CHAPTER 19: PALEOECOLOGY OF MICRO-INVERTEBRATES

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Introduction

The Hohokam are known for the complex and long irrigation canals they built before A.D. 1450 (Haury 1976). The Akimel O'odham, during the Historic period, also used this strategy to irrigate their crops, as more recently settled Anglo-Americans did at the turn of the nineteenth century (WSA 2005a). Hohokam and historic canal irrigation in southern Arizona is a major source of information used to reconstruct ancient aquatic environments and the interaction between humans and nature. Both prehistoric and historic canals still preserve environmental records in the fill sediments that can be used for understanding water management technology, type of use, and length of operation (Adams et al. 2002; Woodson and Neily 1998). Micro-invertebrates are a powerful tool for understanding how past peoples used water and the "quality" of this resource for cultivating the land.

Micro-invertebrates and calcareous algae have been successfully used in numerous irrigation canals from the Phoenix and the Tucson basins including several sites across the GRIC (Palacios-Fest 2002). Ostracodes and mollusks are two of the most common microfossils observed in irrigation canals throughout southern Arizona (Adams et al. 2002). The gyrogonites of calcareous algae also provide important information on the water chemistry and permanence of the system (Feist 2003; García 1994). To date, water chemistry and salinity trends in those canals have been a relevant source of information regarding the canal paleohydraulics, seasonality, and permanence in addition to the two parameters mentioned above.

Sixty-six samples from 13 irrigation canals along the ELXP provided an excellent record of water resources during pre-Classic and Classic Hohokam periods that can be compared with Anglo-American irrigation canals built between 1873 and 1877 that remained in use until 1914.

Materials and Methods

Sixty-six sediment samples from 13 canal features exposed at five sites (GR-893, GR-894, GR-895, GR-1439, and GR-1440) were shipped to Terra Nostra Earth Sciences Research for preparation and analysis of micro-invertebrates. Sample size was 100 g of sediment.

Samples were prepared using routine procedures (Forester 1988) modified by Palacios-Fest (1994). Sediment residuals were analyzed under a low-power microscope. Grain-size and mineral composition were determined by the wet-sieve method and microscopic analysis, respectively. All samples were wet-sieved using a set of three, 3-inch sieves (>1 mm, >106 μm, and >63 μm) stacked to remove the fine fraction through sieving. Thirty-nine of the 66 samples were fossiliferous while 33 contained ostracodes; mollusks were present in 26 samples, and gyrogonites (the oogonia of calcareous algae) occurred in 10 samples.

The sedimentological and mineralogical information was tabulated (Appendices I.1 and I.2) to document the canals stratigraphy and lithology. Sieved sediment fractions were converted into weight percent to estimate the relative abundance of each fraction that allowed for the generation of grain-size diagrams (Figures 19.1-19.5). The micropaleontological and paleoecological information was also tabulated (Appendices I.3 through I.5) to document the canals' paleoenvironmental history. Finally, Table 19.1 (ecology of ostracodes) and Table 19.2 (ecology of mollusks) show the ecological parameters affecting the species present in these canals. Based on the species ecological requirements, faunal assemblages and a paleosalinity index were obtained for the paleoenvironmental reconstruction. The paleosalinity index was prepared assigning the highest positive value to the most salinity-tolerant species in a range that reached the opposite extreme to which the highest negative value was applied to the least salinity-tolerant species. The equation developed for this study is:

SI = [(5 * % *Limnocythere staplini*) + (4 * % *Cyprideis beaconensis*) + (3 * % *Cyprinotus glaucus*) + (2 * % *Cypridopsis vidua*) + (% *Potamocypris smaragdina*)] – [(% *Candona patzcuaro*) + (2 * % *Limnocythere paraornata*) + (3 * % *Herpetocypris brevicaudata*) + (4 * % *Ilyocypris bradyi*)]

Using this paleosalinity index equation, the actual salinity-tolerance range of each ostracode species, and the ecological requirements of mollusks and calcareous algae (gyrogonites of *Chara*), a paleoenvironmental model is proposed to address the questions stated in a previous section of this paper.

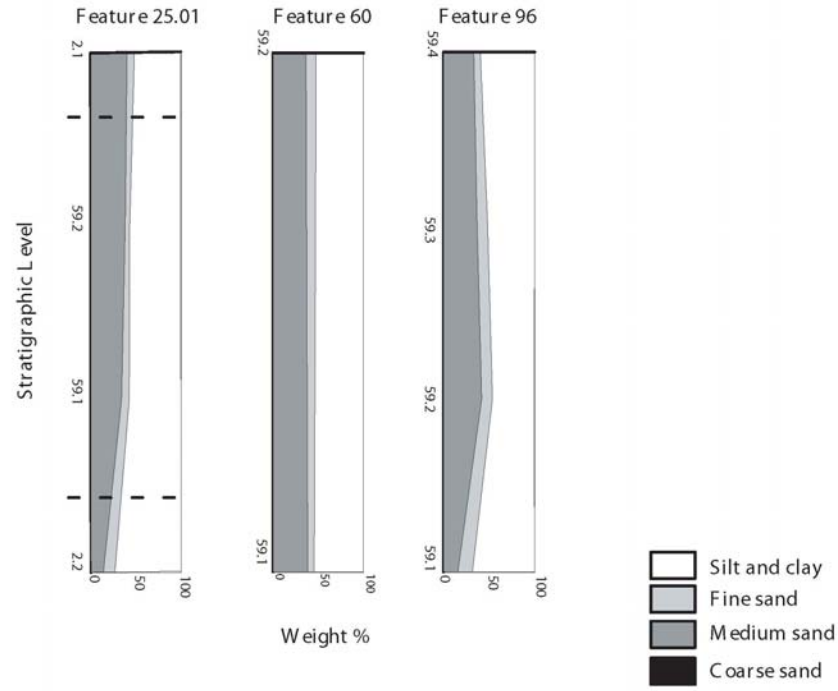
Results

Appendix I.1 shows the sample identification number, stratigraphic level, bulk and residual weight (g). The latter is the sum of the three sieved sand-fractions (g). In addition, the <63 μm fraction was calculated subtracting the residual weight from the bulk weight to estimate the amount of silt and clay (g). Then, the weight percent (Wt. %) per fraction was estimated to generate particle-size diagrams (Figures 19.6-19.15). Sediment texture and color (including the Munsell color code) complete the table.

Appendix I.2 shows the samples' mineral composition. Quartz is the dominant mineral followed by feldspars, biotite, and muscovite. Tufa, charcoal, and rock fragments are moderately common to rare. Gypsum occurs in Features 6 and 10 at GR-894 and once in Feature 19 at GR-895. All other minerals are rare to very rare. Shell, fish, and bone fragments are rare to very rare.

Biologically, 13 of the 14 canals were fossiliferous. The 39 samples containing micro-invertebrates showed moderately high diversity (nine ostracode species and eight mollusk species). Abundance ranges from extremely rare to extremely abundant[*]. Ostracodes, mollusks, and calcareous algae occurred in these samples. Nine ostracodes species were present in these canals: *Ilyocypris bradyi*, *Herpetocypris brevicaudata*, *Limnocythere* sp. cf. *L. paraornata*, *Candona patzcuaro*, *Potamocypris smaragdina*, *Cyprinotus glaucus*, *Cypridopsis vidua*, *Cyprideis beaconensis*, and *Limnocythere staplini*. The ostracode population ranged from one individual to 477 specimens, generally well preserved. The ostracode population per gram of sediment ranged from 0.01 specimens per gram to 4.76 specimens per gram. The taphonomic features indicate low to very high fragmentation and abrasion (5%-70%), no encrustation and coating, and extremely rare staining (mostly clear valves).

[*] Abundance explanation: extremely abundant (n>301), very abundant (101< n <300), abundant (51< n <100), common (21 < n <50), rare (11< n <20), very rare (6 < n <10), and extremely rare (5< n).



WSA

Figure 19.1. Grain-size Analysis of Three Features at GR-893.

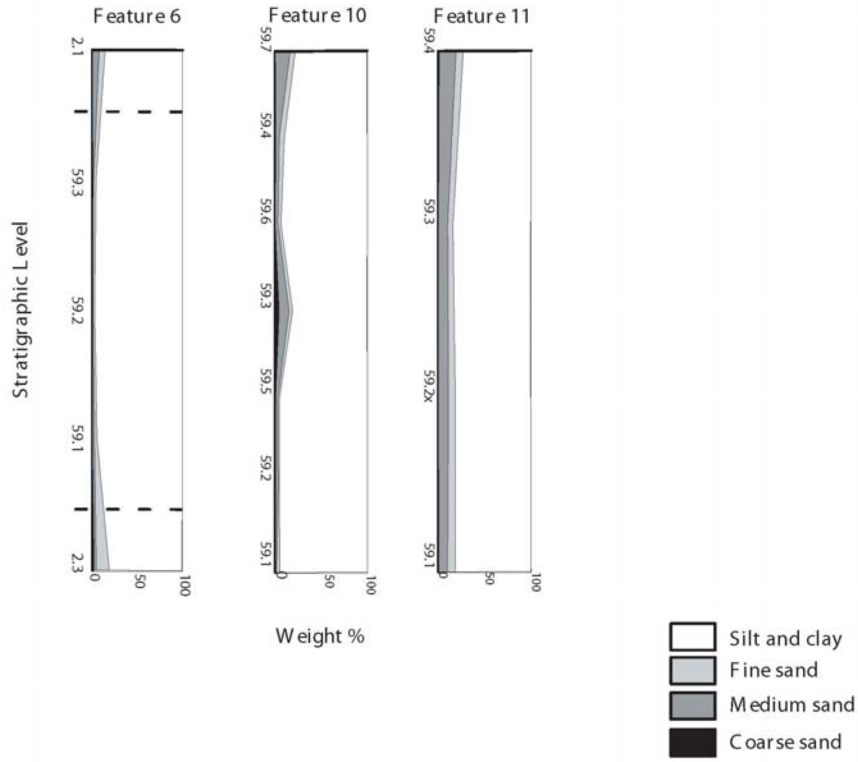


Figure 19.2. Grain-size Analysis of Three Features at GR-894.

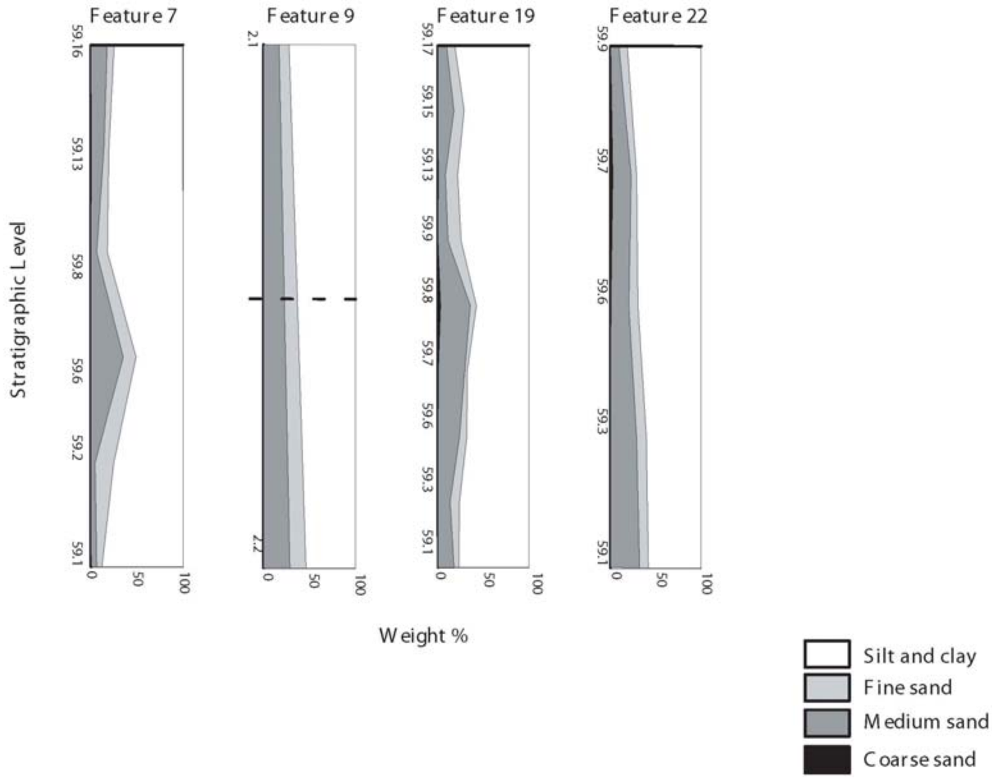


Figure 19.3. Grain-size Analysis of Four Features at GR-895.

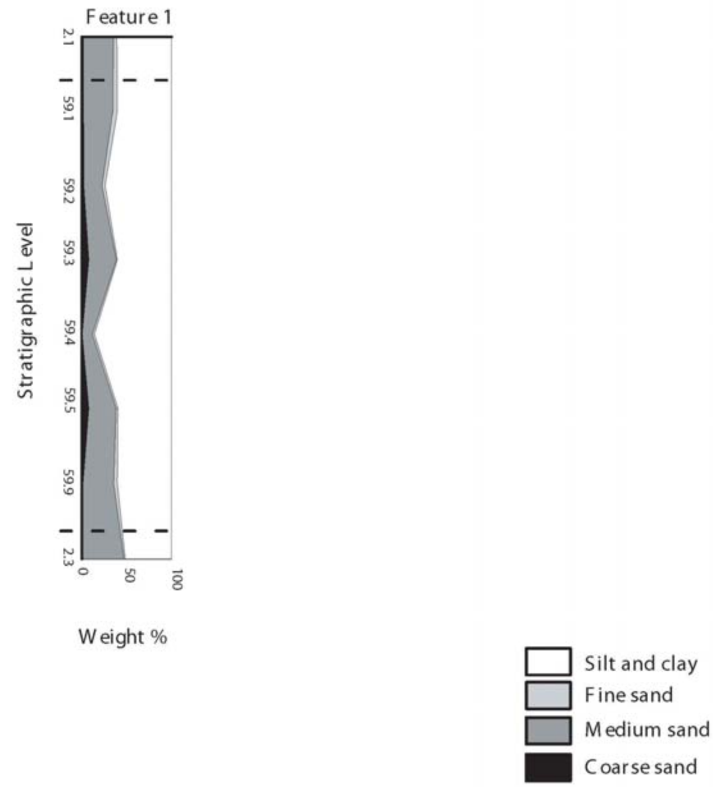


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Figure 19.4. Grain-size Analysis of One Feature at GR-1439.

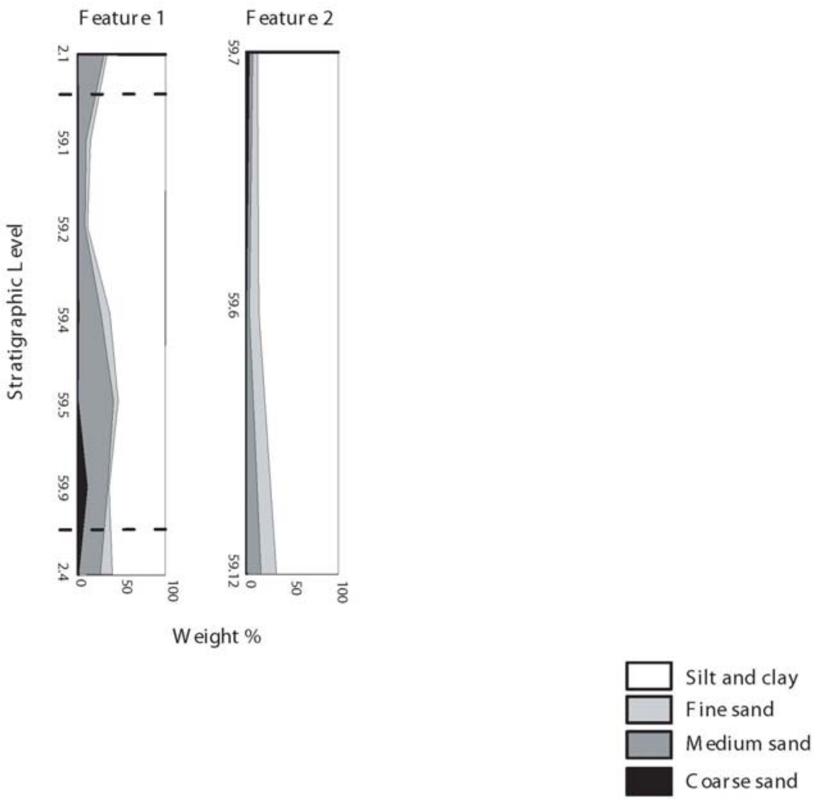

Figure 19.5. Grain-size Analysis of Two Features at GR-1440.

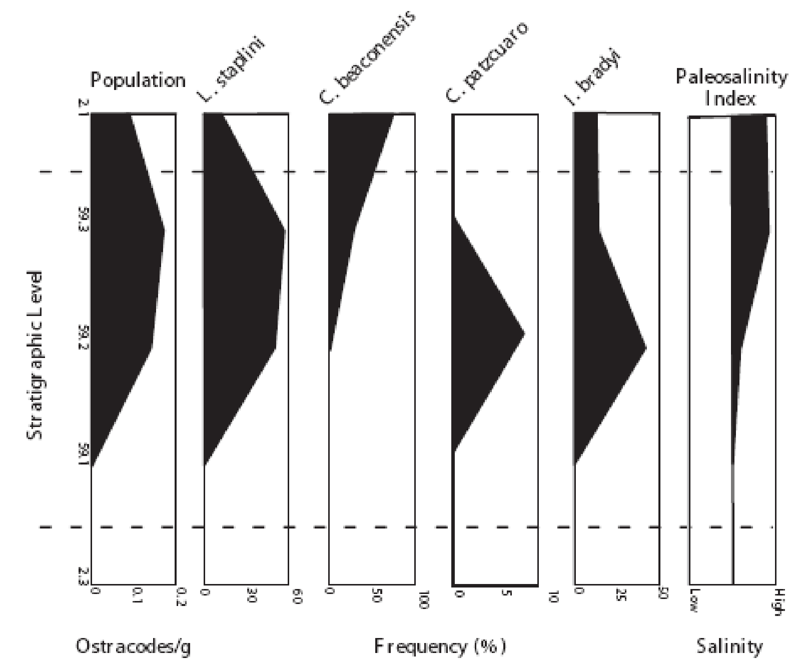

Figure 19.6. Ostracode Chronostratigraphy of Feature 6 at GR-894.

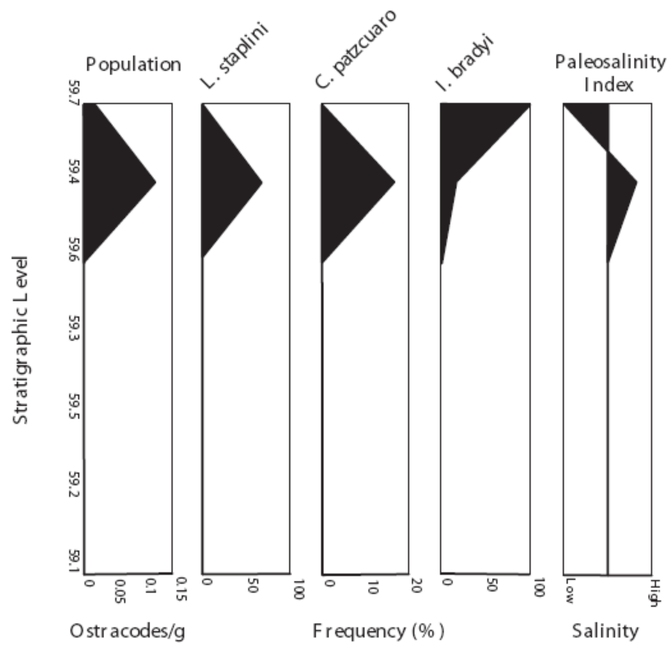

Figure 19.7. Ostracode Chronostratigraphy of Feature 10 at GR-894.

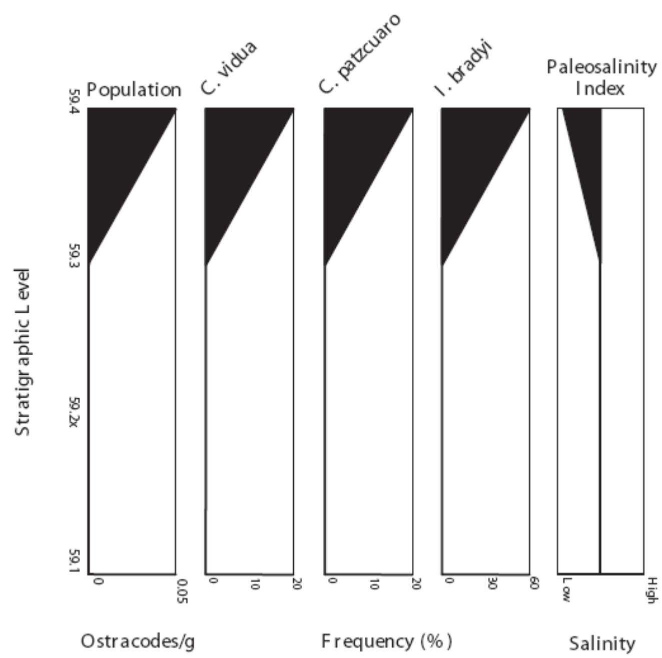

Figure 19.8. Ostracode Chronostratigraphy of Feature 11 at GR-894.

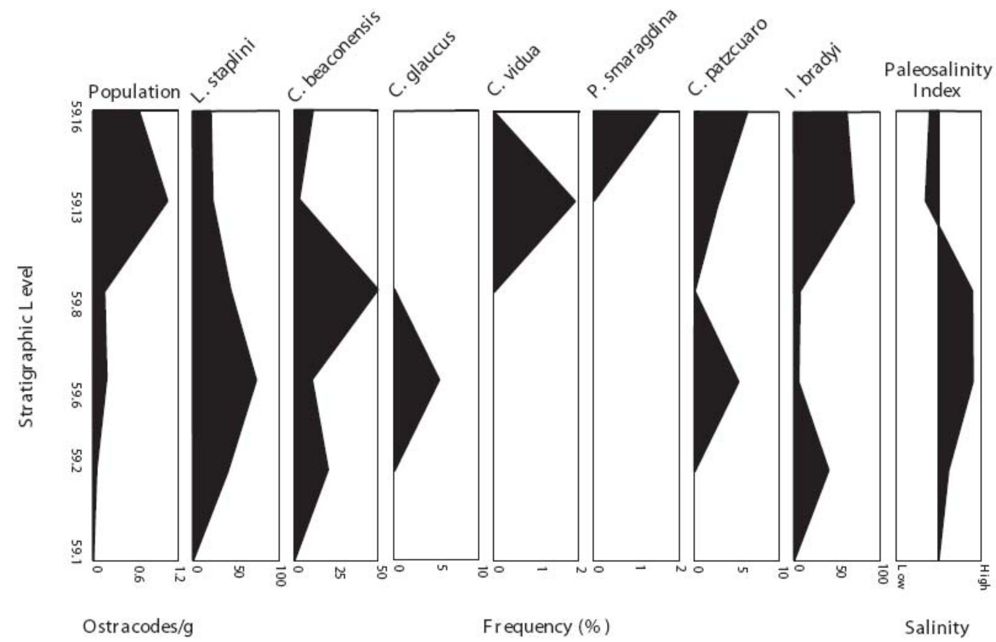

Figure 19.9. Ostracode Chronostratigraphy of Feature 7 at GR-895.

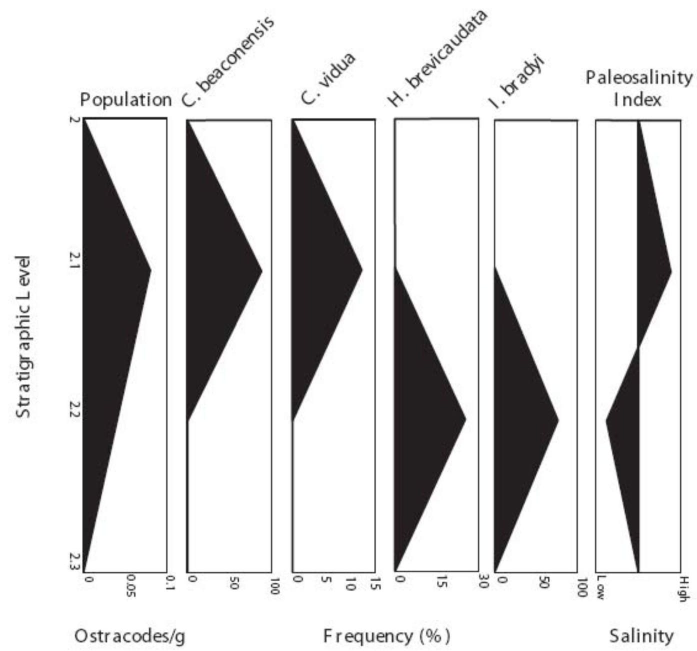

Figure 19.10. Ostracode Chronostratigraphy of Feature 9 at GR-895.

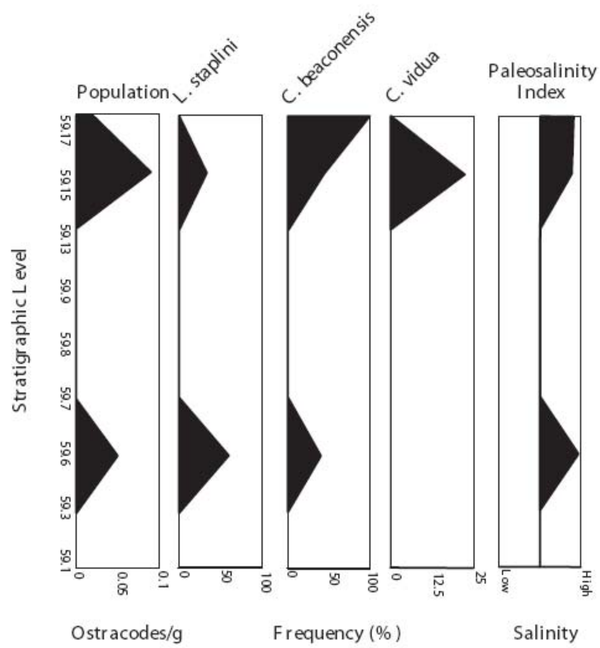

Figure 19.11. Ostracode Chronostratigraphy of Feature 19 at GR-895.

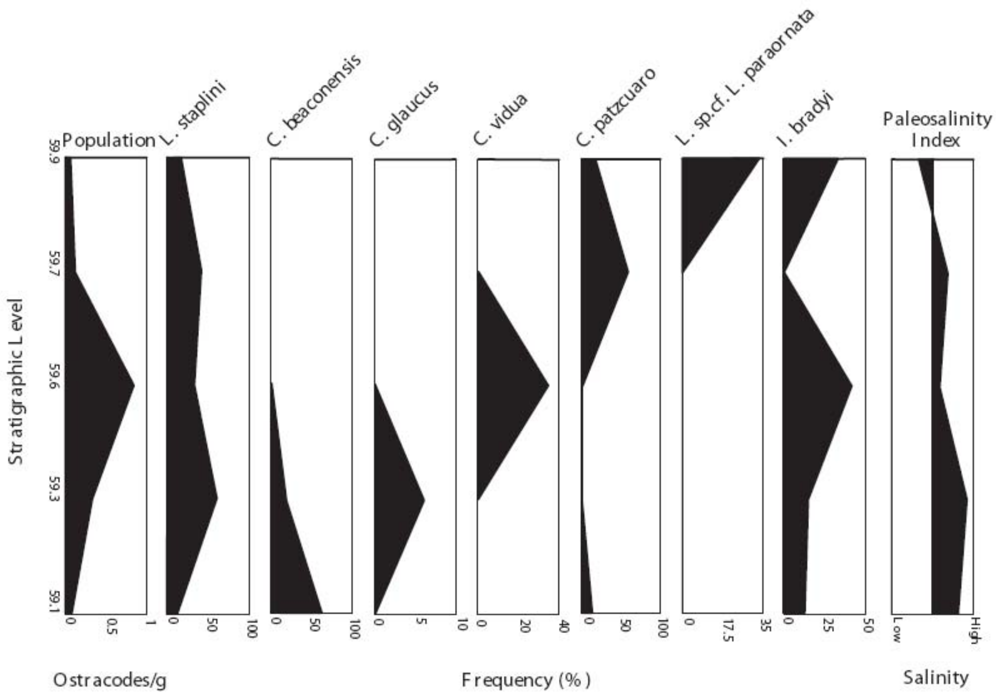

Figure 19.12. Ostracode Chronostratigraphy of Feature 22 at GR-895.

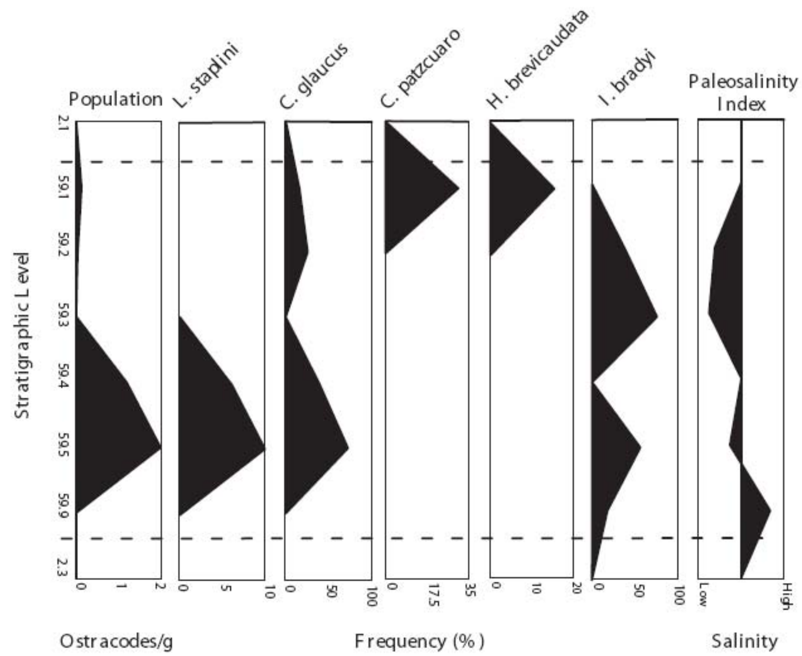

Figure 19.13. Ostracode Chronostratigraphy of Feature 1 at GR-1439.

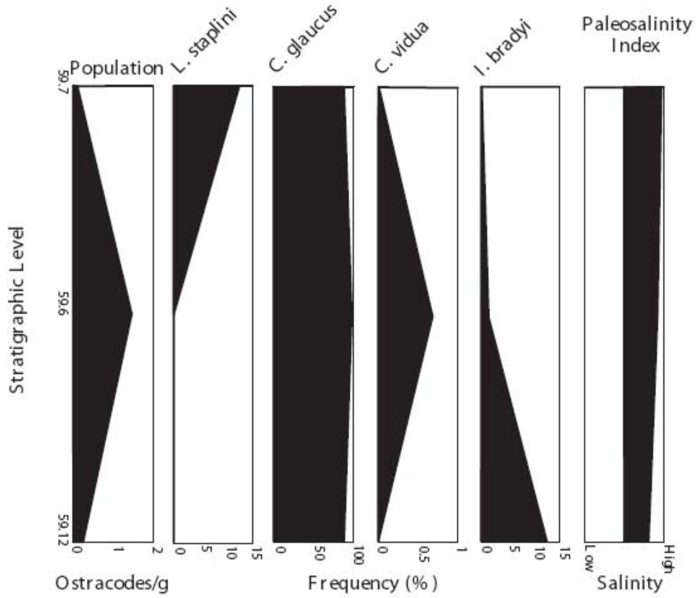

Figure 19.14. Ostracode Chronostratigraphy of Feature 2 at GR-1440.

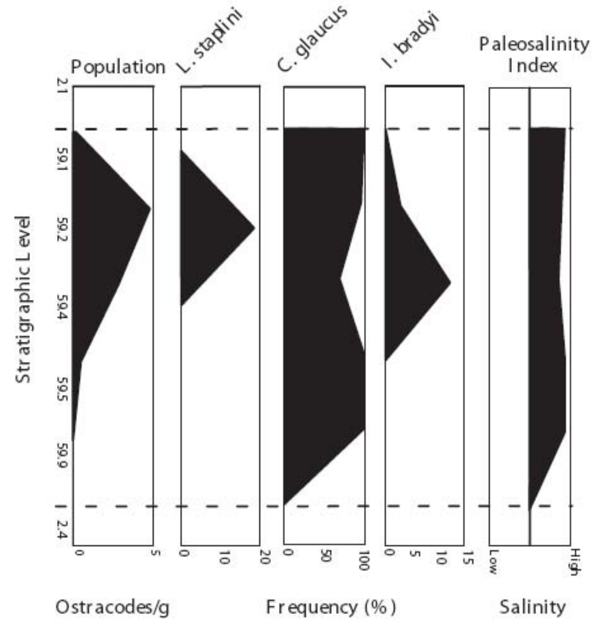

Figure 19.15. Ostracode Chronostratigraphy of Feature 1 at GR-1440.

Table 19.1. Ecological Requirements of Ostracode Species Recovered from the Upper Santan Village Canals

Species	Habitat	Permanence	Temperature	Salinity	Chemistry
Ilyocypris bradyi	Streams, ponds	Permanent	Eurythermic	100-4,000 mg L^{-1}	Freshwater to Ca-rich
*Herpetocypris brevicaudata**	Springs, streams	Permanent	Eurythermic	200-3,000 mg L^{-1}	Freshwater to Ca-rich
*Cyprinotus glaucus***	Springs, seeps, streams	Permanent	Eurythermic	750-4,000 mg L^{-1}	Freshwater to Ca-rich
Cypridopsis vidua	Springs, streams, lakes	Permanent	Eurythermic	100-4,000 mg L^{-1}	Freshwater to Ca-rich
Candona patzcuaro	Lakes, ponds, canals	Permanent	Eurythermic	200-5,000 mg L^{-1}	Freshwater to Ca-rich
*Potamocypris smaragdina***	Lakes, ponds, canals	Permanent	Eurythermic	10-1,000 mg L^{-1}	Freshwater to Ca-rich
Cyprideis beaconensis	Lakes, ponds, canals	Permanent	Eurythermic	100-10,000 mg L^{-1}	Freshwater to Ca-rich with Na, Mg and Cl
Limnocythere sp. cf. *L. paraornata***	Lakes, ponds, canals	Permanent or ephemeral	Eurythermic	100-5000 mg L^{-1}	Freshwater to Ca-rich
Limnocythere staplini	Lakes, ponds, canals	Permanent or ephemeral	Eurythermic	500-75,000 mg L^{-1}	Freshwater to Ca-rich with Na, Mg and SO_4

* Forester (1991).
** Delorme (1970, 1989)
All others Palacios-Fest (1994)

Table 19.2. Ecological Requirements of Mollusk Species Recovered from the Upper Santan Village Canals

Species	Habitat	Permanence	Temperature	Salinity	Chemistry
Gyraulus sp.	Streams, ponds, lakes, canals	Permanent or ephemeral or moist soil	Eurythermic		
Physa virgata	Streams, lakes, ponds, canals	Permanent or ephemeral	Eurythermic		
Physella sp.	Riparian, marshes	Moist soils	Stenothermic		
Stagnicola elodes	Ponds, lakes, marshes	Permanent or ephemeral	Eurythermic		
Fossaria sp.	Riparian, marshes	Moist soils	Eurythermic		
Vivipara sp. cf. *V. intertextus*	Riparian, marshes	Permanent or ephemeral	Stenothermic		
Anculosa sp. cf. *A. praerosa*	Streams and rocky substrates	Permanent	Eurythermic		

Sources:
Vokes and Miksicek, 1987
Miksicek, 1989
Bequaert and Miller, 1973
Webb, 1942

Eight mollusk species were identified in 26 samples from these canals: *Physa virgata*, *Physella* sp., *Anculosa* sp. cf. *A. praerosa*, *Fossaria* sp., *Stagnicola elodes*, *Vivipara* sp. cf. *V. intertextus*, and *Gyraulus* sp., and an unknown clam (see Adams et al. 2002). Extremely rare to common (1 to 11 specimens) mollusks were relatively well preserved. The mollusk population per gram of sediment was 0.01 specimens per gram to 0.30 specimens per gram. The taphonomic characteristics of the shells indicate low to moderate fragmentation and abrasion (10-70%), no encrustation or coating, and no staining of the shell surface.

In addition, the gyrogonites of the calcareous algae *Chara* occurred in 10 of the samples. The state of preservation of these sexual structures is very good to excellent. The population of gyrogonites ranged from 1 to 130, that is, from extremely rare to very abundant. The algae population per gram of sediment is 0.01 specimens per gram to 1.30 specimens per gram.

The sedimentary and biological composition of the 13 canals are described separately by site:

GR-893

Feature 25.01 consisted of four samples, two from canal fill (strata 59.1 and 59.2) and two from natural deposits (strata 2.1 and 2.2) of pale brown (10YR 6/3) to brown (10YR 5/3) sandy silt to clayey silt (Appendix I.1). Quartz and feldspars were the dominant minerals followed by biotite, muscovite, and glass. Other minerals were rare to very rare (Appendix I.2). Mollusks and plant debris were the biological remains recorded (Appendix I.3). Two highly fragmented (40%-60% fragmentation) gastropod shells were the only micro-invertebrates found in this feature. Species represented include *Anculosa* sp. cf. *A. praerosa* and *Gyraulus* sp. (Appendix I.5).

Feature 60 consisted of two samples from strata 59.1 and 59.2 of brown (10YR 5/3) sandy silt (Appendix I.1). Quartz, feldspars, biotite, muscovite, and tufa dominated the canal. Other minerals were rare to very rare (Appendix I.2). The canal was unfossiliferous (Appendix I.3).

Feature 96 consisted of four samples from stratum 59.1 through stratum 59.4 of brown (10YR 5/3) sandy silt (Appendix I.1). Quartz and feldspars were the dominant minerals. Biotite, muscovite, and charcoal were moderately common to very rare. Other minerals occurred intermittently (Appendix I.2). Micro-invertebrates were absent in this canal (Appendix I.3).

GR-894

Feature 6 consisted of five samples, three from the canal fill (stratum 59.1 through stratum 59.3) and two from natural deposits (stratum 2.3, the matrix substrate, and stratum 2.1, the post-abandonment deposits). The canal sediments were brown (10YR 5/3) clay, whereas the natural deposits were pale brown (10YR 6/3) to dark yellowish brown (10YR 4/4) silty clay (Appendix I.1). Quartz, tufa, and feldspars were the dominant minerals. Gypsum was moderately common to very rare. Biotite, muscovite, and charcoal were rare to very rare. Other minerals occurred occasionally (Appendix I.2). Ostracodes, mollusks, and plant debris were recorded in this canal. Fragmentation ranged from low (5%) to high (60%). Abrasion was low to moderately low (5%-15%). Encrustation, coating, and the redox index were not significant (Appendix I.3). *L. staplini* dominated the environment followed by *C. beaconensis*, whereas *C. patzcuaro* and *I. bradyi* were poorly represented (Appendix I.4). The mollusks were represented by extremely rare specimens of *P. virgata* and *Gyraulus* sp. (Appendix I.5).

Feature 10 consisted of seven samples from stratum 59.1 through stratum 59.7 of mostly brown (10YR 5/3) sandy silty clay to clay (Appendix I.1). Quartz, tufa, and feldspars were the dominant minerals. Biotite, muscovite, and charcoal were moderately common to very rare. Gypsum was common to rare when present. Other minerals occurred occasionally (Table 19.2). The upper two samples contained ostracodes, mollusks, gyrogonites, and plant debris. Micro-invertebrates show moderately low (5%-15%) fragmentation and abrasion but no evidence of encrustation, coating, and staining (Appendix I.3). *L. staplini*, *C. patzcuaro*, and *I. bradyi* were the only species present. *I. bradyi* dominated stratum 59.4 but was intrusive to stratum 59.7 (Appendix I.4). *Gyraulus* sp. dominated stratum 59.4, which also contained *P. virgata*. The former species was introduced to stratum 59.7 (Appendix I.5).

Feature 11 consisted of four samples from stratum 59.1 through stratum 59.4 of pale brown (10YR 6/3) to grayish brown (10YR 5/2) sandy silty clay to silty clay (Appendix I.1). Quartz and feldspars were the dominant minerals. Biotite, muscovite, and charcoal were common to very rare. Other minerals occurred occasionally (Appendix I.2). Extremely rare ostracodes and mollusks that show low (5%-15%) fragmentation and abrasion were identified in strata 59.1 and 59.4. No evidence of other taphonomic parameters was recorded (Appendix I.3). Dominated by the ostracode *I. bradyi*, stratum 59.4 also contained *C. vidua* and *C. patzcuaro* (Appendix I.4). Mollusks, represented by *Fossaria* sp. and *Gyraulus* sp., occurred in strata 59.1 and 59.4 (Appendix I.5).

GR-895

Feature 7 consisted of six samples from canal fill sediments of dark yellowish brown (10YR 4/4) to light yellowish brown (10YR 6/4) sandy silt to silty clay (Appendix I.1). Quartz, feldspars, biotite, and tufa were the dominant minerals. Muscovite and charcoal were moderately common to very rare. Other minerals occurred occasionally (Appendix I.2). Ostracodes, mollusks, gyrogonites, and plant debris were extremely rare to abundant. The taphonomic parameters indicate low to moderately low fragmentation and abrasion (5%-15%); other conditions were not evident (Appendix I.3). The ostracode *L. staplini* dominated the record, followed by *I. bradyi*, *C. beaconensis*, and *C. patzcuaro*. The remaining ostracode species (*C. glaucus*, *C. vidua*, and *P. smaragdina*) occurred occasionally (Appendix I.4). Mollusks were extremely rare to rare in two of the samples (strata 59.13 and 59.16), but were represented by *P. virgata*, *Fossaria* sp., and *Gyraulus* sp. (Appendix I.5).

Feature 9 consisted of two samples from natural strata (stratum 2.1 and stratum 2.2), the post-abandonment and matrix units, respectively. The sediments were brown (10YR 5/3) sandy silt and sandy silty clay (Appendix I.1). Quartz and feldspars were the dominant minerals. Biotite, muscovite, and charcoal were moderately common to very rare. Other minerals occurred occasionally (Appendix I.2). Extremely rare to rare ostracodes and plant debris were identified in these samples. Low fragmentation and abrasion (5%) characterized both units. Other parameters were not significant (Appendix I.3). Ostracodes *C. beaconensis* and *C. vidua* occurred in stratum 2.1, whereas *H. brevicaudata* and *I. bradyi* were present in stratum 2.2 (Appendix I.4).

Feature 19 consisted of nine samples from canal fill sediments formed by brown (10YR 5/3) to light brownish gray (10YR 6/2) sandy silt to silty clay (Appendix I.1). Quartz, feldspars, and tufa were the dominant minerals. Biotite, muscovite, and charcoal were common to very rare. Other minerals, including gypsum (in stratum 59.15) occurred occasionally (Appendix I.2). Extremely rare to very rare ostracodes and mollusks occurred in this canal. Low to high fragmentation and abrasion (5%-70%) characterized the sediments. No evidence of encrustation, coating, and staining were recorded (Appendix I.3). The ostracodes *L. staplini*, *C. beaconensis*, and *C. vidua* occurred in Feature 19 (Appendix I.4). Mollusks identified include *P. virgata*, *Fossaria* sp., *Vivipara* sp. cf. *V. intertextus*, *Gyraulus* sp., and an unknown pelecypod (Species 1) (Appendix I.5).

Feature 22 consisted of five samples of canal fill sediments composed of brown (10YR 5/3) to pale brown (10YR 6/2) sandy silt to silty clay (Appendix I.1). Quartz and feldspars dominated the mineralogical record followed by biotite, muscovite, tufa, and charcoal. Other minerals occurred occasionally (Appendix I.2). Ostracodes, mollusks, gyrogonites, and plant debris ranged from extremely rare to abundant. Taphonomically, low (5%-10%) fragmentation and abrasion characterized the canal. No evidence of other parameters was identified (Appendix I.3). *L. staplini* and *I. bradyi* dominated the ostracode record. *C. beaconensis*, *C. glaucus*, *C. vidua*, *C. patzcuaro*, and *Limnocythere* sp. cf. *L. paraornata* occurred occasionally throughout the canal sediments (Appendix I.4). Extremely rare specimens of *P. virgata* were the only mollusks identified in the lower three strata (Appendix I.5).

GR-1439

Feature 1, the only canal analyzed from GR–1439, consisted of eight samples from canal fill sediments (stratum 59.1 through stratum 59.5, and stratum 59.9) and the post-abandonment (stratum 2.1) and matrix (stratum 2.3) natural beds. The sediments ranged from pale brown (10YR 6/2) to dark yellowish brown (10YR 4/4) gravelly sandy silt to silty clay (Appendix I.1). Quartz and feldspars were the dominant minerals. Biotite, muscovite, and charcoal present in all samples were moderately common to very rare. Other minerals occurred occasionally (Appendix I.2). Ostracodes were extremely rare to very abundant, but mollusks were extremely rare to very rare; gyrogonites were very rare to very abundant, and plant debris was present. Fragmentation and abrasion were low to moderately low (5%-15%). No evidence of other parameters was recorded (Appendix I.3). The ostracodes *C. glaucus* and *I. bradyi* dominated the canal, followed by *L. staplini* towards the end of the record. *C. patzcuaro* and *H. brevicaudata* occasionally occurred at the base of the canal history (Appendix I.4). *P. virgata* was the only mollusk identified in Feature 1, including a single, fragmented shell in stratum 2.1 (Appendix I.5).

GR-1440

Feature 1 consisted of seven samples from canal fill sediments and two natural beds (strata 2.1 and 2.4) composed of light brownish gray (10YR 6/2) to dark yellowish brown (10YR 4/4) gravelly sandy clay to silty clay (Appendix I.1). Quartz and feldspars are the dominant minerals followed by biotite, muscovite, and tufa. Other minerals occurred occasionally (Appendix I.2). Ostracodes were extremely rare to extremely abundant. Mollusks were very rare to common. Gyrogonites were extremely rare to very rare. Plant debris was present in most samples. The taphonomic parameters indicate low (5%) fragmentation and abrasion and no evidence of other features (Appendix I.3). *C. glaucus* was the dominant ostracode species, although *I. bradyi* and occasionally *L. staplini* also occurred (Appendix I.4). *P. virgata* was the dominant mollusk; *Gyraulus* sp. rarely occurred (Appendix I.5).

Feature 2 consisted of three samples of canal fill stratigraphically preceding Feature 1. Grayish brown (10YR 5/2) silty clay was the main sediment (Appendix I.1). Tufa, quartz, and feldspars were the dominant minerals; biotite and muscovite were also present. Other minerals occurred occasionally (Appendix I.2). Ostracodes were very rare to very abundant, but mollusks and gyrogonites were extremely rare. Plant debris was present throughout the canal sediments. Low fragmentation and abrasion (5%) characterized the micro-invertebrates. Encrustation, coating, and staining were not present (Appendix I.3). *C. glaucus* was the dominant ostracode; *L. staplini*, *C. vidua*, and *I. bradyi* rarely occurred (Appendix I.4). The mollusk *Gyraulus* sp. occurred once in stratum 59.7 (Appendix I.5).

Interpretation

The paleoecological reconstructions of the irrigation canals found during data recovery for the SFPP East Line Expansion Project require that each feature be analyzed independently. Based upon the ecological requirements of the species present (Table 19.1), three ostracode assemblages were recognized. Using Eugster and Hardie's (1978) hydrochemical pathway model, three water types can be identified; **I**: Ca^{2+}/HCO_3^{-} in equilibrium, dominated by Na^+, Mg^{2+}, SO_4^{2-} or Cl^-; **II**: Ca^{2+}-rich/HCO_3^{-}-depleted, dominated by Na^+, Mg^{2+}, SO_4^{2-} or Cl^-; and **III**: HCO_3^{-}-rich/ Ca^{2+}-depleted, dominated by Na^+, Mg^{2+}, SO_4^{2-} or Cl^- (see Table 19.1).

Assemblage I is dominated by *I. bradyi* and represents a dilute water environment associated with *L. staplini* and decreasing occurrences of *C. glaucus*, *C. vidua*, *C. patzcuaro*, and *P. smaragdina*. The dilute condition of the environment is interpreted from the occurrence of an adulthood index between 40% and 80% among most species present (Appendix I.4). Salinity ranged from 500 mg L^{-1} to 1,000 mg L^{-1} total dissolved solids (TDS); water chemistry was dilute Type I.

Assemblage II is dominated by *C. glaucus*, an increasingly saline environment indicator, and *I. bradyi*; minor occurrences of *L. staplini*, *C. patzcuaro*, *H. brevicaudata*, and *C. vidua* are also documented. This assemblage indicates that salinity was greater than 1,000 mg L^{-1} but less than 4,000 mg L^{-1} TDS in which *C. glaucus*, and to a lesser degree *I. bradyi* and *L. staplini*, established a biocenosis. The adulthood percentage ranged from 5 percent to 80 percent. The water chemistry corresponds to saline Type II.

Assemblage III is dominated by *L. staplini* and *C. beaconensis*, which are indicative of hypersaline conditions; *I. bradyi* is also associated with this assemblage, while *H. brevicaudata*, *C. patzcuaro*, *P. smaragdina*, *C. vidua*, and *C. glaucus* occur infrequently. Salinity ranged between 1,000 mg L^{-1} and 4,000 mg L^{-1} TDS. The high abundance of the hypersaline indicators *L. staplini* and *C. beaconensis* suggests values closer to 4,000 mg L^{-1} TDS. This interpretation is supported by the occurrence of gypsum in canals where this assemblage is recorded. The adulthood percentage ranged from 30 percent to 80 percent and indicates the three main species established a biocenosis. The water chemistry evolved to hypersaline Type II.

The mollusk record was not diverse and rich enough to establish ecological assemblages. However, the occurrence of gastropods and occasionally pelecypods indicates some environmental conditions comparable and complimentary to the ostracode record. Mollusks are related to periods of water input and seasonality based on the occurrence and abundance of juveniles and/or adults (Rutherford 2000). Lotic (well-oxygenated, flowing water) and lentic (poorly-oxygenated, slow or standing water) species provide information about the canal conditions (Rutherford 2000). Species like *Physa virgata* and *Stagnicola elodes* can tolerate some organic pollution and eutrophic conditions (Dillon 2003). The planorbid *Gyraulus* sp. is a cosmopolitan species capable of living in well- or poorly-oxygenated, lentic or lotic waters, that is, it is a eurytopic species (Rutherford 2000) (see Table 19.2). *Fossaria* sp. and *Vivipara* sp. cf. *V. intertextus* are common in riparian and marsh environments, whereas *Anculosa* sp. cf. *A. praerosa* prefers rocky substrates but may occur in stream systems (Webb 1942) (Table 19.2).

The gyrogonites of *Chara* are used in this study as indicators of water alkalinity, time of colonization, and low flow or standing water conditions (Feist 2003). Their occurrence in irrigation canals may imply the first occupation of a biological group in the system. During photosynthesis, *Chara* removes bicarbonate from the water column in the vicinity of its stems, creating a zone of higher pH and causing a shift in the carbonate equilibrium that results in the calcification of the gyrogonites, the fertilized female gametangia (García 1994). García (1994) indicates that *Chara* gyrogonites calcify at different intervals within the same algae, and it is not uncommon for them to be exposed to the atmosphere during times of lower water volume.

Based upon these assemblages, the paleoenvironmental history of each canal is inferred as follows:

GR-893 (Hohokam canals)

No paleoecological interpretation is available for canals in this site due to the absence of micro-invertebrates. The paleohydraulics of the canal, however, are inferred from the grain-size diagrams obtained from each of the three canals. Figure 19.1 shows that Feature 25.01 was dominated by a slow streamflow. Grain-size increased from the fine matrix to the canal fill sediments. Grain-size did not show a significant change after the canal was abandoned. The grain-size cannot explain the poor micro-invertebrate record composed of single shells of *Gyraulus* sp. in stratum 2.2, and *Anculosa* sp. cf. *A. praerosa* in stratum 59.1. Apparently, both shells were intrusive to the site. The poor, intrusive record prevents further interpretation.

Feature 60 consisting of only two samples indicates sediments were transported by a slow streamflow (Figure 19.1). Sediment accumulation remained constant from deposition of stratum 59.1 and stratum 59.2. Absence of micro-invertebrates is not explicable. No paleoecological interpretation is warranted with the current information.

Feature 96 indicates the canal was subject to a slow streamflow with a brief pulse of relatively faster runoff that gradually decreased towards the end of the record (Figure 19.1). Based upon grain-size the unfossiliferous nature of this canal cannot be explained. It is not possible to infer the paleoecology of the canal based on the current record.

GR-894 (pre-Classic to Classic Hohokam period canals)

The Feature 6 canal was excavated into a fine sediment matrix. Streamflow remained slow during canal operation (Figure 19.2). Grain-size increased slightly during deposition of stratum 2.1, the post-abandonment sediments, a typical floodplain deposit. *L. staplini* and *I. bradyi* entered the canal establishing a biocenosis (Figure 19.6). *C. patzcuaro* was also introduced but did not succeed in this environment. The occurrence of gypsum in the sediments indicates a relatively saline environment. Gypsum was present in the matrix sediments, thus it is likely that the presence of calcium sulfate in solute composition inhibited *C. patzcuaro*. *L. staplini*, however, found the optimum environment in which to settle (Forester 1983). Increasing concentration of gypsum is associated with the occurrence of *C. beaconensis* and substantial decrease of *I. bradyi*. The paleosalinity index indicates Feature 6 was probably in use during evaporative environmental conditions (late summer or a hot year). Hypersaline conditions were reached in this canal (1,000 mg $L^{-1} < n <$4,000 mg L^{-1} TDS) as represented by Assemblage III, and most likely conditions were closer to the upper limit as indicated by the occurrence of gypsum. Hypersaline, SO_4^{2-}-rich water indicates the system initially was Type III diluting to Type I with water discharge. Unsaturated sulfates allowed a greater concentration of Cl^-, as indicated by the occurrence of *C. beaconensis*, a species that prefers chloride-rich conditions.

Feature 10 consisted of fine sediments with two brief discharge pulses recorded by the grain-size analysis (Figure 19.2). Slow streamflow initially entered the canal, increased in velocity by stratum 59.3, but rapidly returned to its former velocity. Later in the record (stratum 59.7), water discharge occurred again. Regardless of the slow streamflow, rare ostracodes mollusks and gyrogonites occurred in this canal. Gypsum was moderately common in the lower unfossiliferous strata indicating hypersaline conditions (Appendix I.3). *L. staplini* entered the canal (stratum 59.4), but disappeared to be replaced by *I. bradyi* (stratum 59.7) (Figure 19.7). Ecological relief from Assemblage III to Assemblage I is consistent with a period of increasing water discharge that introduced dilute water. *Gyraulus* sp. and two specimens of *P. virgata* were the only mollusks present in this canal. Both species occurred during deposition of stratum 59.4, consistent with a slow streamflow. The single gyrogonite of *Chara* cannot be interpreted except as an intrusive specimen, however, its occurrence indicates alkaline conditions in good agreement with ostracodes and mollusks. The water salinity decreased from hypersaline to relatively dilute, however, the limited biological content prevents proposing a more specific salinity range.

Feature 11, a canal excavated into Feature 10, was characterized by slow streamflow throughout its record with a minor increase in grain-size in the upper unit (stratum 59.4) (Figure 19.2). Ostracodes were introduced into the canal at the end of the record. Based on the occurrence of adult *I. bradyi*, it is inferred that Assemblage I characterized stratum 59.4 (Figure 19.8), however, the population is extremely poor to make a definite interpretation. Absence of *L. staplini* and *C. beaconensis* in this canal indicates the canal was fed by dilute water. Absence of juveniles suggests the fauna was intrusive. Extremely rare mollusks occurred in stratum 59.1 and stratum 59.4. *Fossaria* sp. and *Gyraulus* sp. were introduced at the base of the canal. As indicated by the adulthood percentage (30%-50%), the two species established an incipient community but the poor record does not allow further interpretation. An intrusive shell of a *P. virgata* juvenile also indicates the micro-invertebrate was introduced but unable to settle (Appendix I.5).

GR-895 (pre-Classic to Classic period canals)

Feature 7 shows that the canal was excavated into a fine sand matrix. The early sediments introduced by slow streamflow allowed the deposit of fine sediments dominated by silty clay. The grain-size diagram indicates that slow streamflow continued through accumulation of strata 59.1 and 59.2 (Figure 19.3). Increasing streamflow is shown by grain-size coarsening during deposition of stratum 59.6, which is consistent with the laminated sand beds of the preceding stratum (59.5, not analyzed for micro-invertebrates). Streamflow decreased and remained slow throughout the rest of the canal history. The biological record indicates that ostracodes, mollusks, and gyrogonites occurred in the canal. Ostracodes entered the canal during deposition of stratum 59.2 (Figure 19.9). Assemblage III (*L. staplini*-dominated) characterized this episode. As *L. staplini* colonized the site, water salinity increased allowing the precipitation of tufa. Assemblage III (*L. staplini*-dominated) characterized the canal history between stratum 59.2 and stratum 59.8. Salinity ranged from 1,000 mg L^{-1} to 4,000 mg L^{-1} TDS. A slight increase in grain-size after stratum 59.8 indicates increasing discharge. Assemblage I (*I. bradyi*-dominated) replaced the saline Assemblage III, but *I. bradyi* alternated with *L. staplini* and with *C. beaconensis,* which indicated the saline origin of the waters. The dilute conditions of the upper sedimentary units allowed a diverse mix of fauna including the gastropods *P. virgata*, *Fossaria* sp., and *Gyraulus* sp., and the gyrogonites of *Chara*. This diversity suggests salinity decreased to concentrations close to 1,000 mg L^{-1} TDS.

Feature 9, represented by two natural deposits, shows a fine sediment composition (Figure 19.3). The grain-size diagram may not be indicative of flow unless the lower stratum (2.2) represents a freshwater marsh as suggested by the occurrence of *I. bradyi* and *H. brevicaudata* (Figure 19.10) and stratum 2.1 represents post-abandonment floodplain sediments. Reporting of the paleoecological history of Feature 9 is not warranted because canal fill samples were not analyzed at this time. Absence of the previously deposited species in the post-abadonment stratum indicates the latter sediments were carried out by saline waters that contained *C. beaconensis* and *C. vidua*. Salinity in the area changed from 1,000 mg L^{-1} to 4,000 mg L^{-1}. No other biological remains were recorded; however, the occurrence of adults and juveniles of *I. bradyi* in stratum 2.2 and *C. beaconensis* in stratum 2.1 is inferred to represent incipient biocenosis, that is, the species settled at this site (Appendix I,4).

Feature 19 shows slow streamflow during deposition of stratum 59.1 through stratum 59.3 (Figure 19.3). Deposition continued, but later the canal was re-shaped. The second canal analyzed in this study consisted of the remaining stratigraphic units documented in Appendix I.1. Three cycles of streamflow characterized canal operation. In stratum 59.6, sediments accumulated during an increasing sedimentation rate. A second discharge episode occurred during deposition of stratum 59.8. Streamflow decreased and a third discharge event occurred, depositing coarser sediments in stratum 59.15. Ostracodes and mollusks were scarce in this canal. Three saline ostracode species were introduced but failed to settle in this system (Figure 19.11). Assemblage III including *L. staplini*, *C. beaconensis*, and *C. vidua* dominated the canal history. Among mollusks, the occurrence of *Fossaria* sp. and *Vivipara* sp. cf. *V. intertextus* (riparian) at slow streamflow intervals and the poor ostracode record indicates water did not last long in this canal. The feature was used during a warm season or year for short periods of time. In other words, each stratum represents a brief period of canal operation.

Feature 22 shows a highly controlled streamflow (Figure 19.3) throughout canal history consistent with the profile description (see Figure 7.77). In general, decreasing discharge may be interpreted from the upwards trend of the occurrence of finer-grained sediments. This canal contained a rich and diverse biological record (Tables 19.3, 19.4, and 19.55). Ostracodes occurred in all five samples, mollusks were not abundant but present in the lower three units, and gyrogonites were common throughout the stratigraphy. Assemblage III, initially dominated by *C. beaconensis* and then by *L. staplini*, entered the canal. Salinity remained relatively high as shown by the increasing abundance of *L. staplini*. A bloom of *I. bradyi* competing with *L. staplini* in stratum 59.6 indicates decreasing salinity in the system (Figure 19.12). *P. virgata* was the only gastropod present in three strata. Towards the end of the record, mollusks and gyrogonites disappeared and ostracodes abruptly declined. The paleosalinity index suggests Assemblage I, a dilute water system, replaced Assemblage III; however, the poor record and the fine sediments are more consistent with a riparian environment prior to canal desiccation. Feature 22 was also used during a warm season or year.

GR-1439 (Santa Cruz Ditch; Historic Canal: 1877-1914)

Feature 1 was characterized by a relatively fast streamflow during the initial discharge (Figure 19.4). A second discharge pulse was recorded at stratum 59.3. Between these two events, flow declined significantly allowing settlement of ostracodes, mollusks, and calcareous algae (Tables 19.3, 19.4, and 19.5). Ostracode Assemblage II (*C. glaucus*-dominated) established a community in this canal. *L. staplini* and *I. bradyi* accompanied *C. glaucus* during the early biocenosis (Figure 19.13). Gradually, *I. bradyi* replaced *C. glaucus* as *L. staplini* also declined, indicating a dilute water environment. Salinity declined from values near 4,000 mg L^{-1} TDS to a range closer to 1,000 mg L^{-1} TDS. Mollusks, however, did not succeed in this environment. Extremely rare to very rare *P. virgata* occurred near the base of the canal but disappeared in later deposits. Similarly, the gyrogonites of *Chara* occurred in lower strata but were absent in upper strata. Current information does not allow for an explaination of the reason(s) for the disappearance of algae and mollusks as the water dilutes.

GR-1440 (Hoover Ditch; Historic Canal: 1873-1914)

Feature 2 shows a continuous slow flow following the initially relatively fast discharge (Figure 19.5). Abundant ostracodes but extremely rare mollusks and calcareous algae characterized this canal (Appendix I.3). An almost monospecific ostracode Assemblage II (*C. glaucus*-dominated) occurred throughout the canal, reaching its optimum in stratum 59.6 (Figure 19.14). Salinity ranged between 1,000 mg L^{-1} early in the history of the canal and 4,000 mg L^{-1} towards the end of the record. A single shell of *Gyraulus* sp. and four gyrogonites were introduced to stratum 59.7.

Feature 1, cut into part of Feature 2, shows a relatively fast streamflow during its early stage. Discharge decreased allowing settling of finer sediments (Figure 19.5). Strongly dominated by *C. glaucus*, Assemblage II characterized the canal history. Minor and occasional occurrences of *L. staplini* and *I. bradyi* broke the monotony of the assemblage (Figure 19.15). It is inferred that salinity was greater than 2,000 mg L^{-1} TDS because of the almost monospecific composition of the assemblage. The poor mollusk and algae records cannot be used to interpret the paleoenvironmental history of the canal.

Discussion and Conclusions

Canal irrigation was an important component of land-use through time in Arizona. Current results indicate that the early agriculturalists in the Tucson Basin developed irrigation in southern Arizona as early as 3200 years ago (Mabry 2000). In recent years, the study of irrigation systems on the GRIC has provided a wealth of information concerning Hohokam and historic Akimel O'odham canals, but little is known about nineteenth and early twentieth century Anglo-American irrigation. The present study provided a unique opportunity to analyze pre-Classic to Classic period Hohokam irrigation in comparison with canals constructed between 1873 and 1877 and that were still in use until 1914. Eleven prehistoric irrigation canals and two historic canals were part of this study.

One of the main findings of this study is the major faunal change between the prehistoric and historic canals. For example, the Hohokam canals were characterized by one of two assemblages: Assemblage I (*I. bradyi*-dominated) frequently alternated with Assemblage III (*L. staplini*- or *C. beaconensis*-dominated); water chemistry evolved from one to the other. At GR-894, the canals were characterized by hypersaline water as indicated by the occurrence of gypsum throughout Feature 6 and several samples in Feature 10. Absence of this mineral is also marked by the absence of *L. staplini* and *C. beaconensis* in Feature 11, indicating the canal was in use during a different season, probably at the beginning of the spring when *Fossaria* sp. and *Gyraulus* sp. were introduced to the system.

Although the ostracode assemblages at GR-895 were the same as those found at GR-894, these canals did not contain gypsum and the occurrence of *C. beaconensis* increased, suggesting salinity decreased, which allowed for a more diverse assemblage including mollusks and algae. Feature 9 included two natural strata but no canal fill sediments. From the canal profile, canal fills seem an important source of information for the reconstruction of canal operation. More importantly, because this canal appears to have been excavated on a marsh deposit it is critical to analyze the canal fill strata for comparison with the historic period canals containing a different ostracode assemblage, as discussed below.

By contrast, the historic canals from GR-1439 and GR-1440 were characterized by an ostracode fauna dominated by *C. glaucus*. Decreasing abundance of *L. staplini* associated with the increasing concentration of *I. bradyi* indicates the canals became more dilute through time. This assemblage indicates two hypotheses; one, that the water chemistry of the Gila River changed since the last Hohokam occupation of the area or two, that the water source for the historic period canals was different. It seems unreasonable to believe that the Gila River water chemistry changed between the prehistoric periods and the historic period to the point of favoring the introduction of a different species mostly absent during Hohokam time. Instead, the most plausible hypothesis is that the Anglo-American settlers used a different water source, such as ground water or wetlands in the vicinity of the site. It is still uncertain if these canals were fed from local wetlands; the presence of wetlands requires further analysis of samples associated with the matrix substrate where these canals were dug at the end of the nineteenth century.

Most canals analyzed started with saline or hypersaline water and gradually changed to more dilute conditions, suggesting that these canals were mostly operated during the hottest season or during highly evaporative years.