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SIGNIFICANCE OF OSTRACODE STUDIES IN GEOARCHÆOLOGY: EXAMPLES FROM THE UNITED STATES SOUTHWEST

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ABSTRACT

Ostracodes are microcrustaceans that inhabit almost any aquatic system. Over the past 12 years, these microcrustaceans have provided valuable information about the hydraulics and chemistry of aquatic systems related to human activity (e.g., irrigation canals, reservoirs) in southwestern North America. This study synthesizes the results obtained in the last decade and suggests how ostracodes may be used in other regions around the world.

RESUMEN

Los ostrácodos son microcrustáceos que habitan casi cualquier ambiente acuático. Durante los últimos 12 años, estos organismos han proporcionado valiosa información sobre las características hidráulicas e hidrodinámicas de sistemas acuáticos relacionados con actividades humanas (e.g., canales de irrigación, aguajes) en el sudoeste norteamericano. Este trabajo sintetiza los resultados obtenidos durante la última década y sugiere cómo podrían ser utilizados en otras regiones del mundo.

Understanding environmental impact by humans in the past has generated a significant number of studies in geoarchæology. The focus of this study is to document some of the best examples of ostracodes (microcrustaceans) as a proxy measure of environmental impact on Precolumbian irrigation systems in the U.S. Southwest, mostly those built by the Hohokam (A.D. 100–A.D. 1450) and their ancestors, the Early Agriculturalists (1900 B.C.–A.D. 100).

Ostracodes are microcrustaceans with a low-magnesium calcite (calcium carbonate) carapace (Figure 1). The carapace consists of two valves (right and left) joined by a hinge on its dorsal portion (Pokorný 1978). The ostracode life cycle consists of nine stages, each involving shedding an exoskeleton before forming a new one. This process takes less than one hour, assuming that a comparison with decapod (crabs) growth is valid (personal observation at a crab farm 1990). The valves are the only parts that are preserved in the geologic record, and thus they can be used for paleontological, paleoecological, and geoarchæological investigations. The species genotype and the environment (phenotype) control the shell morphology and ornamentation. Therefore, a single species may show wide variability that

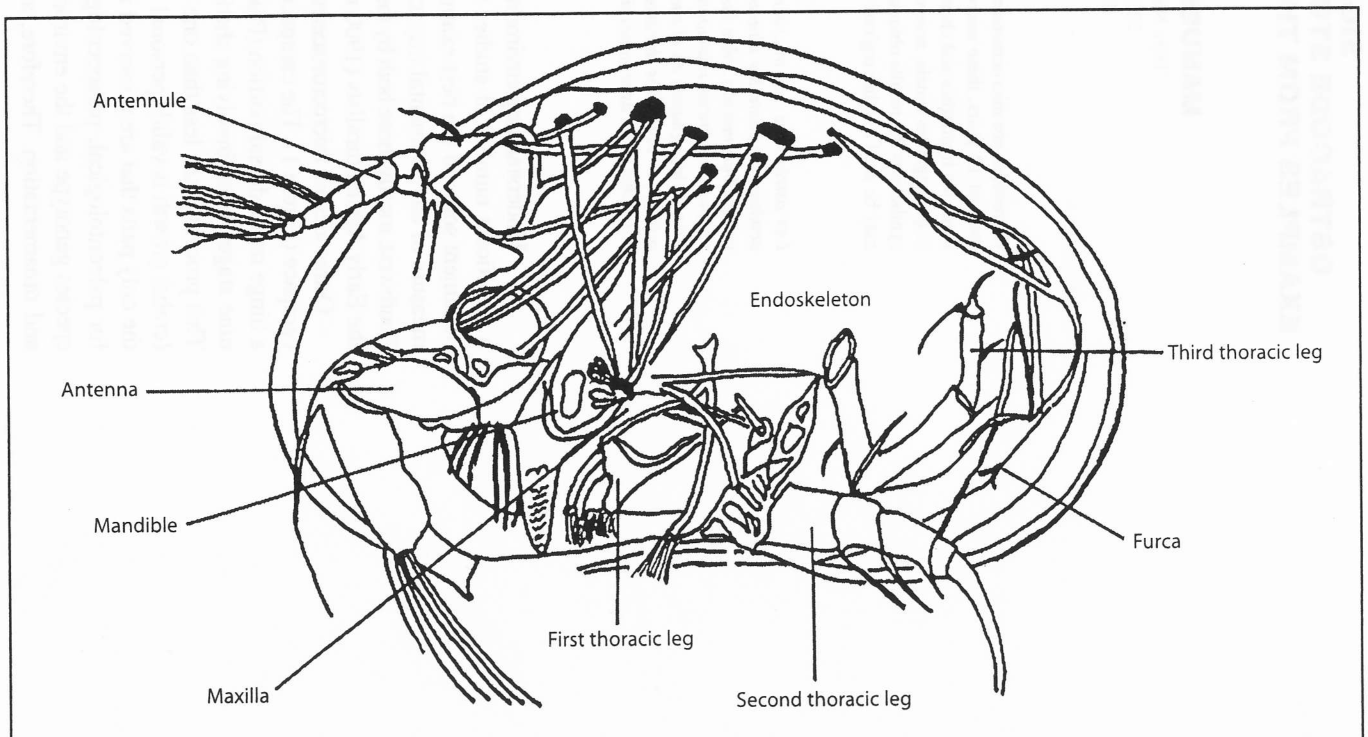


Figure 1. Schematic showing some general characteristics of ostracodes. Notice the arrangement of the dorsal muscle scars (black areas below dorsal margin) and their function in *Cypridopsis vidua* (Muller). Modified from Smith (1965).

may be both very complex (complicating species recognition) and useful for determining the ecology of the site where a given population lived. Ostracodes generally range in size between 0.5 and 2 mm, but some larger species exist (Pokorný 1978).

Ostracodes inhabit marine and nonmarine aquatic systems. Continental or nonmarine ostracodes occur both in fresh and saline waters that are well oxygenated (Pokorný 1978) such as lakes, ponds, wetlands, springs, and streams. These organisms may be eurytopic (tolerating a wide range of environmental conditions) or stenotopic (having restricted tolerance). They respond directly to temperature, salinity, water chemistry, light penetration, and sediment texture (Cohen 1986; Danielopol et al. 1985; Keen 1975; Kotzian 1974; Mourguiart et al. 1986). Most nonmarine forms have a smooth carapace, but some may develop ornamentation in response to water chemistry (Delorme 1969). Species adapted to coarse sediments usually are robust (e.g., *Cypridopsis vidua*; Henderson 1990); however, shell thickness may be controlled by other factors such as water chemistry (ecophenotypical) and predation (selective). Carbonel et al. (1988) and Holmes et al. (1992) suggest that ostracodes respond to lateral zonation of the substrate (Figure 2).

Continental ostracodes are adapted to different water chemistries, and many species are sensitive to chemical changes (Figure 3). For example, Palacios-Fest (1994) related the occurrence of some species in irrigation canals to one or more of the three main water pathways recognized by Eugster and Hardie (1978):

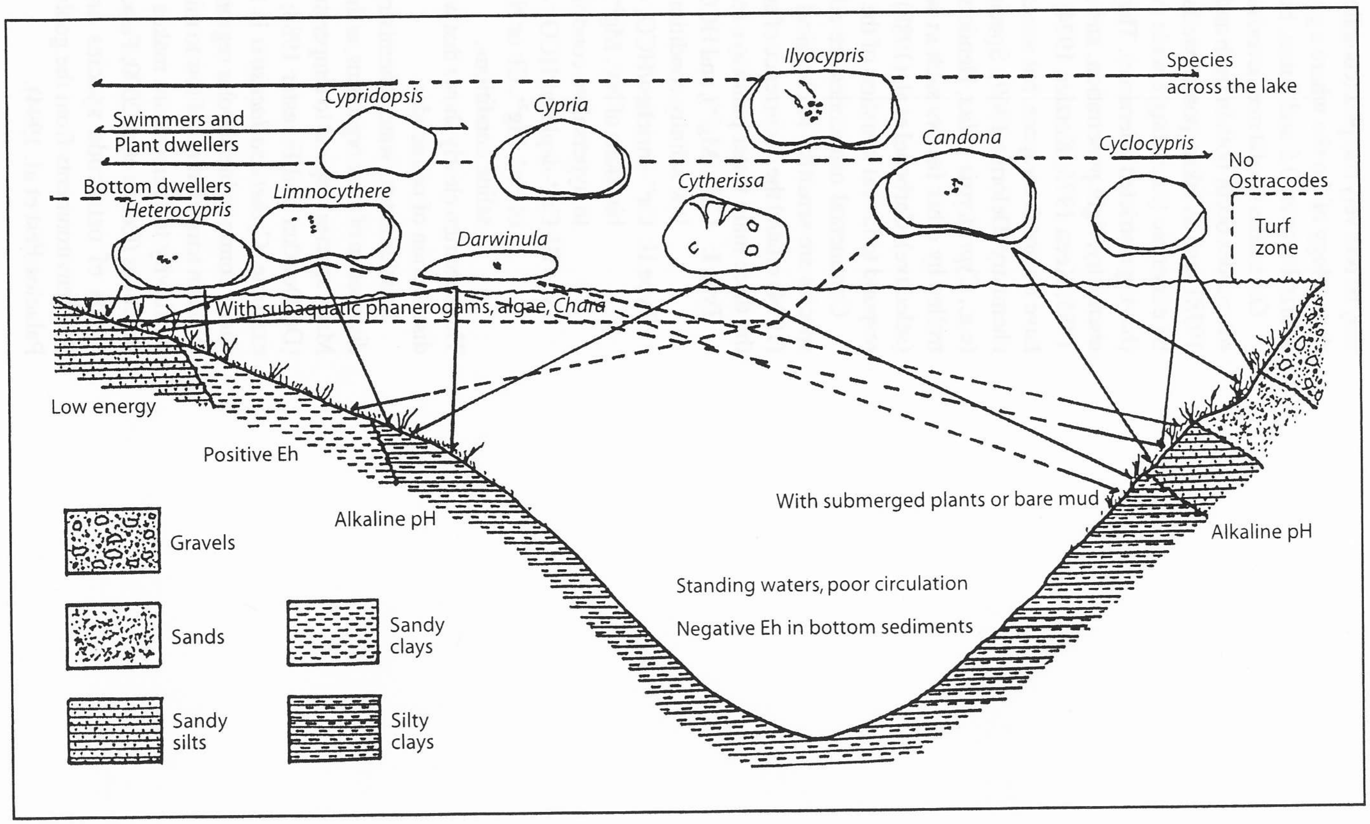
Type I: Ca^{2+}, (Mg^{2+}), and HCO_3^--dominated water; typically freshwater or very low salinity conditions.

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

Type III: Ca^{2+}-depleted/HCO_3^--enriched water; usually containing combinations of Na^+, Mg^{2+}, Cl^- or Na^+, Mg^{2+}, SO_4^{2-}; ranges from low salinity to hyper saline conditions.

This spectrum clearly shows that water chemistry plays a major role in the geographic distribution of ostracodes.

In addition to water chemistry, temperature is another factor that affects the distribution of these organisms, as the latitudinal distribution of ostracodes demonstrates. Many species respond to temperature through both reproductive and survival ability (De Deckker and Forester 1988; Delorme and Zoltai 1984; Forester 1987). For example, *Cytherissa lacustris* is limited to water temperatures lower than 23°C, and is common in subpolar regions, whereas *Limnocythere bradburyi* is restricted to warm temperatures of low to mid-latitudes (Delorme 1978; Forester 1985). Their sensitivity to temperature makes ostracodes very useful for paleoclimate reconstructions (Cohen et al. 2000; Palacios-Fest et al. 2002). Once the ecological requirements of ostracode species are determined, it is possible to reconstruct paleoenvironments from the geologic record (Delorme 1969; Holmes et al. 1992; Palacios-Fest et al. 1994).


Species
across the lake
Ilyocypris
Cypridopsis
Cypria
Swimmers and
Plant dwellers
Candona
Cyclocypris
No
Ostracodes
Bottom dwellers
Heterocypris
Limnocythere
Cytherissa
Turf
zone
Darwinula
With subaquatic phanerogams, algae, Chara
Low energy
Positive Eh
Alkaline pH
With submerged plants or bare mud
Alkaline pH
Gravels
Standing waters, poor circulation
Negative Eh in bottom sediments
Sands
Sandy
clays
Sandy
silts
Silty
clays

Using the chemical composition of ostracode valves, Palacios-Fest (1996) and Palacios-Fest and Dettman (2001) designed regression models to calculate the water temperature at which ostracodes calcify their low-magnesium calcite valves. The rhomboidal structure of the calcite lattice allows Mg to replace Ca, a process that is directly related to water temperature. De Legarra et al. (1985) demonstrated that Mg is incorporated into the hemolymph of some crustaceans *(Procambarus clarkii)* in response to ambient temperature. Mg enters calcite as a trace element. To calculate water temperatures using coefficients, it is necessary to measure the concentrations of Mg and Ca in ostracode valves by means of inductively coupled plasma mass spectrometry (ICP-MS) (Palacios-Fest 1996; Palacios-Fest and Dettman 2001).

Another method for quantifying ambient characteristics where ostracodes grow involves stable isotope analysis. Carbon and oxygen isotopes in ostracode valves are in thermodynamic equilibrium with the host water. The $^{18}O/^{16}O$ ratios in ostracode valves are related to equilibrium constants that are a function of temperature; in a similar way, this relation exists between inorganic carbonates and water (Siegenthaler and Eicher 1986). It is impossible, however, to measure water temperature directly from the $^{18}O/^{16}O$ ratio in ostracodes because additional variables control evapotranspiration/condensation in water and metabolic processes in the organisms (Palacios-Fest et al. 1994). Metabolic processes and other external factors also affect the $^{13}C/^{12}C$ ratios from ostracode valves, thus complicating interpretations and resulting in unreliable data (Palacios-Fest et al. 1994).

One of the most intriguing questions is how ostracodes and their shell chemistry reflect environmental conditions (Figure 4). A more significant question for geoarchæological research is how ecological faunal assemblages may be used to distinguish climatic from anthropogenic impacts.

The use of ostracodes in geoarchæology is neither new nor limited to North America; a significant list of publications on research conducted in Europe and the Middle East exists but is not the focus of this paper. Examples from across the Atlantic Ocean include Boyd (1981), who presented one of the earliest and more valuable studies on ostracodes in geoarchæology by documenting anthropogenic impact on the estuaries of the Fleet and Thames rivers during the medieval period; and Soter et al. (2001), who conducted a paleoenvironmental study in the Helike Delta, Gulf of Corinth, Greece showing how ostracodes indicate an upward transition from marine to lacustrine/ lagoonal conditions, suggesting lagoonal boundaries in Classic times. In this paper,

Figure 2. Ostracode distribution in a hypothetical lake as a response to physical, chemical, and biological parameters. Notice that the genera presented in this diagram are random examples used to illustrate the organisms' preferences. Solid lines (→) indicate areas of occurrence in several lakes. Dashed lines (- - -) suggest other areas where ostracodes may occur. Although ostracodes are not common in the turbulence zone, some interstitial species may survive but are not preserved in the fossil record. Information compiled from Delorme 1969, 1978; Delorme and Zoltai (1984).

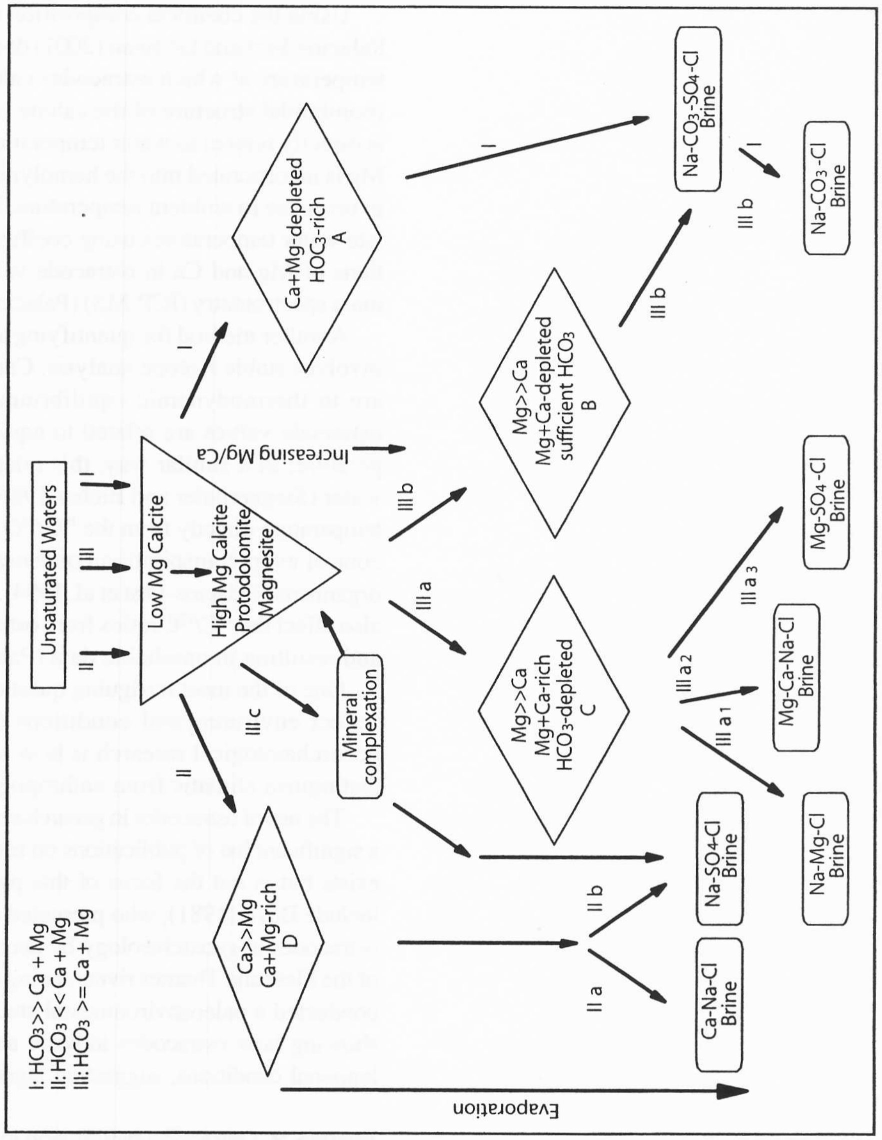


Figure 3. Flow diagram showing the evolution of freshwater bodies until they become brines. The triangle represents the state of initial saturation during the chemical evolution process; diamonds represent the four classic types of chemical composition of freshwater bodies where ostracodes occur. Usually, brines lack ostracodes (salinity is too high). For details see Eugster and Hardie (1978). Modified from Eugster and Hardie (1978).

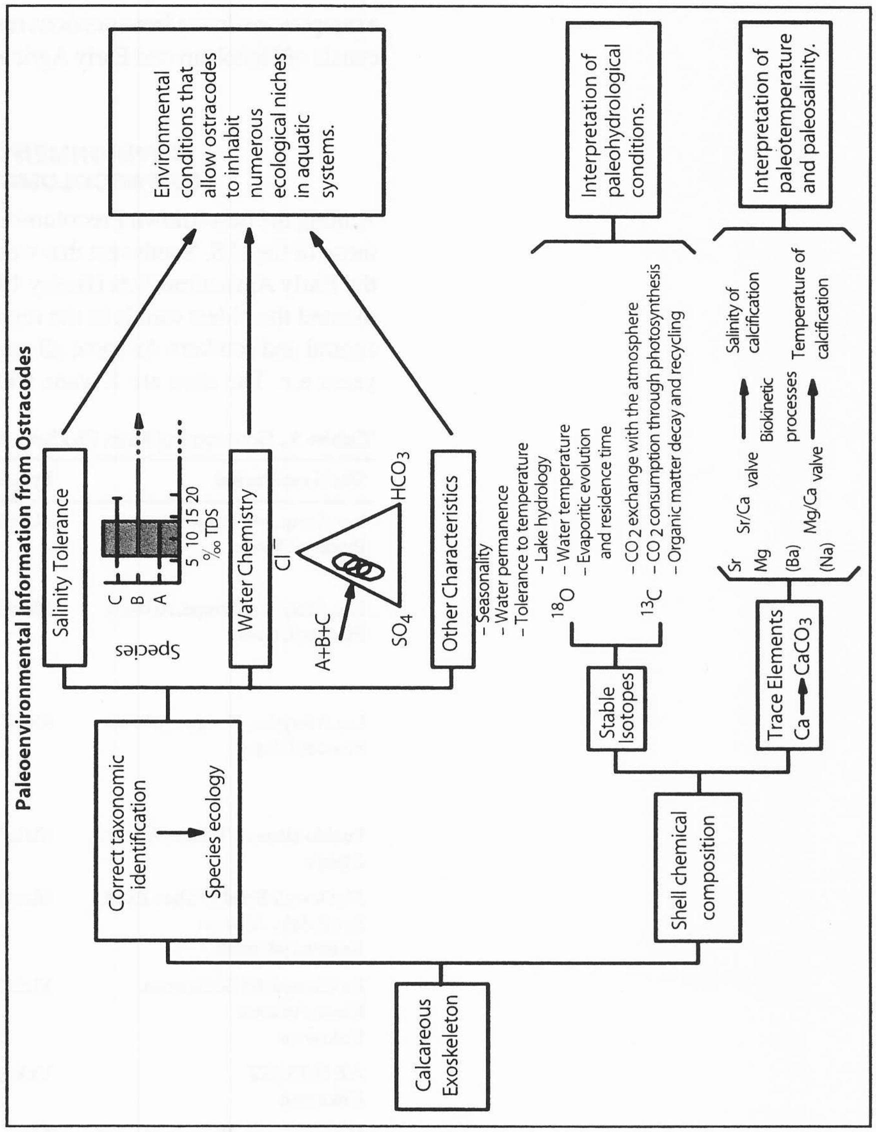


Figure 4. Flow diagram suggesting analytical procedures to obtain the most information possible from ostracodes considering their biological characteristics.

examples are drawn from previous research on ostracode paleoecology from irrigation canals of Hohokam and Early Agriculturalist contexts in the Southwest.

ENVIRONMENTAL RECONSTRUCTIONS OF PRECOLUMBIAN IRRIGATION CANALS

Among the best-known Precolumbian irrigation canal systems of the Americas are those of the U.S. Southwest that were built by the Hohokam and their predecessors, the Early Agriculturalists (Haury 1976). Recently, a number of studies have documented the oldest canals in the region from northern Arizona and New Mexico to central and southern Arizona; all range in age between 2,800 and 3,200 radiocarbon years B.P. The sites are K'yana Chabina and K'yawa:na'a Deyatchinanne, Zuni,

Table 1. Summary of Main Studies on Ostracodes in Irrigation Canal Systems in Arizona.

Site/Area/Period	Type of Canal	Type of Study
Las Acequias, Tempe, Arizona Pioneer/Classic	Main/Distribution/Lateral	Ostracodes
Las Acequias, Tempe, Arizona Pioneer/Classic	Main/Distribution/Lateral	Ostracode shell chemistry
Las Acequias, Tempe, Arizona Pioneer/Classic	Main/Distribution/Lateral	Ostracode shell chemistry
Pueblo Blanco, Tempe, Arizona Classic	Main/Distribution/Lateral	Ostracodes
McDowell Road to Shea Road, Scottsdale, Arizona Sedentary/Classic	Main/Lateral	Ostracodes
La Cuenca del Sedimento, Mesa, Arizona Unknown	Main/Distribution	Ostracodes
AZ U:15:282 Unknown	Unknown	Ostracodes/Mollusks
Unknown site, Phoenix, Arizona Unknown	Main	Ostracodes
Pecos Road, Sacaton, Arizona Sedentary/Classic	Main/Distribution	Ostracodes/Mollusks/Pollen
Las Capas, Tucson, Arizona San Pedro Phase (Early Agricultural)/Classic	Main/Distribution	Ostracodes

New Mexico (Damp and Kendrick 2000; Damp 2001); Costello-King, Tucson Arizona [AZ AA:12:503 (ASM)] (Ezzo and Deaver 1998); and Las Capas, Tucson, Arizona [AZ AA:12:753 (ASM)] (Mabry 2000). Las Capas is the only site where ostracodes have been analyzed for a paleoenvironmental reconstruction (Palacios-Fest et al. 2001). These are as old as the oldest canals reported for Mesoamerica (Doolittle 1990) except for the recent discovery of a 4,000-year-old canal in Caral, Peru (Pringle 2001). Table 1 summarizes some of the studies conducted in the Phoenix and Tucson areas where most of these investigations have focused.

Before summarizing these studies it is important to note that some publications are available on ostracode studies related to human activity in the Americas. For example, Bradbury et al. (1987) reported the occurrence of ostracodes in natural channels in Albion Island, Belize and related them to Mayan agricultural activities.

Main Conclusions	Comments	Bibliographic References
Ostracodes document environmental change in irrigation canals	First study of ostracodes in irrigation canals	Palacios-Fest (1989)
Three species show similar chemical trends through time, suggesting climate change	First study of ostracode shell chemistry in irrigation canals Curves are interpreted as climate change	Palacios-Fest (1994)
From estimated temperatures it is suggested that Hohokam canals were mainly used between late winter to early summer	First study where mathematical standard coefficients from the Mg/Ca ratios of *L. staplini* were applied to calculate temperatures	Palacios-Fest (1997a)
Microstratigraphic analysis shows canal operation	First microstratigraphic study of ostracodes in canal systems	Palacios-Fest (1995a) Palacios-Fest (1997c)
Alternate periods of water input and desiccation		Palacios-Fest (1996)
Evidence of seasonal canal operation		Palacios-Fest (1997d)
Reworked fauna	Not enough data to conduct an environmental reconstruction	Palacios-Fest (1997e)
First occurrence of *Cyprideis beaconensis* in irrigation canals		Palacios-Fest (1997f)
Alternate periods of water input and desiccation	First study to combine ostracode and mollusc data	Palacios-Fest (1997b) Adams et al. (2002)
Recognition of opportunistic and functional canal operation Interpretation of evolution in water management	First study to document ostracodes in pre-Hohokam canals	Palacios-Fest et al. (2001)

More recently, Curtis et al. (1995) and Goman and Byrne (1998) related ostracodes to Maya agriculture in Guatemala, based on the association of shells with cultigen grains in lacustrine sediments. None of these studies, however, directly related irrigation canal operation with ostracodes. Consequently, the first studies from Precolumbian irrigation canals are those of Palacios-Fest (1989, 1994). In the Hohokam area, paleoenvironmental reconstructions have been made based on the assumption that fossil assemblages share the same ecological needs as those recovered from modern lakes, ponds, springs, and streams. In addition, these studies assume that faunal assemblages represent the last time the canals were used.

EXAMPLES OF IRRIGATION CANAL STUDIES IN ARIZONA

The following section summarizes the most relevant studies of Hohokam irrigation canal systems. This review concentrates on the criteria necessary for recognizing human activity, evolution of water technology, streamflow control, and canal operation.

Canal Construction and Evolution of Water Technology

Is it possible to recognize through paleoecological analysis the timing for water control in irrigation canals? A recent study suggests that ostracodes may shed critical information on solving this question because the faunal associations reflect sources of water (Palacios-Fest et al. 2001). Palacios-Fest et al. (2001) used ostracodes as indicators of hydraulic properties in canals at the Las Capas site, located on the T2 terrace of the Santa Cruz River. They documented how farmers from the San Pedro phase of the Early Agricultural period (3000–2400 B.P.) transitioned from opportunistic to functional canal operation (Mabry 2000). At the time of opportunistic operation, farmers were limited to the rainy season to flood their fields. No evidence is available for pre-canal agriculture on the Santa Cruz River floodplain, but as farmers learned to control streamflow, they were in a position to manipulate water by diverting it from the Santa Cruz River to agricultural fields established on the floodplain. Variations in ostracode assemblages at Las Capas indicate alternate periods of salinization and water input related to episodes of headgate operation. Irrigation increased maize productivity, as recognized by archæologists (Mabry 2000). Waters (1988) suggested that the Santa Cruz River floodplain was affected by human activity through control of water input cycles, a hypothesis supported by ostracode studies (Figure 5).

For paleoenvironmental reconstructions, Palacios-Fest (1989) developed the salinity index (SI) shown in Figure 4.

Canal Operation and Hydraulic Flow Regimes

Changes in ostracode assemblages in irrigation canals have been used to reconstruct hydraulic properties (Palacios-Fest 1995b, 1997b). These changes are interpreted

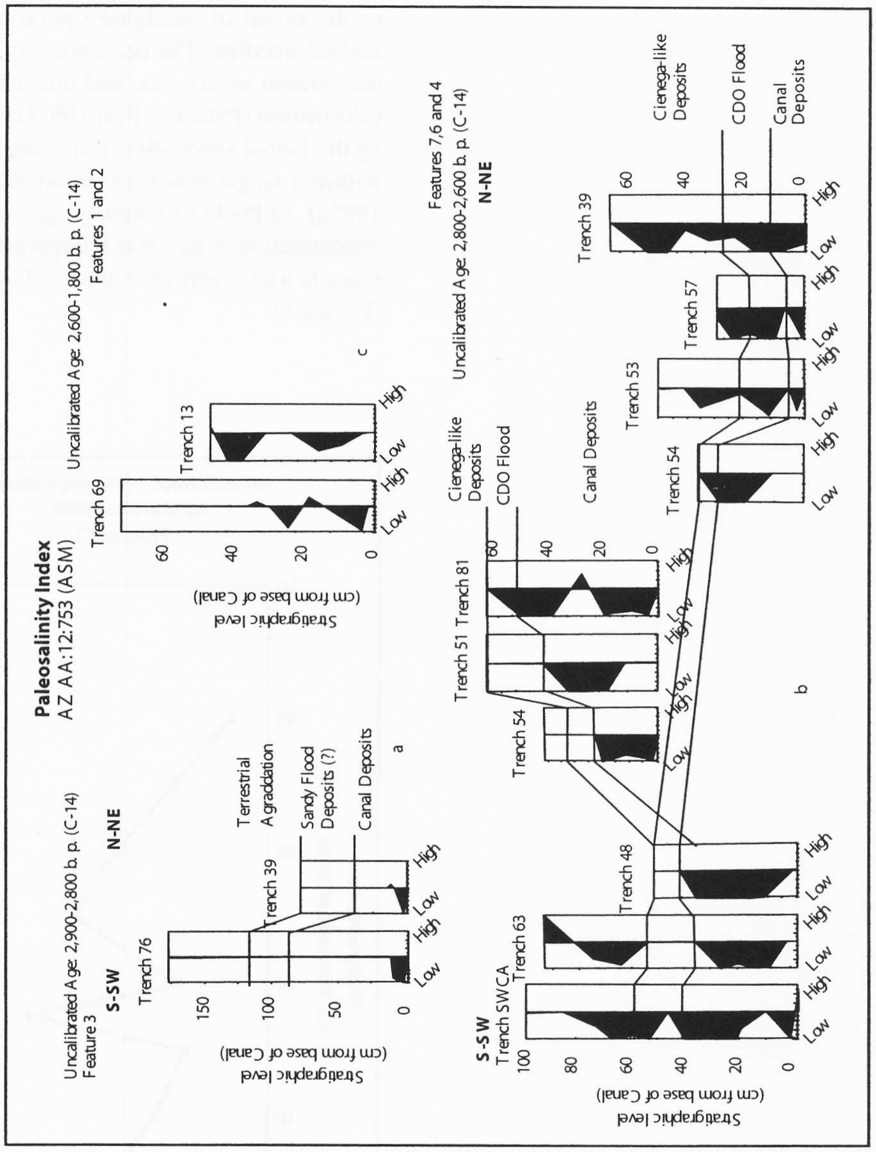


Figure 5. Technological evolution of irrigation canal operation using the paleosalinity index (SI) from the relative abundance of ostracode species present at Las Capas, Tucson, Arizona (AZ AA:12:753 ASM). Note how salinity patterns change in response to periods of water input and desiccation as a result of canal operation and water management evolution suggested in the text. For details see Palacios-Fest et al. (2001).

as the result of headgate operation that induced episodes of water dilution and salinization. The occurrence of *Cyprideis beaconensis* in irrigation canals is uncommon in Arizona, and thus its presence indicates an episode of increasing salinization (Palacios-Fest 1997f). Better evidence of hydraulic flow is provided by the faunal variability from sample to sample in a microstratigraphic sequence within a single canal, as reported at Pueblo Blanco in Phoenix (Palacios-Fest 1995a). At Pueblo Blanco, progressive salinization resulted from gradual mineral concentration, which was interpreted as caused by regulated input because changes occur in a relatively short time and show several cycles in the stratigraphic sequence (Figure 6).

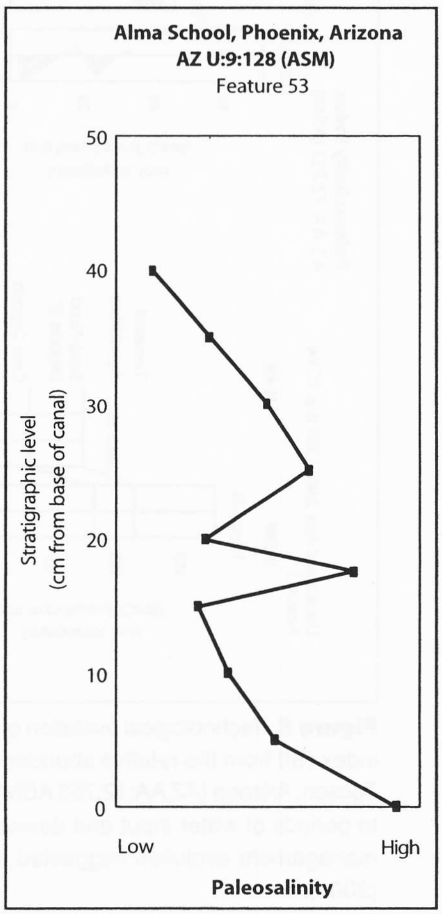


Figure 6. Example of canal operation in Hohokam irrigation canals at Alma School, Phoenix, Arizona (AZ U:9:128 ASM), Feature 53. Modified from Palacios-Fest (1997c).

Seasonal Canal Operation

Ostracode faunal associations and their shell chemistry may be used to recognize seasonal variation in canal use (Palacios-Fest 1997a, c). The first study to estimate water temperature was based on the shell chemistry of *Limnocythere staplini* using the Mg/Ca ratios of the valves (Palacios-Fest 1997a). These data indicate that shell calcification occurred at low temperatures, coinciding with minimum temperature values recorded in the Phoenix Basin for the last 119 years (1876–1995) (Figure 7). These estimates are consistent with the shedding habits of other crustaceans (e.g., decapods: crabs) that shed their exoskeletons between midnight and dawn, that is, during minimum temperature hours (personal observation at a crab farm 1990). In addition, standard paleoecological studies also indicate qualitative climate change interpretation

(Palacios-Fest 1997c). For example, at the Las Acequias site (AZ U:9:44 [ASM]), the ostracode record indicates two major flood events between A.D. 855 and 910 and prior to A.D. 1350; a drought between A.D. 1365 and 1425 was also documented (Palacios-Fest 1994).

Types of Prehistoric Irrigation Canals

Three types of canals are known in the Southwest: (1) main canals fed directly from the source (river, spring); (2) distribution canals excavated from the main canals; and (3) lateral canals that flood the agricultural fields. *Ilyocypris bradyi* is common in main and distribution canals due to its ability to live in a streamflow. *Candona patzcuaro* and *Herpetocypris brevicaudata* or related species are common in distribution canals but rare in main canals (unless streamflow has decreased or ceased). *Limnocythere staplini* and *Cypridopsis vidua* are often found in lateral canals where flow is slow or water becomes stagnant. These species, however, may appear in main or distribution canals as streamflow decreases or ceases. More detailed studies are needed to support these observations.

Irrigation Technology through Time

Irrigation technology developed over several millennia and irrigation engineering became gradually more complex. The canals studied cover a wide temporal spectrum, starting as early as the Early Agricultural period (San Pedro phase) in Las Capas in Tucson, to the canals of the Hohokam Classic period in Pueblo Blanco in Phoenix (Palacios-Fest 1995a; Palacios-Fest et al. 2001). Most studies have focused on the pre-Classic and Classic periods of Hohokam culture. Because of the limited number of studies conducted and the broad chronological frame they represent, it is impossible to more precisely define the patterns of technological progress in terms of time. It is possible, however, to recognize that early irrigation was small scale, with canals feeding the floodplains that were active at that time. Later canals in the Phoenix and Gila basins expanded greatly to water higher landforms, e.g. Pleistocene terraces.

CONCLUSIONS

Ostracode remains preserved in prehistoric irrigation canals provide relevant information that aids our understanding of agriculture in Precolumbian cultures of the U.S. Southwest. Ostracodes and other faunal records, shell chemistry, and the sedimentary record should be integrated as a way to better understand the evolution of water control technology. Distinction of anthropogenic from climatic signatures should be made for establishing environmental impacts in prehistory. Ostracodes should be incorporated in geoarchæological investigations to improve our ability to recognize the type of canal, seasonal variability in canals, and periods of canal

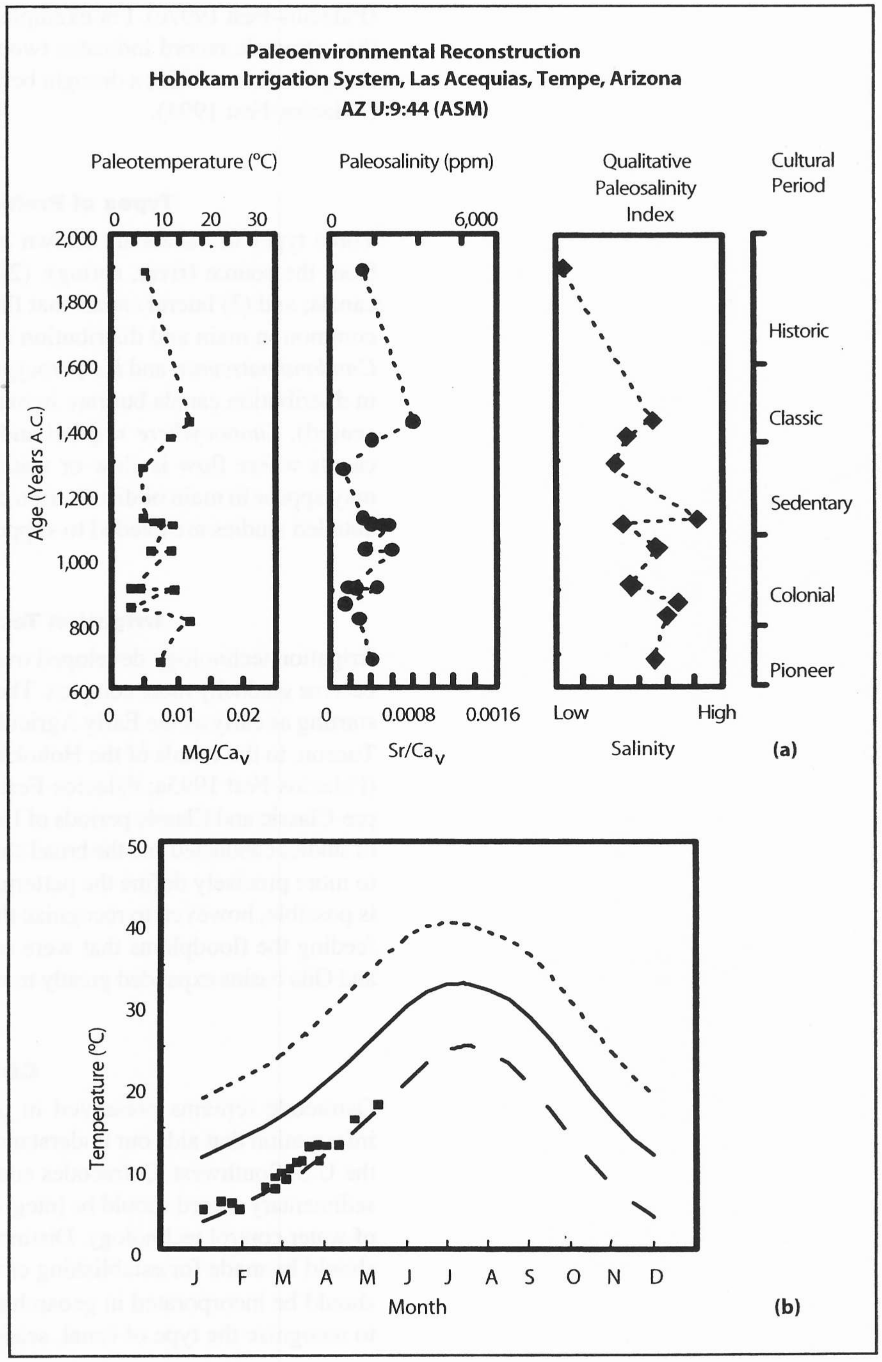

Paleoenvironmental Reconstruction
Hohokam Irrigation System, Las Acequias, Tempe, Arizona
AZ U:9:44 (ASM)
Paleotemperature (°C)
Paleosalinity (ppm)
Qualitative Paleosalinity Index
Cultural Period
Age (Years A.C.)
Historic
Classic
Sedentary
Colonial
Pioneer
Mg/Ca$_V$
Sr/Ca$_V$
Low
High
Salinity
(a)
Temperature (°C)
J F M A M J J A S O N D
Month
(b)

Figure 7. Comparison of paleoecological and geochemical reconstructions of Hohokam canals at (a) Las Acequias, Tempe, Arizona (AZ U:9:44 ASM) with (b) mean (—), minimum (– – –) and maximum (- - -) temperatures recorded in the Phoenix Valley from 1876 to 1995. ■ = estimated temperatures for *Limnocythere staplini* using Mg/Ca ratios from shells; ● = estimated water salinity using Sr/Ca ratios from the same species; ◆ = paleosalinity index (SI). Data compiled from the National Climatic Data Center files for the period 1876–1995. Modified from Palacios-Fest (1997a).

operation from periods of canal desiccation. The application of shell chemistry should be used for inferring water temperature and salinity as a tool to understand the effects of salinization on human development.

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