogging and salinization of soils. The geologic record along the Lehi-Mesa Terrace of the Salt River shows evidence of these destructive events (Palacios-Fest, 1989). However, to date, it has been difficult to distinguish the climatic signature from the human one.

One possible approach for resolving human vs. climate damage to canal systems is to examine the fossils of these canals. The fossil record of organisms sensitive to hydrochemical changes in canal waters can provide useful data to reconstruct human/environment relationships in the prehistoric past.

The purpose of this article is to introduce ostracode shell chemistry analysis as a new tool for understanding canal water chemistry, intensity of land use, and human impacts to soil. Using this technique, it is possible to identify climatic factors that most likely affected the Hohokam in southwestern North America and to separate them from human factors.

PREVIOUS WORK

Martin and Plog (1973), Ackerly (1989b), Crown (1991), and Gumerman (1991) summarized the history of archaeological research on Hohokam cultural evolution, including their subsistence strategies, agricultural irrigation systems, and the possible effects of climate on Hohokam life. Haury (1945) recognized the inadequacy of records available to understand the role of climate in Hohokam life, and his subsequent work provided the framework to improve our knowledge on the Hohokam environment. Gumerman (1991) shows how poor age control of Hohokam events limits the understanding of Hohokam origins, technological evolution, and external exchange relationships. In addition, the lack of a detailed climatic framework has hampered environmental reconstruction of the southwestern desert during Hohokam times.

Recent studies of flood frequency in the Phoenix Basin have shown how climatic perturbations may have affected Hohokam life (Graybill, 1985; Graybill and Nials, 1989; Nials et al., 1989). These studies concluded that the Hohokam endured at least eight major flooding events along the Salt and Verde Rivers between the 8th and 14th centuries. They further proposed that floods in A.D. 899 and 1352 had devastating effects, resulting in irrigation system disuse, abandonment, and population relocation. However, Huckleberry (personal communication, 1993) suggests that the Gila River hydrology differs from that of the Salt River; thus Nials et al.'s (1989) flood chronology model cannot be applied to all of the Hohokam sites. Other floods may have had similar effects.

In contrast, Ackerly (1989c) summarized the evidence for impacts of Hohokam agricultural practices on the environment and on their own subsistence in the Phoenix Basin. Macrobotanical and palynological data provide some information on the seasonal operation of the canals (Gish, 1989; Miksicek, 1989). Analyses of ostracode and gastropod found in canal sediments suggest alternating wet–dry cycles, salinization, and waterlogging (Palacios-Fest, 1989; Miksicek, 1989). Ackerly (1989c) proposed that, during the Sedentary and Classic periods, canals become increasingly more saline as a result of irrigation practices.

THE MODERN ENVIRONMENT

The Phoenix Basin lies in the Lower Sonoran Desert between 30 and 1200 m above sea level (masl), averaging 600 masl (Figure 1). It is drained by the Salt and Gila Rivers. The Salt and the Gila River drainages originate in east-northeastern Arizona and western New Mexico and run southwestward through the region (Cordell, 1984; Fish and Nabhan, 1991). Today the Phoenix Basin receives an annual average precipitation of less than 13 cm.

The Salt River is joined by its main tributary, the Verde River, about 40 km upstream from Phoenix, increasing the water volume reaching the study area. Below its confluence with the Verde, the Salt drains an extensive area of the Tempe Quadrangle (33,670 km^2) through the basin (Ruff, 1971). The Gila River drains 53,400 km^2 (Ackerly, 1989a). Prior to modern damming, these rivers provided perennial flow over an extensive area including the Phoenix Basin (Fish and Nabhan, 1991).

Although the water resources were limited, the confluence of the Gila, Salt, and Verde Rivers near Phoenix provided the Hohokam an ideal region for settlement because of their perennial flow. Modern hydrochemical analyses of the Salt and Gila Rivers indicate a freshwater to slightly saline composition dominated by Na^+, Mg^{2+}, and $SO_4^=$ (Hem, 1985). Other intermittent or smaller perennial drainages such as the Santa Cruz River, reaching Hohokam land, originate in lower, less massive uplands within the Sonoran Desert.

AGRICULTURAL SYSTEMS AND CANAL STRATIGRAPHY

Alluvial terraces flank the major drainages within the Phoenix Basin. The Mesa and Lehi Terraces, two of the five terraces formed in the basin during the Pleistocene or earlier, are of particular interest to this study because they are transepted by the Las Acequias canals (Figure 2). The Mesa Terrace consists of indurated gravel cemented by laminated caliche. This heavily eroded terrace occurs about 3 m above the Salt River bed. In contrast, the Lehi Terrace of late Pleistocene/early Holocene (?) age is characterized by slightly calcareous, unconsolidated gravel and overbank sands. It rises gently to the south and forms the modern floodplain in the Tempe area (Péwé et al., 1985). Based on the occurrence of early Hohokam artifacts (pre A.D. 700) in the zone of carbonate accumulation in the Lehi Terrace, Katzer (1989a) proposed that the alluvium must be older than 700 years. However, no radiocarbon dates from these carbonates are available to establish the terrace's age. The stratigraphic relationships between the alluvium and the canals are critical for constraining the age of the canals (Katzer, 1989a).

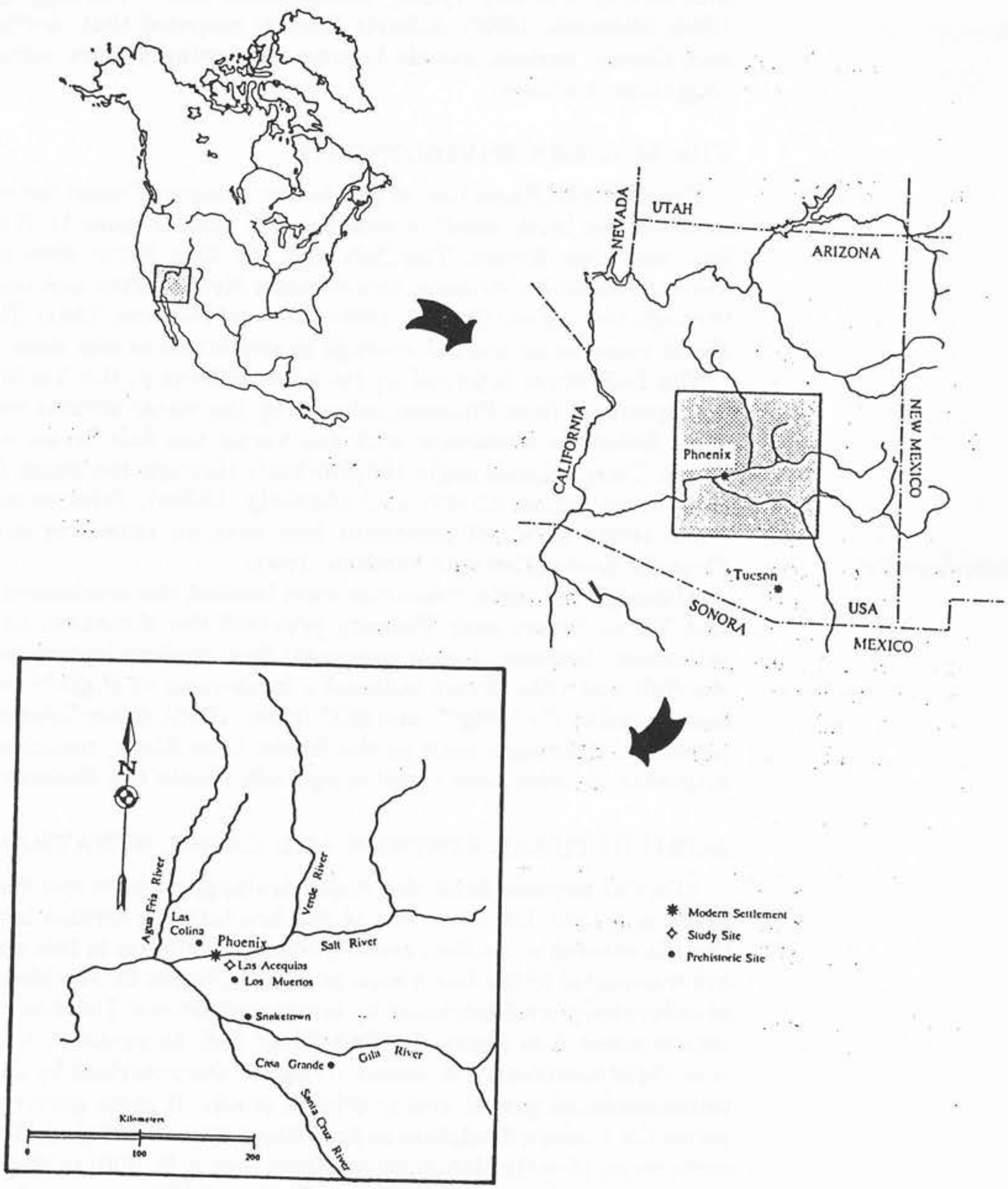


Figure 1. Location map of Las Acequias archaeological site in Tempe, Arizona. Hohokam irrigation canals, exposed during the construction of the Tempe Outer Loop Corridor, were dug along the north and south rims of the Salt River. These canals reached a maximum length of about 25 km.

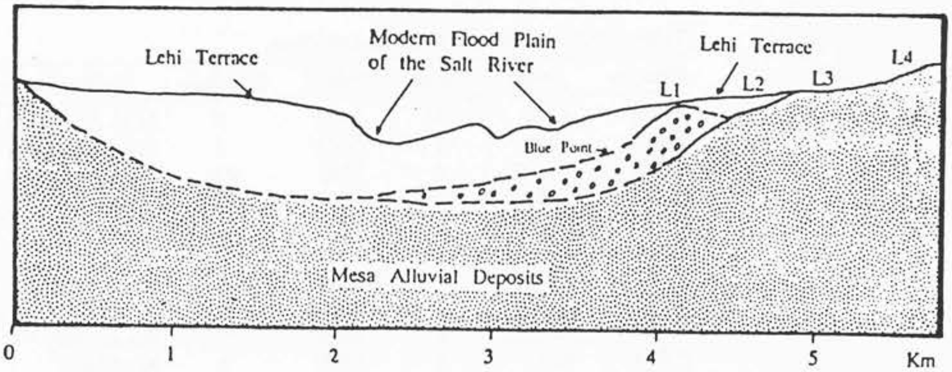


Figure 2. Geological cross section of the Salt River in the vicinity of the Tempe Outer Loop Corridor. Hohokam canals were dug on the Lehi Terrace surface (after Katzer, 1989).

Four Hohokam Cultural Periods are recorded at Las Acequias (Pioneer, Colonial, Sedentary, Classic); additionally, a historic record is incorporated for comparison (Table I). Ostracode samples of historic age are available from the Peterson Ditch, a canal used by Anglo inhabitants of this region late in the last century (between 1885 and 1892). This canal provides a useful comparison with ancient Native American canals.

Irrigation canals were located close to the Hohokam villages (i.e., Las Acequias, Figure 3). The Las Acequias system consisted of 37 canals characterized by different sizes of prehistoric water distribution. Patterns of cyclical construction and abandonment evident in Las Acequias canals can be related to paleoflood episodes (Ackerly, 1989a). Masse (1991) recognized three major agricultural technologies developed by the Hohokam that were applied depending on agricultural needs: floodwater farming (floodplain inundation and "akchin"), dry farming, and irrigation. Hohokam irrigation systems developed as early as A.D. 600–700 (Snaketown or Pioneer Period) and abruptly ended sometime before A.D. 1450. During this interval significant changes in canal structure and irrigation system's framework occurred (Cordell, 1984; Katzer, 1989b; Masse, 1991).

Several assumptions must be made in developing theoretical scenarios for the paleohydrochemical history of the canals and their effects on the Hohokam agricultural system. The first assumption is that the preserved stratigraphic record in the canals recorded the last time the canals were operated by the Hohokam; this assumption rests on the fact that modern rustic agricultural systems are subject to yearly or seasonal cleaning before the canals can be reused; thus any previously deposited sedimentary layering is obliterated. Because of ostracode valve brittleness, this assumption is validated by the small degree of abrasion and shell breakage observed in these fossils; a high proportion of abraded and fragmented valves, on the other hand, would suggest

Table I. Canal and sample identification.

Sample	Canal	Locus	Trench	Stratum	Sediments	Assemblage	Age
F-567	C-61	2	2014	2	Silty clay loam	2	E. Pioneer
F-573	C-61	2	2014	2	Silty clay loam	3	E. Pioneer
F-742	C-102	1	1007	23	Mixed sand	2	Colonial
S-703	C-5	2	2005	1	Sandy loam	*	Colonial
S-924	C-5	3	3020	1	Sandy silt	1	L Colnl
F-608	C-5	2	Junc 3/5	5	Basal silty clay	*	Col/Sed
F-609	C-5	2	Junc 3/5	5	Basal silty clay	*	Col/Sed
S-696	C-5	2	2005	3	Sandy clay	*	Early Sed
F-537	C-5	3	3008	1	Sandy clay	*	Early Sed
S-568	C-5	3	3008	1	Sandy silt	3	Early Sed
S-577	C-5	3	3008	1	Sandy silt	1	Early Sed
F-644	C-5	3	3020	1	Mixed sand	*	Early Sed
F-610	C-5	2	Junc 3/5	5	Basal silty clay	2	Sedentary
F-560	C-4	2	2006	3	Silty clay loam	2	Sedentary
F-563	C-4	2	2006	2	Silty clay loam	2	Sedentary
F-575	C-10	2	2002	2	Silty clay loam	3	Sedentary
F-582	C-10	2	2002	3	Sandy silt	3	Sedentary
F-591	C-16B	2	2012	5	Mixed sand	2	Sedentary
S-987	C-16B	2	2012	2	Sandy silt	*	Sedentary
S-1076	C-16B	2	2012	3	Sandy silt	3	Sedentary
F-643	C-3	3	3020	3	Silty clay	3	Sedentary
F-700	C-3	2	2068	15	Mixed sand	1	Sed/Clssc
F-529	C-1	3	3008	5	Clayey silt	3	Classic
F-513	C-2	4	Junc 2/5	1	Clay	2	Classic
F-514	C-2	4	4013	2	Clayey silt	*	Classic
F-517	C-2	4	Junc 2/5	1	Silty clay	*	Classic
S-500	C-3	4	4001	8	Silty clay	3	Classic
F-777	Peterson	Ditch	Episode	A	Silty clay	1	Historic
F-778	Peterson	Ditch	Episode	B	Sandy clay	4	Historic
F-779	Peterson	Ditch	Episode	C	Clay	1	Historic

redeposition of formerly precipitated valves. The second assumption is that the chronology of events shown in this article match well with the current stratigraphic sequence and archaeomagnetic and radiocarbon dates (Henderson, 1989; personal communication, 1992). The combination of the relative stratigraphic correlation among the canals with the measured chronologies provide a reasonable sequence of events affecting Hohokam irrigation practices (Table II). A final assumption is that the major factors affecting ostracode assemblage changes were environmental variations caused by climate or human activity.

OSTRACODES: BIOLOGY AND ENVIRONMENT

Ostracodes are aquatic crustaceans with low Mg–calcite carapace formed by two valves attached by a dorsal hinge and a ligament (Plate 1). Their life cycles involve nine stages, during which ostracodes shed their valves (probably in

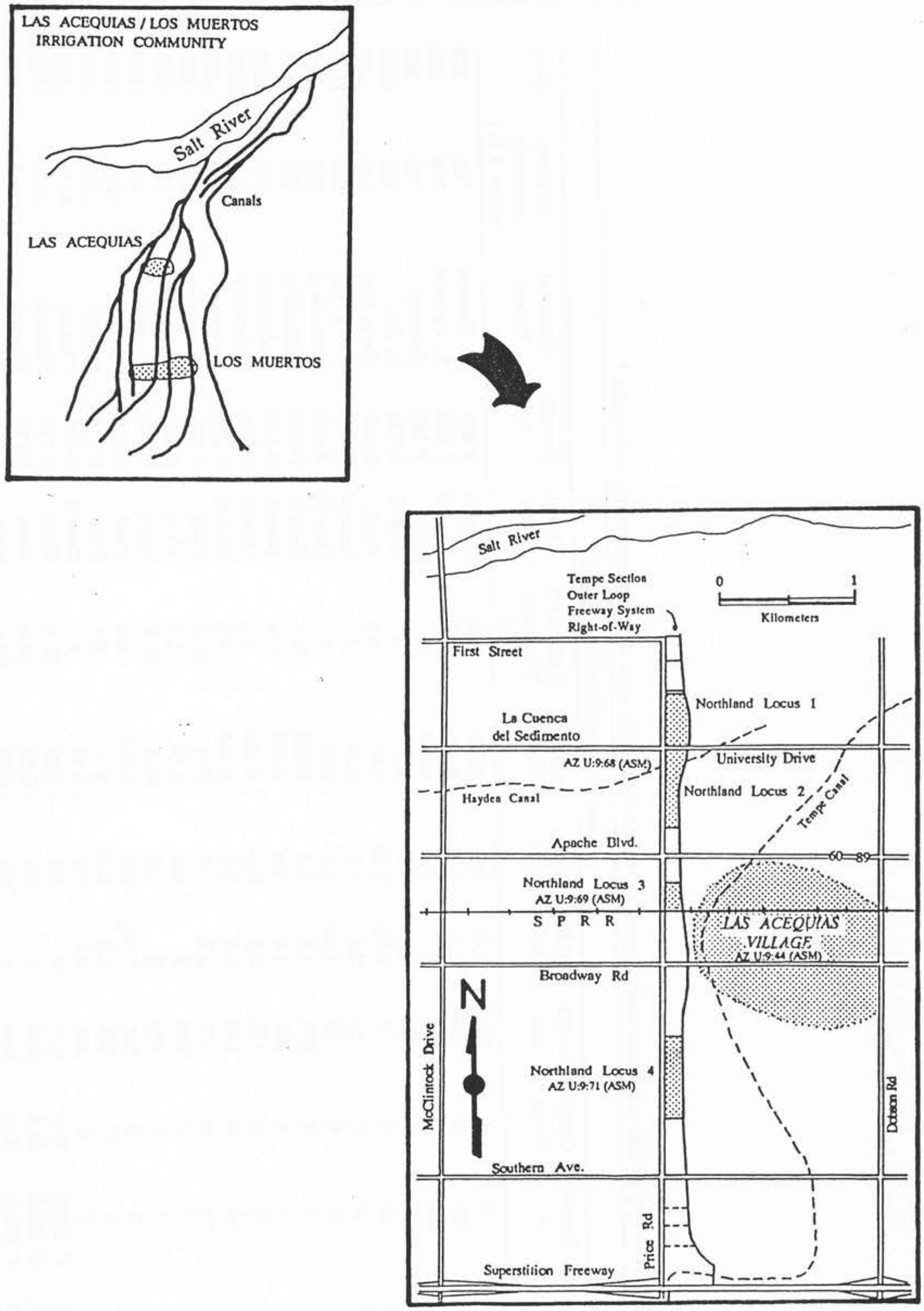


Figure 3. Las Acequias irrigation system (after Ackerly, 1989a).

Table II. Physical characteristics and cultural and archaeomagnetic ages of canals containing ostracodes.[a]

Las Acequias Hohokam Canals												
Locus #	Canal #	Canal Group	Length (m)	Width (m)	Depth (m)	Gradient (m/km)	Water CPY Discharge (cfs)	Canal Type	Sample #	Cultural Period	Archaeo-magnetic (years A.D.)	Date
2	4	A	206	1.3	0.8	0.802	N/A	Distrib	F-567	E. Pioneer	700	925
2	10	A	120	2.2	0.6	0.455	0.8	Distrib	F-573	E. Pioneer	700	925
1	102	D	164	6	1	0.632	11	Main	F-742	Colonial	750	950
3	5	C	206	1.3	0.6	−0.9	3	Distrib	S-924	L. Col.	855	1025
3	8	A	4	0.65	0.25	−1.07	0.5	Field	S-568	Early Sed	910	1025
3	2	C	15	2.4	0.7	N/A	4	Distrib	S-577	Early Sed	910	1025
2	5	C	60	1.45	1.1	0.81	4	Distrib	F-610	Sedentary	925	1255
2	4	A	206	1.3	0.8	0.802	N/A	Distrib	F-560	Sedentary	925	1255
2	4	A	206	1.3	0.8	0.802	N/A	Distrib	F-563	Sedentary	925	1255
2	10	A	120	2.2	0.6	0.455	0.8	Distrib	F-575	Sedentary	925	1255
2	10	A	120	2.2	0.6	0.455	0.8	Distrib	F-582	Sedentary	925	1255
2	16	A	57	1.2	0.9	N/A	N/A	Field	F-591	Sedentary	925	1255
3	3	C	205	3	0.9	−0.62	3.1	Main	F-643	Sedentary	925	1255
2	3	C	159	8	1.8	N/A	N/A	Main	F-700	Lsedeclsc	980	1260
4	3	B	266	1.25	0.8	0.214	0.6	Field	S-500	Classic	1275	1450
4	2	C	268	1.8	0.33	0.4	0.5	Field	F-513	Classic	1300	1550
3	1	C	190	3.5	0.7	−0.17	3	Distrib	F-529	Classic	1275	1550
N/A	P. Ditch	N/A	N/A	6	0.4	−0.92	N/A	Field	F-777	Historic	1885	1892
N/A	P. Ditch	N/A	N/A	6	0.4	−0.92	N/A	Field	F-778	Historic	1885	1892
N/A	P. Ditch	N/A	N/A	6	0.4	−0.92	N/A	Field	F-779	Historic	1885	1892

[a] Canal grouping based on canal width only. Group A exhibits below average widths and depths; group B consists of the most common canals with average widths and depths; group C contains the second most common type of canals, with values slightly above average; and group D shows the highest width and depth values. For a detailed description of canals, see Ackerly and Martynec (1989) and Katzer (1989a, 1989b). Cultural and archaeomagnetic data from Henderson (1989; and personal communication, 1992).

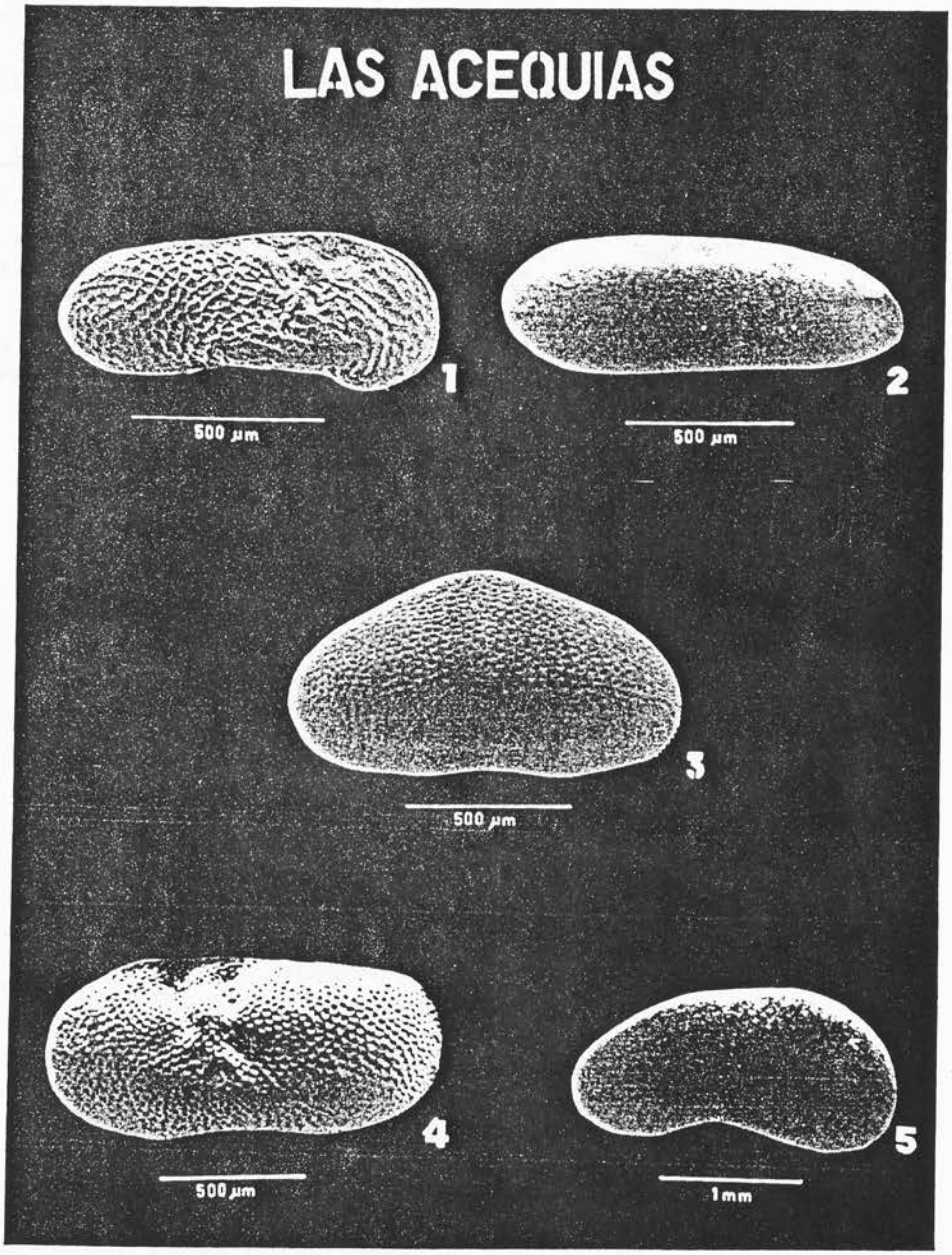


Plate 1. (1) *Limnocythere staplini*, right valve of a male specimen. Sample F-529; magnification 89×. (2) *Darwinula stevensoni*, left valve (no sexual dimorphism evident). Sample F-778; magnification 79.3×. (3) *Cypridopsis vidua*, right valve (no sexual dimorphism evident). Sample F-529; magnification 77.2×. (4) *Ilyocypris bradyi*, left valve (no sexual dimorphism evident). Sample F-742; magnification 67×. (5) *Candona patzcuaro*, left valve of a male specimen. Sample F-742; magnification 33×.

Table III. Environmental conditions where nonmarine ostracodes grow.[a]

Las Acequias Hohokam Canals				
Habitat	Permanence	Temperature	Salinity	Chemistry
Stream: Channeled flow Standing: Low or no flow	Permanent: Perennial Ephemeral: Periodical dry-out	Eurythermic: Organisms adapted to a wide range of temperature Stenothermic: Organisms constrained to a narrow temperature range Thermobiont: (20–25°C) Thermophillic: (~20°C) Cryobiont: (>10°C) Cryophillic: (10–15°C)	Euryhaline: Organisms adapted to a wide range of salinity Stenohaline: Organisms constrained to a narrow salinity range	Type I: Ca^{2+}, Mg^{2+}, HCO_3^- dominated (freshwater) Type II: Ca^{2+}-rich/HCO_3^--depleted Na^+, Mg^{2+}, $SO_4^=$ or Na^+, Mg^{2+}, Cl^- dominated (hardwater) Type III: Alkali-rich/Ca^{2+}-depleted Na^2, Mg^{2+}, Cl^- or HCO_3^- or $SO_4^=$

[a] Some eurytopic species occur under a combination of water factors shown in this chart. Stenotopic organisms are restricted to one or maybe two water chemistry conditions. A combination of factors (i.e., temperature, salinity) also limit ostracode development.

less than 1 hr) to generate a new carapace. Both adult and juvenile valves (called instars) may be preserved as fossils, and both are useful for paleontologic studies. The carapace morphology and shape are both environmentally and genetically controlled (Pokorny, 1978).

Nonmarine ostracodes are widely distributed in fresh and saline waters, normally under well-oxygenated conditions. They occur in lakes, ponds, springs, and streams. Palacios-Fest (1989) described the ecologic parameters which control ostracode distribution in continental waters (Table III). Ostracode species may be eurytopic (i.e., able to tolerate a wide range of environmental conditions) or stenotopic (i.e., tolerant of a restricted range of environmental conditions). Based on their known ecologic tolerances, fossil ostracode species can provide preliminary criteria for reconstructing paleoenvironments.

Continental ostracodes inhabit waters of different hydrochemical composition, but at the species level many are very sensitive to water chemistry. Ostracode species assemblages can be used to recognize the three major water types defined by Eugster and Hardie (1978):

Type I: Ca^{2+}, (Mg^{2+}), and HCO_3^--dominated water; typically freshwater or very low salinity conditions.

Type II: Ca^{2+}-enriched/HCO_3^--depleted water; additionally containing the combinations of Na^+, Mg^{2+}, $SO_4^=$, or Na^+, Mg^{2+}, Cl^-; ranges from low salinity to hypersaline conditions.

Type III: HCO_3^- + $CO_3^=$ (alkaline)-enriched/Ca^{2+}-depleted water; usually containing combinations of Na^+, Mg^{2+}, Cl^-, or Na^+, Mg^{2+}, $SO_4^=$; ranges from low salinity to hypersaline conditions.

OSTRACODE SHELL CHEMISTRY

The chemical composition of ostracode carapaces has been investigated by several authors (Sohn, 1958; Turpen and Angell, 1971; Bodergat, 1983; Chivas et al. 1983, 1985). As a new carapace is precipitated from ions in solution, it forms in thermal and chemical equilibrium with the host water (Chivas et al., 1983, 1986a). Turpen and Angell (1971) demonstrated that calcium in solution is the exclusive source of Ca^{2+} for ostracode valve calcification. Among the 25 trace elements detected in ostracode valves, Mg^{2+}, Sr^{2+}, K^+, and Ba^{2+} are the most common (Bodergat, 1983). Mg^{2+} is the most abundant trace element incorporated into the calcite structure. Sr^{2+} is also present in the calcite lattice despite its different crystallographic structure (Sr^{2+} precipitates more readily in aragonite). Magnesium and strontium uptake by ostracode valves occur in a similar manner to calcium uptake (Chivas et al., 1983). However, the Mg^{2+} concentration is dependent upon both temperature and water chemistry, whereas Sr^{2+} concentration is exclusively controlled by water chemistry independent of temperature (Chivas et al., 1986a, 1986b; De Deckker et al., 1988). Therefore, the Mg/Ca and Sr/Ca molar ratios from ostracode valves can be used to indicate the paleohydrochemical evolution of a water body. De Deckker and Forester (1988) summarized the possible changes in water properties reflected by varying Mg/Ca and Sr/Ca molar ratios.

MATERIAL AND METHODS

Thirty sediment samples were analyzed from Las Acequias at the Tempe Outer Loop area for ostracode content (Figure 3; Table I). These samples were selected to allow comparisons (a) within a single stratum at different locations within a single canal, (b) between different strata within a single location, (c) between different canals in a single locus or time period, and (d) between canals at different loci and of differing ages.

Samples were collected from four locations (loci) at Las Acequias located about 7–12 km from the canal headgates on the Salt River (Figure 3). Locus 1 encompasses the northernmost agricultural fields studied in this project. It is situated on the boundary between the floodplain and the Lehi-Mesa Terraces of the Salt River (Ackerly and Martynec, 1989) and holds one of the main canals studied here. Locus 2 situated on the Lehi-Mesa Terraces immediately south of the Hayden Canal contain a complex variety of canals from main and distribution canals to field or lateral canals. Locus 3 located between Broadway and Southern Avenues east of Price Road is similar to the previous site with the exception that Locus 3 comprises a higher proportion of large distribution canals than does Locus 2. Locus 4 situated north or Southern Avenue and bounded to the west by Price Road primarily comprises medium to large size distribution canals with only a few field canals. Canals at Las Acequias are, most commonly, between two and three times as wide as they are deep (Table II). These canals appear to cluster by varying width and depth values (Ackerly and Martynec, 1989).

Many of the canals intersected one another at all loci allowing Henderson (1989) to assess the relative stratigraphic sequence at Las Acequias. Table I and Figure 4 indicate the stratigraphic horizon within each canal from which samples were collected. Since many samples were equivalent or close in age, it has been necessary to cluster several samples together by chronologic affinities according to Henderson's chronology (1989).

A modified version of Forester's (1991) freeze and thaw technique was used to obtain the cleanest ostracode specimens for geochemical analysis. Residuals were examined under a low power stereoscopic microscope. Routine paleontological study of all 20 fossiliferous samples was performed to determine fossil content and faunal composition. Paleoecologic assemblages were defined and grouped according to species abundance.

Two hundred and eighty-eight individual valves from the 20 fossiliferous samples were removed for spectrometric analysis. Between three and 10 specimens from each of the species considered for this study were selected: *Limnocythere staplini, Cypridopsis vidua,* and *Candona patzcuaro*. Specimens were thoroughly cleaned with 18 MΩ water and a fine brush (000). Valves were weighed in a Cahn 29 electronic balance, and dissolved in a 2% HCl distilled solution for trace metal (Mg^{2+} and Sr^{2+}) study using a VG-TN7200 inductively coupled plasma mass spectrometer (ICP-MS). Calcium content in ostracode valves was determined stoichiometrically. Spectrometric data were grouped by species, sample, and archaeomagnetic age to generate a trace element chronology.

RESULTS

Ostracode Assemblages at Las Acequias

Table IV summarizes the species present and environmental conditions controlling ostracode assemblages occurring at Las Acequias. Six species occurred in the canals; the dominant species from all samples were *Limnocythere staplini, Cypridopsis vidua,* and *Candona patzcuaro*. Other species (*Darwinula stevensoni, Ilyocypris bradyi,* and *Physocypria pustulosa*) occurred occasionally. Based upon the occurrence and relative abundance of these species, four assemblages were recognized, all of which typify type I (dilute) to type II (Ca-enriched waters dominated additionally by Na^+, Mg^{2+}, and $SO_4^=$). Modern water analyses from the Salt and Gila Rivers indicate near-equivalent proportions of bicarbon-

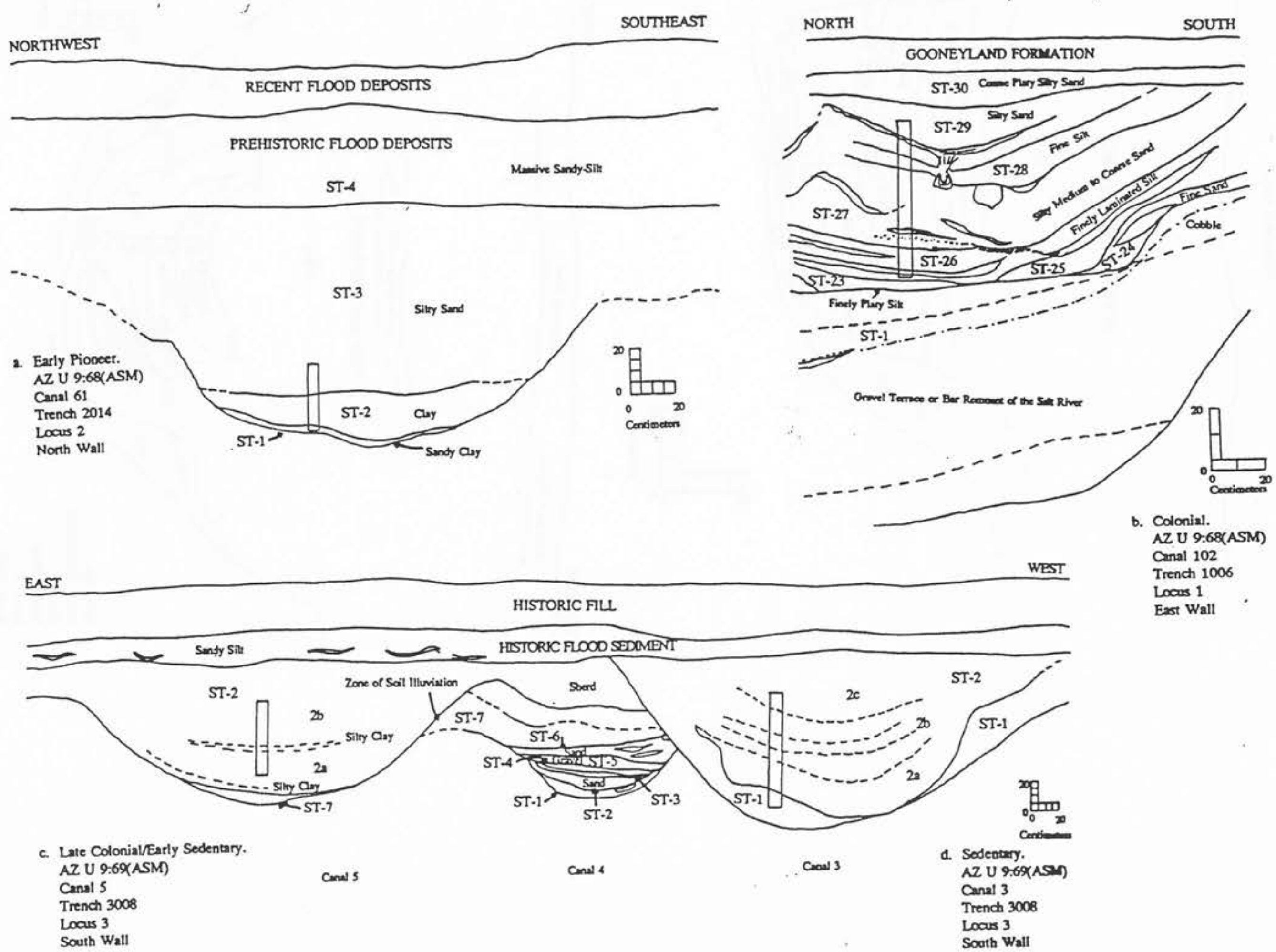


Figure 4A. (*Continues*)

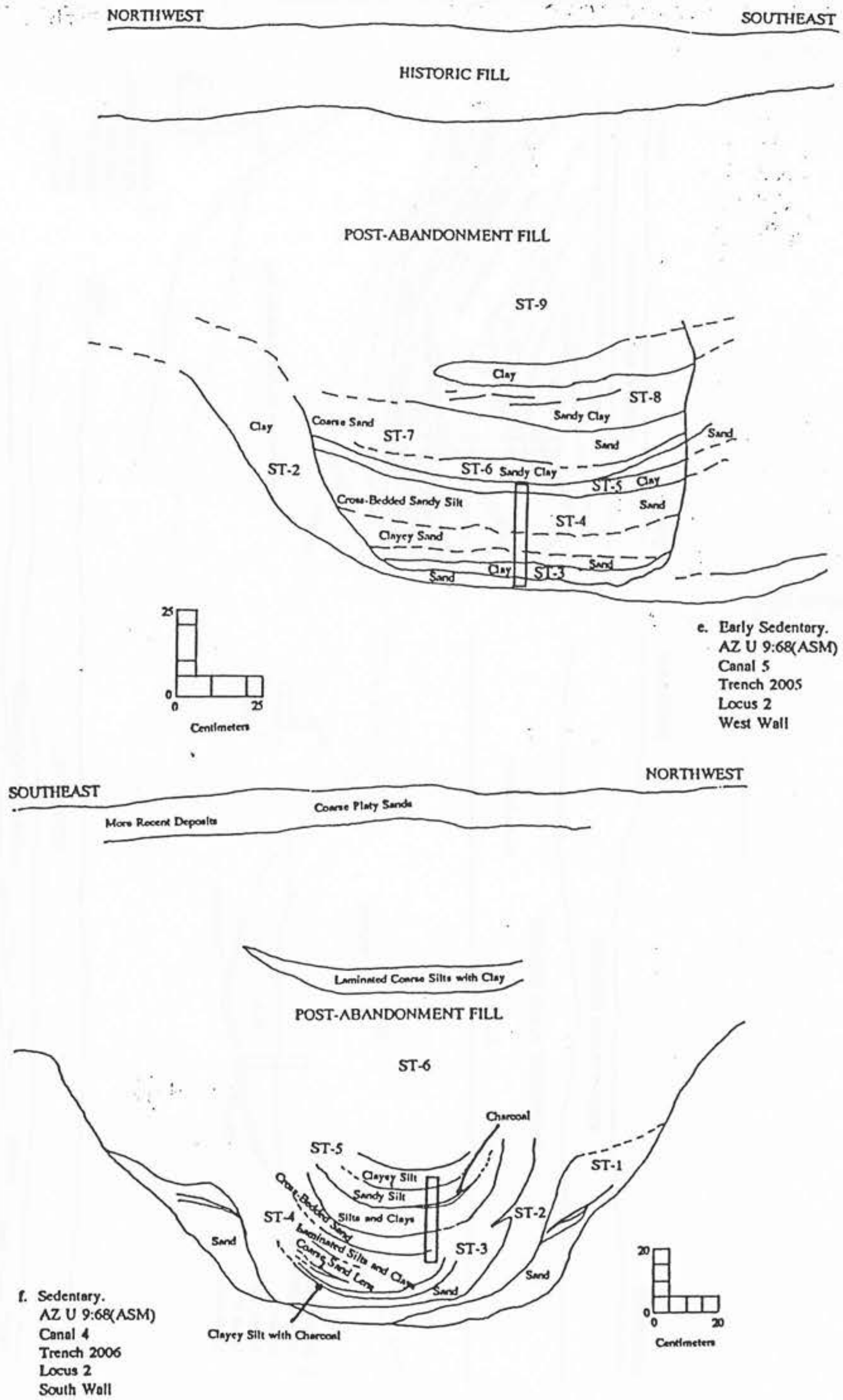


Figure 4B. (*Continues*)

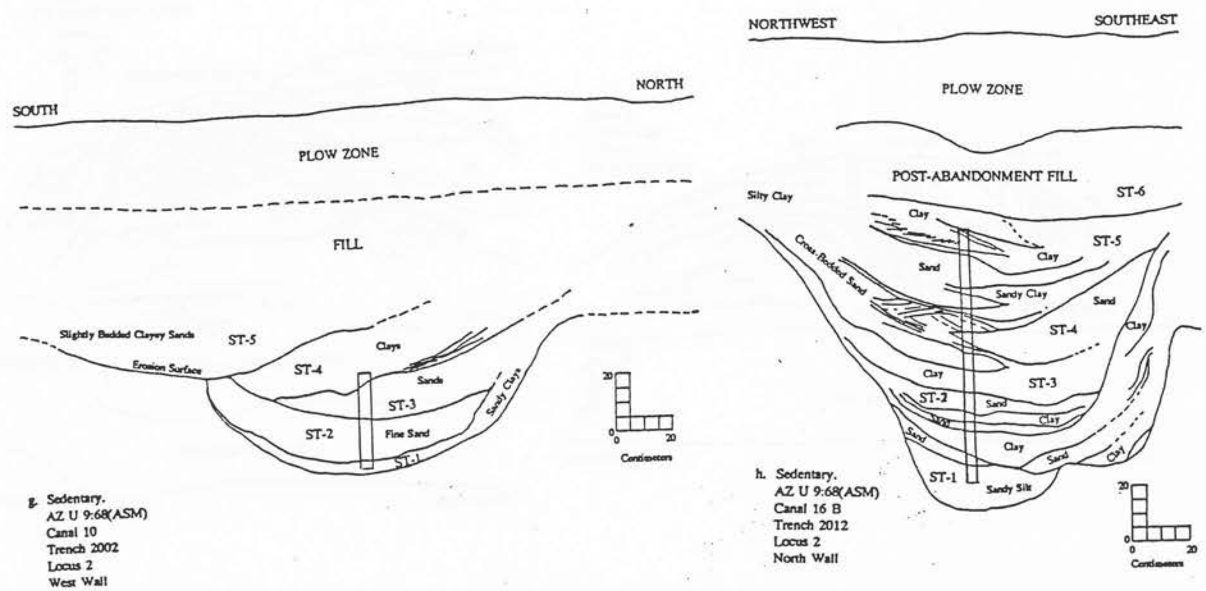
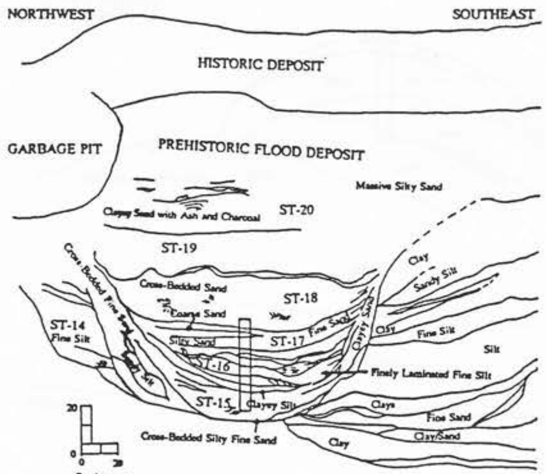
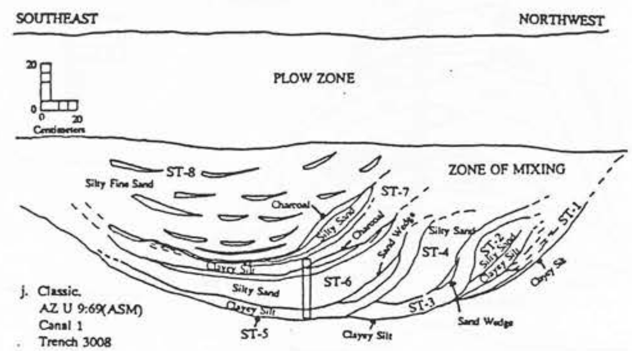


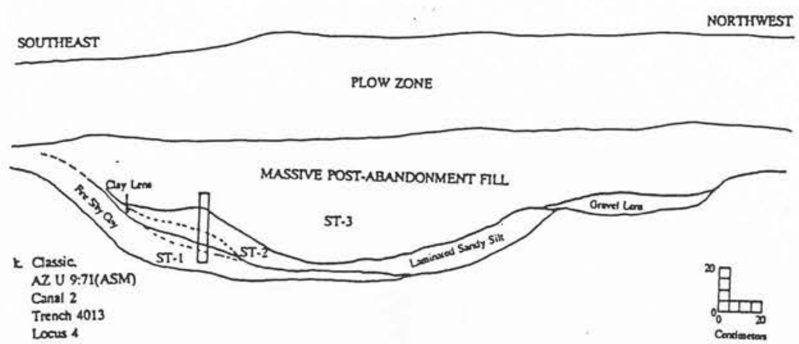
Figure 4C. (*Continues*)



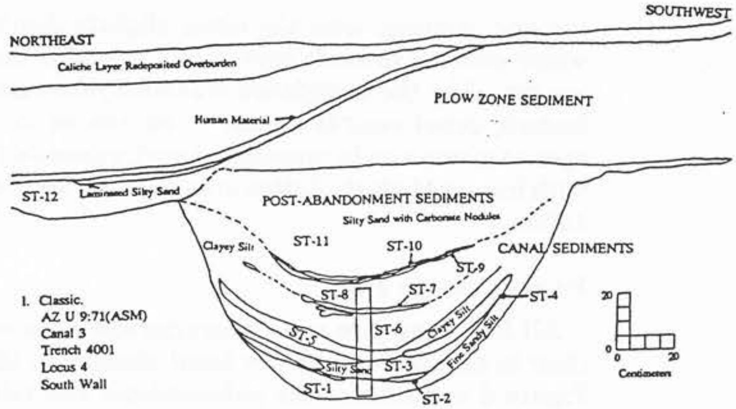
i. Late Sedentary/Early Classic.
AZ U 9:68 (ASM)
Canal 3
Trench 2068
Locus 2
South Wall



j. Classic.
AZ U 9:69(ASM)
Canal 1
Trench 3008
Locus 3
South Wall



k. Classic.
AZ U 9:71(ASM)
Canal 2
Trench 4013
Locus 4
South Wall



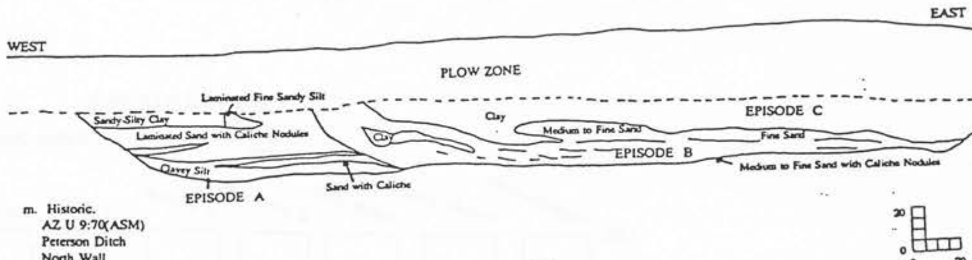


Figure 4E.

Figure 4. Individual canal cross sections and stratigraphic horizons from where ostracode samples were taken (a–m). Only the area of interest is reproduced in this article; for detailed canal stratigraphic description, see Ackerly and Martynec (1989).

Table IV. Generalized environmental conditions controlling nonmarine ostracode assemblages from Las Acequias Irrigation system in the Tempe Outer Loop, Tempe, Arizona.[a]

Species	Habitat	Permanence	Temperature	Salinity*	Chemistry*
Candona n. sp., cf. C. patzcuaro	Lake or pond	Permanent or ephemeral	Eurythermic	200–5000 ppm	Type II (eventually type III)
Limnocythere staplini	Lake or pond	Permanent or ephemeral	Eurythermic	500–75,000 ppm	Type II
Cypridopsis vidua	Lake, pond, spring or stream	Permanent or ephemeral	Eurythermic	100–4000 ppm	Types I and II
Ilyocypris bradyi	Stream or pond	Permanent or ephemeral	Eurythermic	100–4000 ppm	Types I and II
Darwinula stevensoni	Lake, stream, or spring	Permanent	Stenotopic ?	50–2000 ppm	Type I
Physocypria pustulosa	Lake or pond	Permanent or ephemeral	Thermophillic	100–600 ppm	Type I or II

[a] See Table III for definition of terms. (*Forester, personal communication, 1989).

ate and calcium, with the latter slightly dominant (Hem, 1985). This type I water evolved towards type II in the canals under evaporative conditions, as suggested by the abundance of *Limnocythere staplini*. *Darwinula stevensoni* in historic canal records appear to be related to human activity; although this species is common in unmodified environments, it is well known to be associated with human-disturbed sites in eastern Africa (Cohen, personal communication, 1992).

Paleoecologic Data

All fossil samples were characterized by a relatively low species diversity (four to six species) and low fossil abundance (50–360 specimens/g sediment). Figure 5 synthesizes the paleoecologic and relative abundance diagrams for each species present. Table V summarizes the four assemblages recognized from the diversity and entropy index profiles.

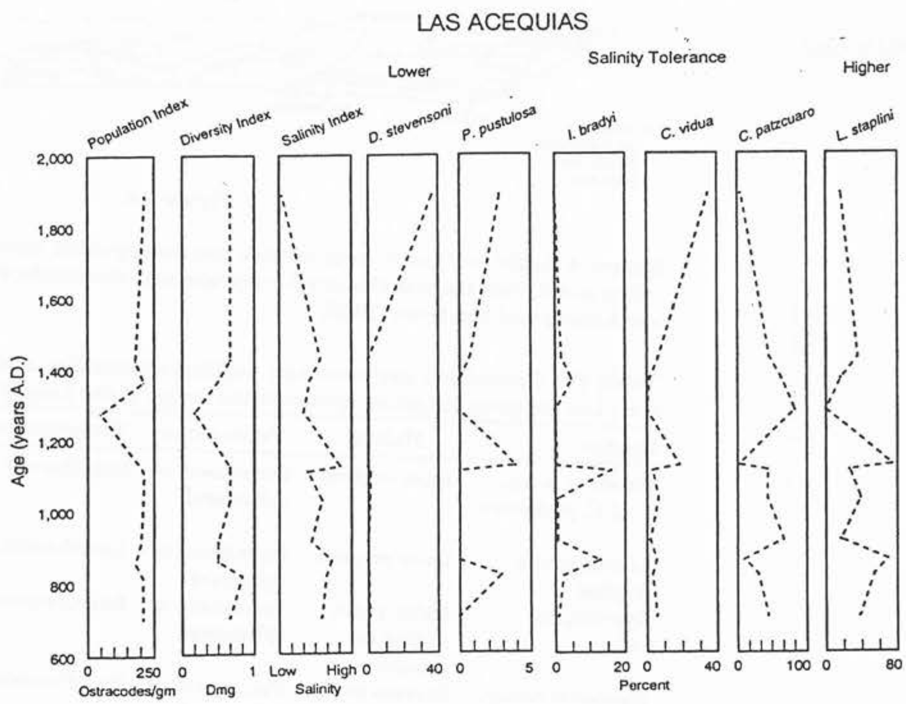


Figure 5. Ostracode paleoecology. The diversity index and entropy diagrams indicate the ostracode response to environmental changes derived from the relative abundance charts. The relative abundance diagrams are plotted according to the known salinity tolerances of the six species found in the irrigation system, with the lowest salinity tolerant species to the left and the highest salinity tolerant species to the right.

Table V. Ostracode assemblages present at Las Acequias irrigation system.[a]

Assemblage	Sample	L s	C p	C v	I b	P p	D s	Environment (Water Chemistry Type II)
I	F-700 S-577 S-924 F-777 F-779	1	2	3	4	5	6	Moderate salinity, slow flowing, short to moderate operational time waters
II	F-742 F-560 F-563 F-567 F-610 F-591 F-513	1	1	3	—	4	4	Low to moderate salinity, seepage, moderate to long operational time waters
III	F-573 F-575 F-582 S-1076 F-529 F-643 S-568 S-500	2	1	3	4	—	5	Low to moderate salinity, seepage or slow flowing to stagnant and long operational time waters
IV	F-778	3	5	2	—	4	1	Low salinity, flowing or seepage and long operational time waters; human disturbed environment

[a] See text for assemblage composition. Abbreviations: Ls = *Limnocythere staplini*, Cp = *Candona patzcuaro*, Cv = *Cypridopsis vidua* (a species known in human-disturbed waters), Ib = *Ilyocypris bradyi*, Pp = *Physocypria pustulosa*, Ds = *Darwinula stevensoni* (a species common in human-disturbed waters). Numbers indicate relative abundance, from (1) the most abundant to (6) the least abundant. Environmental interpretation based on Palacios-Fest (1989), derived from their relative abundances.

Paleohydrochemical Data

Canal ostracodes preserve an unaltered geochemical record which is unlikely to be altered through time. Figure 6 summarizes the shell chemistry record of Las Acequias canals during Hohokam and Historic operation. The three species used for this analysis, *L. staplini*, *Cypridopsis vidua*, and *Candona patzcuaro*, show similar trends. The fact that all three species show covariant Mg/Ca and Sr/Ca molar ratio trends indicates that the ostracode's uptake of ions in solution is not being masked by vital effects particular to an individual species (i.e., no biofractionation).

Well-defined covariant trends of Mg/Ca and Sr/Ca molar ratios are evident throughout the canals' history, suggesting that salinity rather than tempera-

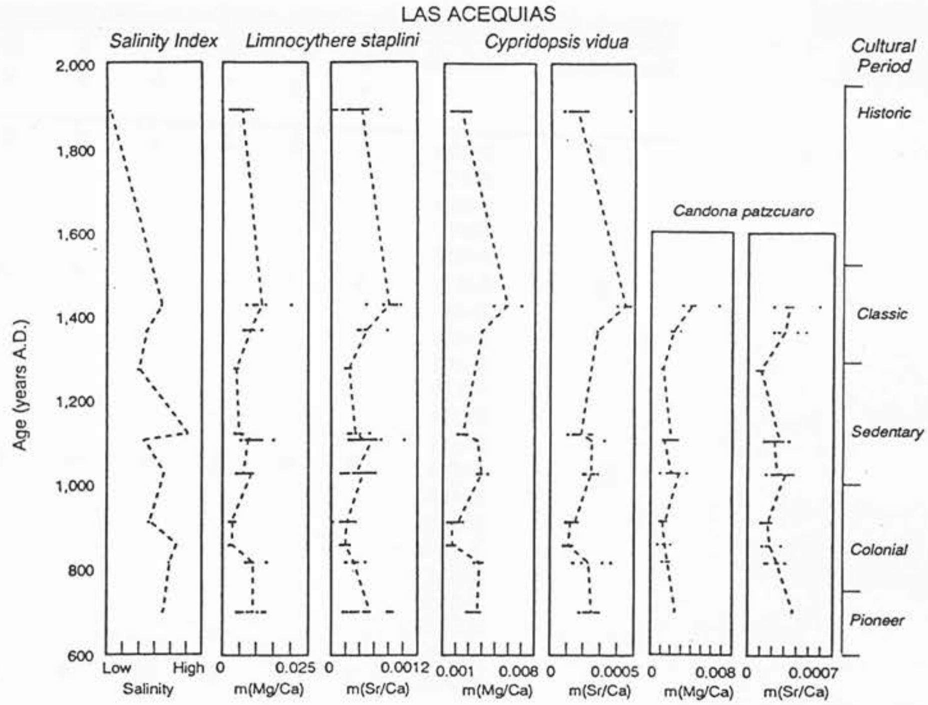


Figure 6. Ostracode paleohydrochemistry. The Mg/Ca and Sr/Ca ratios of each species used in this study indicate the salinization processes of the Hohokam canals through time. Notice the similarity of trends both between the trace metal curves and among species. Salinity (Sr/Ca molar ratio) appears to have affected ostracode occurrences and life whereas temperature (Mg/Ca molar ratio) variations show to be irrelevant; this is a typical situation in shallow water environments. The similarity among species indicates that environment is a major factor in ostracode trace metal uptake. However, different species show distinct trace element concentrations most likely due to biokinetic effects.

ture controlled the Mg^{2+} and Sr^{2+} concentration in ostracode valves. Alternating periods of low versus high Mg/Ca and Sr/Ca molar ratios are associated with changes in the concentrations of these ions in canal waters.

Trends in the Mg/Ca and Sr/Ca molar ratios generally correlate with those of the salinity index. However, significant exceptions are evident like a large salinity spike at about A.D. 1130 (Figures 6 and 7), which does not correlate with the trace element geochemistry. It is possible that departures between the inferred salinity index and the trace element trends mostly resulted from species occurrence and abundance. The fact that a species is present in a given site does not strictly imply that the environment was A or B, an assumption made in using the inferred salinity. The temporal boundaries between the four Hohokam cultural intervals are also shown on the trace element diagrams. During the Early Pioneer Period (pre A.D. 700; samples F-567 and F-573), trace elements suggest that water chemistry was dilute to moderately saline, although the paleoecologic data indicate moderate salinity only. Trace element geochemistry suggests that canal hydrochemical compositions became more dilute during the Colonial Period (A.D. 700–910; samples F-742 and S-924), then becoming more saline during the Early Sedentary Period (A.D. 910–1025; samples S-568 and S-577). The inferred salinity is consistent with the trace element trends, except for a small spike at about A.D. 840, which may result from species occurrence and abundance. During the Sedentary Period (A.D. 1025–1275; samples F-560, F-563, F-575, F-582, F-591, F-643, and F-700), no clear direction of variation is evident, although both the inferred salinity and the trace element records suggest increasing salinity after A.D. 1350. A drastic increase in water salinity is marked by both the inferred salinity and the trace elements during the Classic Period (A.D. 1275–1425; samples F529 and F-513). In historic times, both the paleoecologic and geochemical data suggest that canal water chemistry was more dilute (samples F-777, F-778, and F-779).

Paleoecologic Interpretation

Two hypotheses are drawn from the paleohydrochemical record of ostracode valves: first, the recognition of a paleoclimatic signature, which suggests that major climatic events were responsible for Hohokam activities and movements; second, the identification of human impact, which suggests that most of the paleohydrochemical trends resulted from canal operation.

The Las Acequias Hohokam irrigation system provides important paleoenvironmental information for understanding the human–environment relationship in southwestern North America. Throughout the operational history of the canals, episodes of water salinization and freshening are evident.

During the Early Pioneer (pre A.D. 700; samples F-567 and F-573), canals were operated under the influence of low to moderately saline type II waters. The assemblage was dominated by the co-occurrence of *L. staplini* and *C. patzcuaro*. The rarity of *Darwinula stevensoni* adults and absence of juveniles suggest that this species was flushed into the canals during headgate opening. Trace element concentrations from all three species (*L. staplini, C. patzcuaro,* and *C. vidua*) indicate moderately saline waters.

During the Colonial Period (A.D. 700–910; samples F-742 and S-924), a simultaneous decline occurred in ostracode diversity and abundance as well as in trace metal concentrations. These changes probably occurred as a result of either higher streamflows or the flooding of diluted canal waters (still within the range of type II waters). Higher streamflows are commonly associated with coarser sediments which in turn become a hazard to most ostracode species (see Table I for sediment description). Low trace metal concentrations suggest rapid water dilution. All three species show correlated decline in trace metal values.

Based on study of molluscs and seeds associated with canal deposits Miksicek (1989) concluded that the canals experienced pulses of flow probably in response to flooding during this time. Nials et al. (1989) and Gregory (1991) also reported evidence of intense flooding events in this area during the Colonial Period. As a whole, this body of evidence suggests that a strong climatic signature has been registered by both ostracode shell chemistry and the overall fossil record.

During the Early Sedentary Period (A.D. 910–1025; samples S-568 and S-577), higher trace metal concentrations and fossil data indicate that moderately concentrated type II waters reside in the canals. The occurrence of adults (only) of *I. bradyi* and *D. stevensoni* probably results from flushing by flowing waters into the system. The occurrence of *L. staplini* and the trace metal record suggest increasing evaporation. The canals appear to have operated under the influence of moderately saline, slow flowing type II waters for relatively short periods of time. *Candona patzcuaro* a species common in type III waters has a higher total dissolved solid (TDS) tolerance in type II waters (Table IV); furthermore, it is unlikely to expect some canals to evolve towards alkaline waters whereas all others evolve into Ca^{2+}- and $SO_4^=$-rich waters. The occurrence of abundant *Candona patzcuaro* juveniles and the appearance of *Ilyocypris bradyi* support this interpretation. Miksicek (1989) also concluded that canals were subject to short flooding periods during the early part of this interval, but [held pond water through its latter part. *Limnocythere staplini* and *Cypridopsis vidua* trace metal data indicate increasing evaporation within a wide range of fluctuation, a likely situation under periodic canal operation and water salinization.

During the Sedentary Period (A.D. 1025–1275; samples F-560, F-563, F-575, F-582, F-591, F-643, and F-700) paleoecologic and trace metal data demonstrate fluctuating salinity conditions within type II waters. The wide range in trace element concentrations suggest periodic water salinization within the interval. The interval is dominated by *L. staplini* and *C. patzcuaro* accompanied by *C. vidua* and *I. bradyi* suggesting that the canals operated under continuous seepage and flow conditions. *Cypridopsis vidua* and *Candona patzcuaro* show similar trends; however, *Limnocythere staplini* displays increasing evaporation, suggesting fluctuating periods of water salinization.

Towards the end of Hohokam occupation (Classic Period: A.D. 1275–1425; samples S-500, F-529, and F-513), trace metal and paleoecologic evidence mark a drastic increase in salinity within type II waters immediately after a dilution episode early in the period. During this time, canals were mostly inhabited by *L. staplini* and *C. patzcuaro* with minor occurrence of *C. vidua,* suggesting that these canals underwent increasing salinity, probably beyond the known salinity tolerance of *C. vidua* (4000 ppm). *C. vidua* occurrence probably resulted from headgate opening and survival in the canals until salinity reached too high a level. The high Sr/Ca ratios shown by these three species towards the end of the Classic Period support this interpretation.

The Mg/Ca and Sr/Ca values reached maxima in all species, suggesting input of saline waters into the canals in response to increasing regional evaporation rates. The high Mg^{2+} and Sr^{2+} content in ostracode valves of this age is consistent with previous reports of high temperature and dry conditions probably responsible for Hohokam abandonment of the area during the "Anasazi Warm Period" characterized by droughts and high temperatures (Davis, 1992).

During historic time (A.D. 1885–1892; samples F-777, F-778, and F-779), intensive irrigation was practiced in this area, fostering dramatic rises in groundwater levels in spite of the higher permeability of soils in the southern portions of the study area (Ackerly, 1989d). Groundwater levels ranged from 0.6 to 2.1 m (2–7 ft) below the surface in the Tempe-Mesa area prior to significant groundwater pumping. However, at the turn of the century, the water table declined from 7.6 to 15.2 m (25–50 ft) beneath the surface. The salinity gradient in the study area ranged from 800 to 1200 ppm and the total dissolved solids (TDS) at the Salt River averaged about 1100 ppm by 1900 (Ackerly, 1989d). The *Cypridposis vidua*/*Darwinula stevensoni* dominant assemblage indicates long periods of canal operation. The occurrence of *Physocypria pustulosa* (with a maximum known salinity tolerance of 600 ppm TDS; Forester, personal communication, 1988) suggest dilute water composition whereas *C. vidua* suggests human-influenced environments, if Taylor's explanation for *C. ockeechobei* can be applied to other species of the same genus (Taylor, 1991).

An alternative explanation for changes in canal hydrology and chemistry is that changes in canal water as revealed by ostracodes were caused by humans. The chemistry of the water in the canals was probably modified by Hohokam activity on the input water. Shell chemistry variations of nonmarine ostracodes may result from continuous operation of the irrigation canals instead of climate and, hence, provide a clue to recognize soil salinization and possibly degradation caused by humans.

The extent of soil degradation due to prehistoric irrigation along the Salt and Gila River valleys is not easily discernible through interpretation of traditional physical features within the geologic record (Huckelberry, 1992). The impact of nested irrigation canals is a significant source of soil degradation in several ways (i.e., soil leaching, loss of soil fertility, canal and field siltation, or water and soil alkalinization and salinization), and could result in the abandonment of agricultural fields and irrigation canals.

Human-disturbed environments are sometimes characterized by increased ostracode abundances associated with increased alkalinity and salinity (Taylor, 1991). Diversity and abundance may increase as a result of artificially induced water input into the canals. It is likely that some of the flood irrigation techniques employed by the Hohokam modified not only soil chemical properties but also effected canal water chemistry. Based on the ostracode assemblages and shell chemistry, canal hydrochemistry fluctuated widely within the range of type II waters.

The covariance of Mg/Ca and Sr/Ca ratios with the salinity index suggests that ostracode diversity corresponds with variations in water chemistry (Figure

6). The hydrochemical spectra shown by the trace element trends were induced by the Hohokam in three possible ways. First, salinization would result from long-term operation (decades) of the main canals. Under these circumstances a salt crust was likely to form on the canal surface; main canals were not cleaned as frequently as the distribution and field canals were. Thus, if these canals were used once again, the salt crust was dissolved, and solutes were transported to the agricultural fields. Second, salinization would result from short-term canal operation of the nested system (1 season or 1 year), mimicking a climatic effect by introducing extensive soil salinization. Salinization from small canals was a short but consistent event which was induced seasonally despite canal cleansing. Even assuming that canal waters were relatively dilute, their final evaporation in the agricultural fields was responsible for soil salinization. Third, continuous canal operation, headgate opening, flooding, and canal cleansing could flush dissolved salts to the agricultural fields. Canals were subjected to continuous flooding and drying, which in turn induced hydrochemical dilution and concentration. Thus, it is possible that canal salinization occurred at different rates depending on canal type, depth, and length. Water chemistry became more saline in irrigation canals towards their distal end, and, in the shallower lateral canals as well, as shown by ostracode paleoecologic and trace metal data from the lateral canals.

DISCUSSION

Two main aspects of the data presented in this article are discussed: One is the significance of comparing geochemical data from three ostracode species from the same site with each other. The other is the application of this information to geoarchaeological research and its implications for understanding the human/environment relationship. Interspecific geochemical information is discussed first.

The similarity of geochemical profiles among species throughout the canals' history provides significant evidence to argue that water chemistry is the dominant environmental factor controlling ostracode mineral uptake. To what extent biofractionation can effect individual species shell chemistry has been a subject of debate (Turpen and Angell, 1971; Chivas et al., 1983). Turpen and Angell (1971) results suggest that despite the species involved, shell chemistry reflects water chemistry at the time of calcification. However, it is also apparent that, although the trace element/calcium ratios are parallel, their absolute values differ among species, because the species life cycle controls the calcite precipitation rate.

Forester (personal communication, 1989) suggested that ostracode life cycles range from 1 to 3 months, depending on species. However, one given species can complete its cycle very fast if nothing inhibits egg hatching. *Limnocythere staplini's* life cycle is usually about 1 month long whereas *Cypridopsis vidua* and *Candona patzcuaro's* life cycles are most commonly about 3 months long each, with slight differences possible between the two species. The distinctive life cycles of these species may contribute to a species-specific calcite precipitation rate. Turpen and Angell (1971) demonstrated that juvenile individuals precipitate their valves faster than the preadult/adult transition, which may account for the higher Mg^{2+} content found in juvenile specimens. However, these authors speculated that the Mg^{2+} concentration may vary among species. Palacios-Fest (unpublished data) found that several species (*Limnocythere staplini, Limnocythere ceriotuberosa*, and *Candona patzcuaro*) precipitate their valves within 60 min. Trace element concentrations observed in the present study from the three species certainly confirm Turpen and Angell's (1971) speculation and demonstrate that the combined analysis of several species present in the same locality provide substantial information for paleoenvironmental reconstructions.

The application of ostracode geochemistry to geoarchaeology will prove to be critical in the search for understanding the human/environment relationship. Nonmarine ostracode shell chemistry provides information on the water "quality" of irrigation canals constructed and used by ancient cultures of the world. In previous sections, it was shown how climate may have imprinted its signature and what the signature may have been if it were produced by human activity.

Table VI summarizes Las Acequias canals' paleohydrochemical history. All except two climatic events, large enough not to be masked by human activity, where disguised because of Hohokam agriculture. Although agricultural soils do not preserve any physical evidence of chemical modifications, ostracode shell chemistry can record these effects in canals near the fields. However, rigorous interpretations will require more accurate stratigraphic control for canal samples. The ostracode chronology provides a context in which to reconstruct canal water chemistry and to speculate about the climatic vs. human cause of those changes. From the climatic signature discussed in this article, it is clear that at least two major natural events affected Hohokam life between A.D. 700 and 1450. These are, on the one hand, a major water freshening between A.D. 855 and 910, consistent with Nials et al. (1989) and Ely's (1992) evidence of periods of increased flood frequency prior to A.D. 900. On the other hand, the ostracode record also indicates a period of increasing evaporation between A.D. 1275 and 1425 consistent with Masse's (1991) and Petersen's (1988, 1992) evidence of depressed effective precipitation and Ely's (1992) record of diminished flood frequency in the Hohokam environment in south-central Arizona.

Other evidence of environmental change derived from ostracode shell chemistry may have been generated from agricultural practices. Ostracode data indicate a period of fluctuating hydrochemistry (shown by the wide variation of values within samples). In contrast, evidence of increasing salinization towards the end of Hohokam occupation is suggested by the high trace element concentrations in ostracode valves. Hohokam irrigation may have introduced this artificial trademark to the environment.

Table VI. Summary of the paleohydrochemical and paleoecologic history of the Hohokam canal system.

Age (years A.D.)	Hohokam Cultural Period	Paleohydrochemical History
Pre-700	Early Pioneer	Canals were operated under low to moderate saline water conditions
700–910	Colonial	Canals were used while water chemistry was subject to rapid dilution and remained diluted between A.D. 855–910. Water dilution probably was as low as 600 ppm TDS
910–1025	Early Sedentary	Canal waters initiated an increasing salinity process probably in response to a decrease in effective precipitation; probably salinization increased around 2000 ppm TDS
1025–1275	Sedentary	Canal water chemistry fluctuates widely probably in response to alternating flooding and evaporating events; apparently a major period of human disturbance; water salinity fluctuated between 1000 and 2000 ppm TDS
1275–1425	Classic	Canal water chemistry reaches its maximum concentration after a catastrophic flood maybe before A.D. 1350; agricultural fields salinization occurs in response to severe drought and possibly excessive human disturbance; area must be abandoned; at this time salinization probably reached values higher than 4000 ppm TDS
1885–1892	Non-Hohokam Cultural Historic Period	Peterson Ditch held dilute waters probably under 1000 ppm TDS; intense human disturbance is marked by the abundance of *Cypridopsis vidua* and *Darwinula stevensoni*

In conclusion, the ostracode stratigraphy of Hohokam canals records water chemistry changes correlative with human activity although climate certainly left its imprint. In the future it will be necessary to analyze several samples along the same canal and to compare the shell chemistry patterns generated from them. Also sampling strategies for ostracode samples should include sampling intervals within a single trench, collection of sediments where abundant *in situ* plant debris occurs, and obtaining main canal samples for paleoclimatic evidence.

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REFERENCES

Ackerly, N.W. (1989a). The Study of Canals within the Las Acequias Irrigation System. *In* N.W. Ackerly and T. K. Henderson, Eds., *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace: Perspectives on Hohokam Irrigation Cycles,* pp. 1–6. Flagstaff: Northland Research.

Ackerly, N.W. (1989b). A History of Research on Hohokam Irrigation Systems. *In* N.W. Ackerly and T.K. Henderson, Eds., *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace: Perspectives on Hohokam Irrigation Cycles,* pp. 7–17. Flagstaff: Northland Research.

Ackerly, N.W. (1989c). Paleohydrodynamic Impacts on Hohokam Irrigation Systems. *In* N.W. Ackerly and T.K. Henderson, Eds., *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace: Perspectives on Hohokam Irrigation Cycles;* pp. 46–83. Flagstaff: Northland Research.

Ackerly, N.W. (1989d). Changes in the study area during the historic period. *In* N.W. Ackerly and T. K. Henderson, Eds., *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace: Perspectives on Hohokam Irrigation Cycles,* pp. 18–45. Flagstaff: Northland Research.

Ackerly, N.W., and Martynec, R.J. (1989). Descriptive Characteristics of Canals within the Las Acequias Irrigation System. *In* N.W. Ackerly and T.K. Henderson, Eds., *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace: Perspectives on Hohokam Irrigation Cycles.* Chap. 6, pp. 94–145. Flagstaff: Northland Research.

Bodergat, A.M. (1983). Les Ostracodes, Temoins de Leur Environnement: Approche Chimique et Ecologique en Milieu Lagunaire et Oceanique. *Documents des Laboratoires de Geologie de la Faculté des Sciences de Lyon* **88**, 1–246.

Chivas, A.R., De Deckker, P., and Shelley, J.M.G. (1983). Magnesium, Strontium and Barium Partitioning in Nonmarine Ostracode Shells and their Use in Paleoenvironmental Reconstruction: A Preliminary Study. In R.F. Maddocks, Ed., *Applications of Ostracoda,* pp. 238–249. Houston: University of Houston, Geoscience.

Chivas, A.R., De Deckker, P., and Shelley, J.M.G. (1985). Strontium Content of Ostracods Indicate Lacustrine Paleosalinity. *Nature* **316**, 251–253.

Chivas, A.R., De Deckker, P., and Shelley, J.M.G. (1986a). Magnesium and Strontium in Non-Marine Ostracod Shells as Indicators of Paleosalinity and Paleotemperature. *Hydrobiology* **143**, 135–142.

Chivas, A.R., De Deckker, P., and Shelley, J.M.G. (1986b). Magnesium Content of Non-marine Ostracod Shells: A New Palaeosalinometer and Palaeothermometer: *Palaeogeography, Palaeoclimatology, Palaeoecology* **54**, 43–61.

Cordell, P.S. (1984). *Prehistory of the Southwest.* Academic Press, Orlando: Academic Press.

Crown, P.L. (1991). The Hohokam: Current Views of Prehistory and the Regional Systems. *In* P.L. Crown and W.J. Judge, Eds., *Chaco and Hohokam: Prehistoric Regional Systems in the American Southwest,* pp. 135–157. Santa Fe: SAR Press.

Davis, O.K. (1992). The Correlation of Summer Precipitation in the Southwestern United States with Isotopic Records of Solar Activity during the Medieval Warm Period. Manuscript in possession of author.

De Deckker, P., and Forester, R.M. (1988). The Use of Ostracodes to Reconstruct Paleoenvironmental Records. *In* P. De Deckker, J.P. Colin, and J.P. Peypouquet, Eds., *Ostracoda in the Earth Sciences,* pp. 175–200. Amsterdam: Elsevier.

De Deckker, P., Chivas, A.R., and Shelley, J.M.G. (1988). Paleoenvironment of the Messinian Mediterranean "Lago Mare" from Strontium and Magnesium in Ostracode Shells. *Palaios* **3**, 352–358.

Ely, L.L. (1992). Large Floods in the Southwestern United States in Relation to Late-Holocene Climatic Variations. Ph.D. Dissertation, Department of Geosciences, University of Arizona, Tucson.

Eugster, H.P., and Hardie, L.A. (1978). Saline Lakes. *In* A Lerman, Ed., *Lakes: Chemistry, Geology, Physics,* pp. 237–293. New York: Springer-Verlag.

Fish, S.K., and Nabhan, G.P. (1991). Desert as Context: The Hohokam Environment. *In* G.J.

Gumerman, Ed., Exploring the Hohokam: Prehistoric Desert Peoples of the American Southwest, pp. 29–60. Albuquerque: Amerind Foundation.

Forester, R.M. (1991). Ostracode Assemblages from Springs in the Western United States: Implications for Paleohydrology. *Memoirs of the Entomological Society of Canada* **155**, 181–200.

Gish, J.W. (1989). A Pollen Evaluation of the Las Acequias Canal System. *In* N.W. Ackerly and T.K. Henderson, Eds., *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace: Perspectives on Hohokam Irrigation Cycles,* pp. 279–332. Flagstaff: Northland Research.

Graybill, D.A. (1985). Paleoclimate of the Hohokam Area: Problems and Prospects: *In* A. Dittert and D. Dove, Eds., *Proceedings of the 1983 Hohokam Symposium,* pp. 29–44. Tucson: Arizona Archaeological Society. Occasional Paper 2.

Graybill, D.A., and Nials, F.L. (1989). Aspects of Climate, Streamflow, and Geomorphology Affecting Irrigation Systems in the Salt River Valley. *In* D.A. Graybill et al., Eds., *The 1982–1984 Excavations at Las Colinas: Environment and Subsistence,* pp. 5–23. Tucson: Arizona State Museum Archaeological Series No. 162.

Gregory, D.A. (1991). Form and Variation in the Hohokam Settlement Patterns. *In* P.L. Crown and W.J. Judge, Eds., *Chaco and Hohokam: Prehistoric Regional Systems in the American Southwest,* pp. 159–193. Santa Fe: SAR Press.

Gumerman, G.J. (1991). Understanding the Hohokam. *In* G.J. Gumerman, Ed., *Exploring the Hohokam: Prehistoric Desert Peoples of the American Southwest,* pp. 1–27. Albuquerque: Amerind Foundation.

Haury, E.W. (1945). The Excavation of Los Muertos and Neighboring Ruins in the Salt River Valley, southern Arizona. *Peabody Museum of American Anthropology* **24**, 1–223.

Hem, J.D. (1985). Study and Interpretation of the Chemical Composition of Natural Water. USGS Water Supply Paper 2254. Washington, D.C.: U.S. Geological Survey.

Henderson, T.K. (1989). The Chronology of the Las Acequias Canals. *In* N.W. Ackerly and T.K. Henderson, Eds., *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace: Perspectives on Hohokam Irrigation Cycles,* pp. 184–199. Flagstaff: Northland Research.

Huckleberry, G. (1992). Soil Evidence of Hohokam Irrigation in the Salt River Valley, Arizona. *Kiva* **57**, 237–249.

Katzer, K.L. (1989a). The Geological and Cultural Sediments of the Tempe Outer Loop Corridor. *In* N.W. Ackerly and T. K. Henderson, Eds., *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace: Perspectives on Hohokam Irrigation Cycles,* pp. 200–221. Flagstaff: Northland Research.

Katzer, K.L. (1989b). The Hydrologic Characteristics of the Las Acequias Canals. *In* N.W. Ackerly and T.K. Henderson, Eds., *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace: Perspectives on Hohokam Irrigation Cycles,* pp. 222–234. Flagstaff: Northland Research.

Martin, P.S., and Plog, F. (1973). *The Archaeology of Arizona: A Study of the Southwest Region.* Garden City, N.Y.: Natural History Press.

Masse, W.B. (1991). The Quest for Subsistence, Sufficiency and Civilization in the Sonoran Desert. *In* P.L. Crown and W.J. Judge, Eds., *Chaco and Hohokam: Prehistoric Regional Systems in the American southwest,* pp. 195–223. Santa Fe: SAR Press.

Miksicek, C.H. (1989). Snails, Seeds and Charcoal: Macrofossils from the Las Acequias Canal System. *In* N.W. Ackerly and T.K. Henderson, Eds., *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace: Perspectives on Hohokam Irrigation Cycles,* pp. 235–262. Flagstaff: Northland Research.

Nials, F.L., Gregory, D.A., and Graybill, D.A. (1989). Salt River Streamflow and Hohokam Irrigation Systems. *In* C.A. Heathington and D.A. Gregory, Eds., *The 1982–1984 Excavations at Las Colinas: Environment and Subsistence,* pp. 59–76. Tucson: Arizona State Museum Archaeological Series 162.

Palacios-Fest, M.R. (1989). Late-Holocene Ostracodes as Hydrochemical Indicators in the Phoenix Basin. *In* N.W. Ackerly and T.K. Henderson, Eds., *Prehistoric Agricultural Activities on the Lehi-Mesa Terrace: Perspectives on Hohokam Irrigation Cycles,* pp. 263–278. Flagstaff: Northland Research.

Petersen, K.L. (1987). Implications of Anasazi Impact on the Landscape. *In* K.L. Petersen and J.D. Orcutt, Eds., *Dolores Archaeological Program: Supporting Studies: Settlement and Environment*, pp. 147–184. Washington, D.C.: U.S. Department of the Interior, Bureau of Reclamation.
Petersen, K.L. (1988). Climate and the Dolores River Anasazi. University of Utah Anthropology Paper No. 113. Provo: University of Utah.
Petersen, K.L. (1992). A Warm and Wet Little Climatic Optimum in the Southern Rocky Mountains, U.S.A. Abstract. Workshop Medieval Warm Period, Tucson.
Péwé, T.L. (1978). Terraces of the Lower Salt River Valley in relation to the Late Cenozoic History of the Phoenix Basin, Arizona, *In* D.M. Burt and T.L. Péwé (Eds.), *Guidebook to the Geology of Central Arizona*. Special Paper No. 2. Tucson: Arizona Bureau of Geology and Mineral Technology.
Pokorny, V. (1978). Ostracodes. *In* B.U. Haq and A. Boersma, Eds., *Introduction to Marine Micropaleontology*, pp. 109–150. Amsterdam: Elsevier.
Ruff, P.F. (1971). *A History of the Salt River Channel in the Vicinity of Tempe, Arizona, 1868–1969*. Phoenix: Arizona Historical Foundation.
Sohn, I. (1958). Chemical Constituent of Ostracodes; Some Applications to Paleontology and Paleoecology. *Journal of Paleontology* **32,** 730–736.
Taylor, L.C. (1991). The distribution of *Cypridopsis okeechobei* in the Duffins Creek-Rouge River Drainage Basins and Its Potential as an Indicator of Human Disturbance. Manuscript in possession of author.
Turpen, J.B., and Angell, R.W. (1971). Aspects of Moulting and Calcification in the Ostracod *Heterocypris*. *Biological Bulletin* **140,** 331–338.
Waters, M. (1988). The Impact of Fluvial Processes and Landscape Evolution on Archaeological Sites and Settlement Patterns along the Santa Cruz River, Arizona. *Geoarchaeology* **3,** 205–219.

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