

**PALEOENVIRONMENTS OF THE BAY OF CARTHAGE  
BASED ON OSTRACODE FAUNA**

**A thesis submitted to the faculty of the Graduate School  
of the University of Minnesota**

**by**

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## TABLE OF CONTENTS

ACKNOWLEDGMENTS .....	i
TABLE OF CONTENTS .....	ii
LIST OF TABLES .....	iv
LIST OF TEXT-FIGURES .....	iv
INTRODUCTION .....	1
STUDY AREA .....	6
METHODS .....	7
RESULTS .....	13
Faunal Analyses .....	13
Sediment Analyses .....	25
Microprobe Analyses .....	29
DISCUSSION .....	38
SYSTEMATIC DESCRIPTIONS .....	46
<u>Cytheridea</u> sp. ....	46
<u>Cyprideis torosa</u> .....	46

<u>Hemicytherura</u> sp. . . . .	46
<u>Aurila convexa</u> . . . . .	46
<u>Lepthythere</u> cf. <u>fabaeformis</u> . . . . .	46
<u>Loxoconcha elliptica</u> . . . . .	47
<u>L. rhomboidea</u> . . . . .	47
<u>Actinocythereis</u> sp. . . . .	47
<u>Carinocythereis carinata</u> . . . . .	47
<u>Xestoleberis</u> sp. . . . .	47
REFERENCES . . . . .	48
PLATES . . . . .	52

## LIST OF TABLES

Table I. Ostracode assemblages and their related environments . . . . .	15
Table II. Sediment analyses data from Cores 1, 6, 11, 12, 14, and 20 . . . . .	26
Table III. Microprobe analyses for Cores 12 and 20 (the data are given in weight percent). . . . .	35

## LIST OF TEXT-FIGURES

Figure 1. Map showing location of Carthage and inset map of Tunisia, Africa (from Rapp and Gifford, 1985). . . . .	2
Figure 2. Map of Carthage showing ancient ruins as well as remnants of the Punic harbors (after Raban et al., 1985). . . . .	3
Figure 3. Medjerda River Basin (after Mansouri-Menaouar, 1979). . . . .	4
Figure 4. The geomorphic evolution of northeastern Tunisia between 6000 B.C. and 1600 A.D. (after Thornton, 1980). . . . .	5
Figure 5. Location of surficial sediment samples on the harbor area (map after Rapp and Gifford, 1985) . . . . .	8
Figure 6. Location of surficial sediment samples in the Lake of Tunis. . . . .	9
Figure 7. Drill core locations in the circular and rectangular harbors. . . . .	10
Figure 8. Speculative time-sequence diagrams of the evolution of the harbors. . . . .	30
Figure 9. Speculative time-sequence diagram of the evolution of the Punic harbors. . . . .	31
Figure 10. Mg/Ca ratios of ostracode carapaces from Core 12. . . . .	33
Figure 11. Mg/Ca ratios of ostracode carapaces from Core 20. . . . .	36

**Figure 12. Speculative diagrams of the evolution of the harbors; a) harbors during time of Punic Carthage, b) Roman Carthage, c and d) isolation and restriction of harbors from the Mediterranean from longshore drift . . . . . 44**

## INTRODUCTION

This work describes the reconstruction of the paleoenvironmental and paleogeographical conditions of two harbors near the ancient city of Carthage. Ancient Carthage was located on the Mediterranean Sea in what is now northern Tunisia, along the Gulf of Tunis (figure 1). The two harbors lay on the western edge of the Gulf, adjacent to modern Carthage (figure 2).

Carthage was first settled by the Phoenicians in the 9th century B.C. The Punic Carthaginians (Punic is derived from Phoenician (or Poenicus) and refers to the race or culture of the Carthaginians as well as their city built an elaborate set of harbors to house both naval and commercial vessels. The remnants of those harbors, which occur adjacent to the modern city of Carthage, stand as ghosts to the once powerful Punic naval regime. In 146 B.C., Punic Carthage was conquered by the Roman Empire during the Third Punic War. The Romans set the stage for many of the physical changes that occurred in the area surrounding Carthage (Warmington, 1967).

The Romans deforested much of northern Africa, particularly in the area of the Medjerda River basin, for the production of grain (figure 3). Although the intent was to increase arable land, the results were disastrous. After deforestation, the erosion rate increased dramatically. Large amounts of sediment were carried by the Medjerda River and deposited in the Mediterranean Sea. The deposition of the large influx of sediment caused the formation of a large delta at the mouth of the Medjerda River. Sediments were also picked up by longshore currents and redeposited downshore. Over the centuries the redeposition caused many changes in the coastal morphology (figure 4), including the formation of baymouth bars, spits, and local sabkhas (Thornton, 1980).

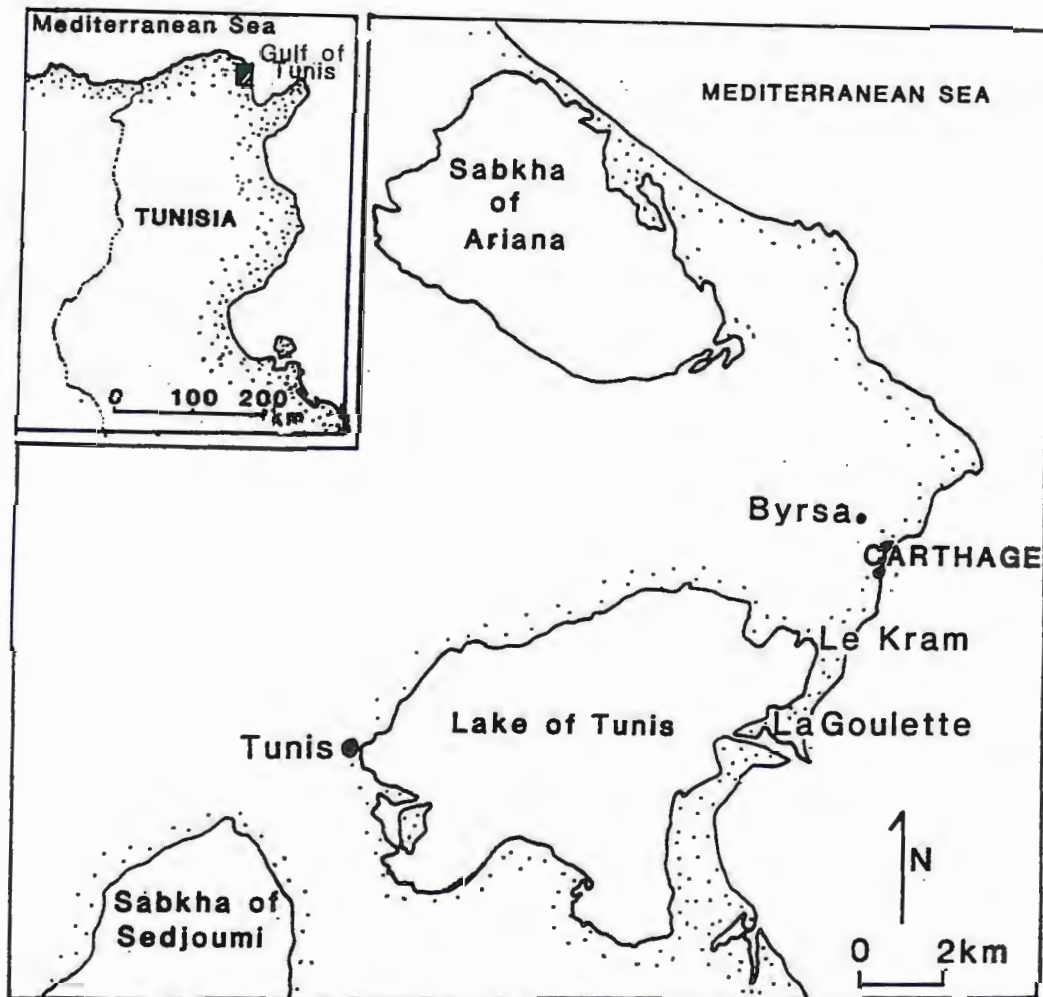


Figure 1. Map showing location of Carthage and inset map of Tunisia, Africa (from Rapp and Gifford, 1985).



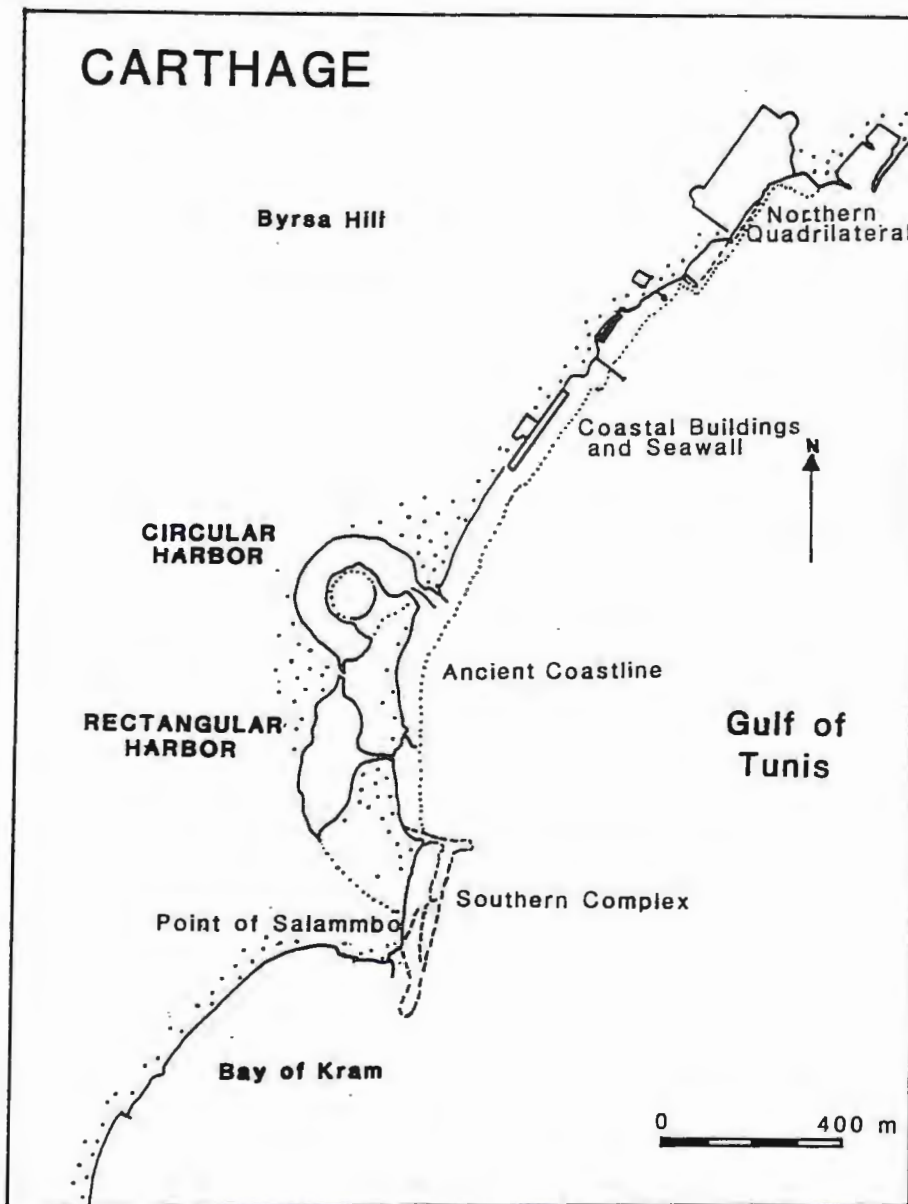


Figure 2. Map of Carthage showing ancient ruins as well as remnants of the Punic harbors (after Raban et al., 1985).

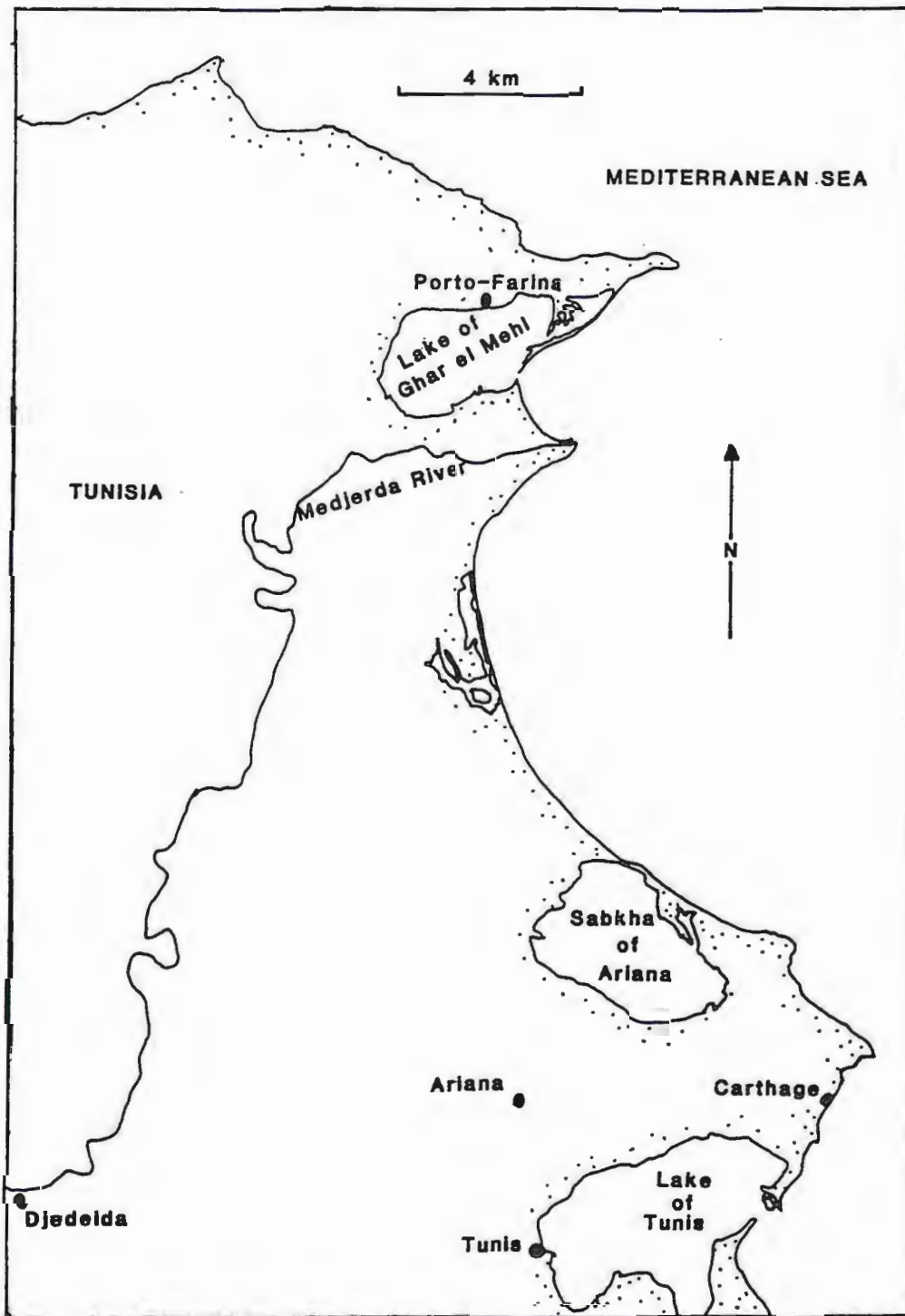


Figure 3. Medjerda River Basin (after Mansouri-Menaouar, 1979).

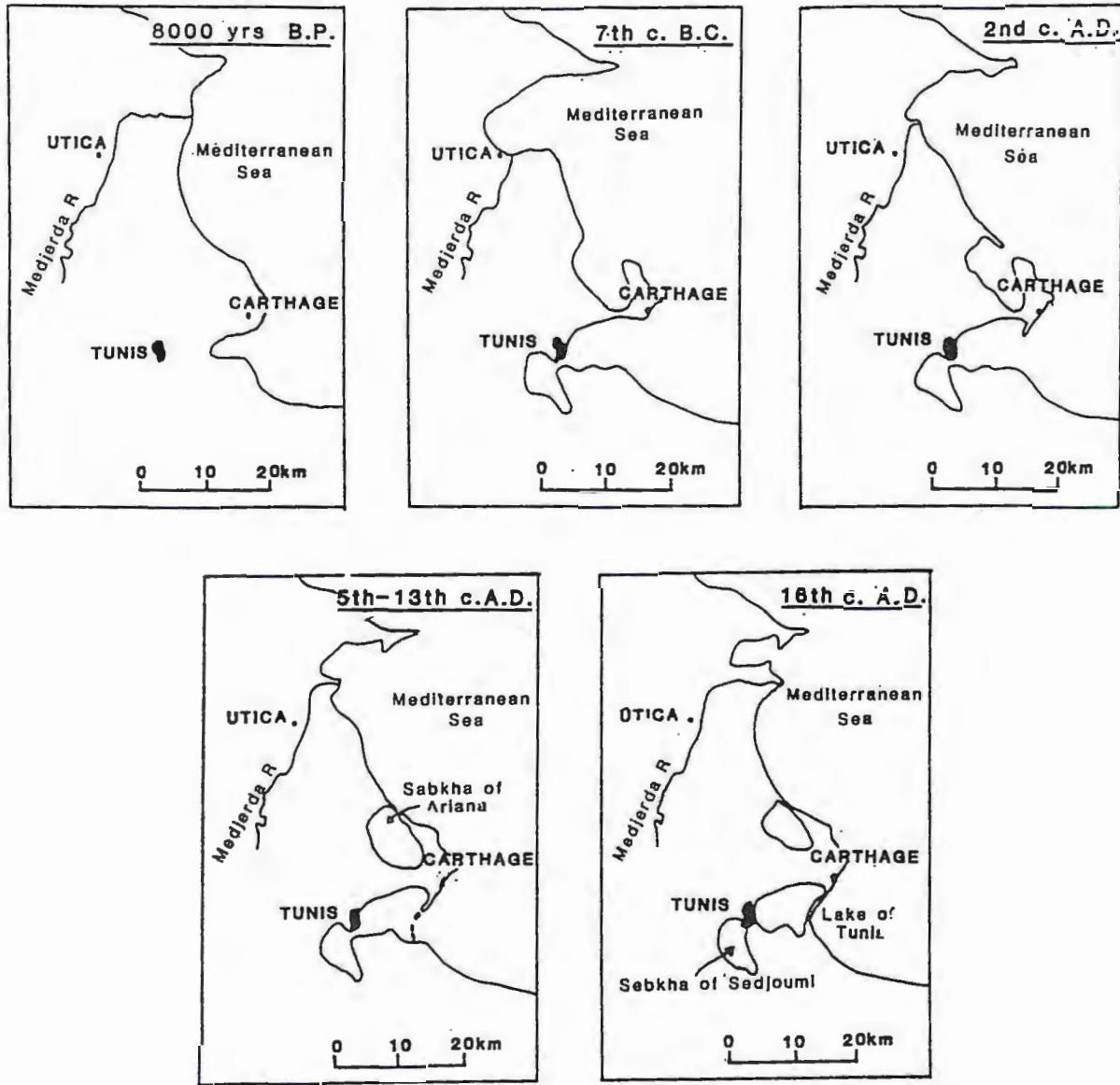


Figure 4. The geomorphic evolution of northeastern Tunisia between 6000 B.C. and 1600 A.D. (after Thornton, 1980).

The accessibility of the Carthaginian harbors was thought to have been directly affected by these geomorphic changes that occurred after the Roman deforestation. Therefore, the morphologic changes within the Bay of Carthage are a significant component of historical research on ancient Carthage. The location of the harbors and their entrance is of importance when unravelling the history of the development and downfall of Punic Carthage.

The reconstruction of the harbors is based primarily on the correlations of ostracode (Crustacea: Ostracoda) faunal assemblages from four surficial sediment samples and eight cores drilled within the area. Additional information for the reconstruction was gained from Mg/Ca ratios of ostracode carapaces and from sediment analyses.

This study is part of a large project, headed by Dr. George Rapp, involving the reconstruction of pre-Roman Carthage. The objective of this study is to reconstruct the geography of the area occupied by the harbors from Punic to Roman time in order to better understand Punic Carthage and the changes that resulted from the Roman occupation.

The interpretations of the paleoenvironments of Carthage are presented in terms of significant geologic changes that have occurred during the past several thousand years, changes which have affected the accessibility to the harbors.

## STUDY AREA

Classic ostracode work in the Mediterranean has been completed by Brady (1880), Muller (1984), Reys (1961), Rome (1964), and Puri et al. (1969). Microfaunal analyses and sediment analyses have been completed on sediments collected near the city of Carthage. The

ostracode faunal associations from the Lake of Ghar-el-Melh and the Sabkha of Ariana (figure 3) were described by Mansouri-Menaouar (1979). He also completed a number of sediment studies, including particle size analyses and x-ray diffraction of the clays. Ostracode faunal assemblages from surficial sediments and drill core from the Lake of Tunis have been studied by Jouirou (1982) as well as by Carbonel and Pujos (1981 and 1982). Thornton (1976) briefly describes the ostracode assemblages in the Lake of Tunis in his sedimentologic description of the lake. Unpublished paleoenvironmental reconstructions have been completed on samples identical to those within this study: pelecypod work by J. Zaouili and foraminiferal analyses by Omrane. The variations in ostracode assemblages and sediment analyses, as the Punic harbors changed through time, will be used to provide a paleoenvironmental reconstruction.

The harbors of Carthage are of two different forms, one circular and the other rectangular. The circular naval harbor, centered by a quay that held as many as 220 military vessels, was 330 meters in diameter. This was connected by a small channel to the rectangular harbor. The rectangular harbor, 530 x 330 meters, housed the commercial vessels (Warmington, 1967). The entrance to the ports is thought to have been on the south side of the rectangular harbor (Raban, 1985). The study area includes the circular and rectangular harbors and the probable entrance to the harbors as well as the Lake of Tunis (see figures 5 and 6).

## METHODS

Samples were collected by George Rapp, Jr. and John Gifford during the summers of 1985 and 1986. The samples were processed for micropaleontology and grain size distribution at the University of Minnesota-Duluth. Eight of the twenty cores drilled within the area were used in this reconstruction (figure 7). Cores 4, 7, and 11 were drilled in the circular military harbor. Cores 1 and 12 were drilled within the rectangular harbor. Core 14 was drilled in the

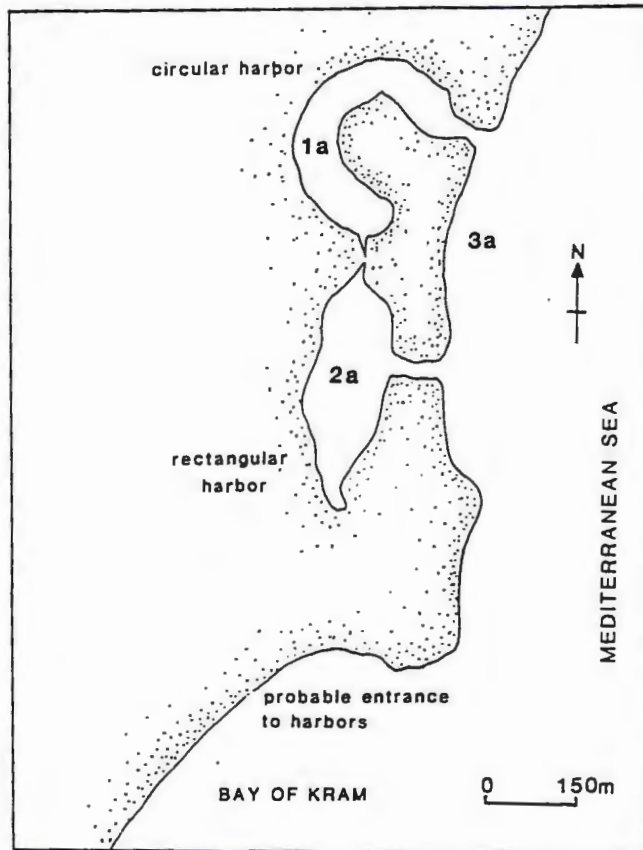
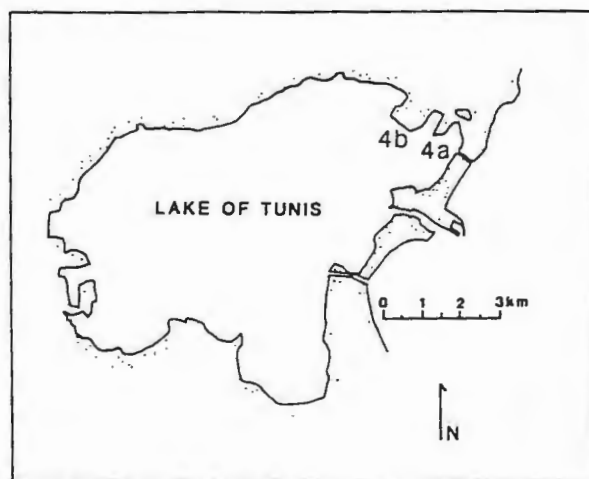


Figure 5. Location of surficial sediment samples on the harbor area (map after Rapp and Gifford, 1985)

topographic low south of the rectangular harbor, and Core 20 was drilled off-shore in the Bay of Kram; Cores 14 and 20 are thought to be at the site of the harbor entrance. Core 19 was drilled in the Lake of Tunis. Surficial sediments were sampled in four locations: the rectangular and circular harbors, in an open marine environment east of the harbors, and in the Lake of Tunis.



**Figure 6.** Location of surficial sediment samples in the Lake of Tunis.

After the cores were logged, one representative sample was taken from each stratigraphic unit. The samples were then bagged and mailed to the Archaeometry Laboratory at the University of Minnesota-Duluth. The grab (surficial) samples were put into 250 ml Nalgene bottles with 10% formalin solution and brought back to UMD for processing. The samples were then dried and split into 20.0 g and 7.5 g sub-samples for micropaleontology and sediment analyses, respectively. Individual ostracodes were also removed for the microprobe analysis.

**Micropaleontology:** For the micropaleontology work the 20.00 g sub-samples were washed through #40, 60, and 120 screens (0.35mm, 0.25 mm, and 0.125 mm respectively)

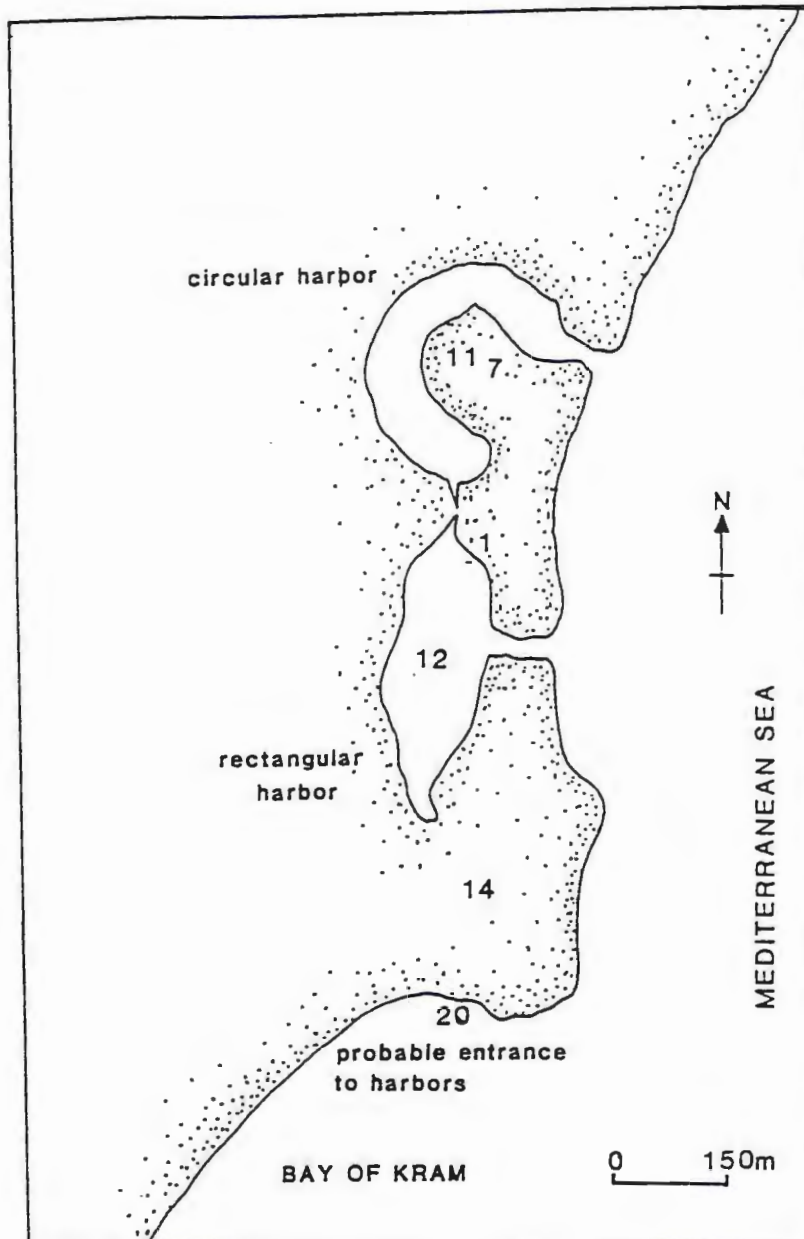


Figure 7. Drill core locations in the circular and rectangular harbors.

and the residue dried. The sieves were rinsed between individual sample runs in an alizarin red-S solution (Friedman, 1954). The solution red-stained the carapaces caught in the mesh of the sieves, allowing the recognition and avoidance of contamination in subsequent samples. The samples were spread on numbered counting trays and 100 ostracodes were removed with



a 00 sized brush. The ostracodes were placed on a labeled slide with tragacanth gum. Ostracode species, faunal assemblages, and faunal densities were then identified (Benson et al., 1985).

Sediment analyses: The 7.5 g sub-samples were separated in the laboratory for sediment analyses. The sand was separated from the silt and clay by wet sieving the sediment through twelve 3-inch sieves at one-half phi intervals (from -1.0 to 4.5 phi). The sand sized particles were dried and weighed. The fine fraction (silt and clay) that washed through the sieves was transferred to a 1000 ml settling cylinder. Twenty ml of buffered sodium hexametaphosphate dispersant of known weight was added to the fine fraction, and enough distilled water to make 1000 ml of liquid in the settling cylinder. The fine fraction analysis was completed by withdrawing 20 ml aliquots of suspended particles and dispersant solution at timed intervals. Samples were pipetted at whole phi intervals through 10 phi. After the pipetting was completed, the material was resuspended and a 20 ml sample was drawn at the 8 phi time for x-ray diffraction analysis.

After the samples were dried and weighed, the weights were entered into a grain-size distribution program designed by Gary Cabellaro at the University of Minnesota. Size class distributions and other statistical analyses, including skewness and kurtosis, were completed, and sand/silt/clay ratios were graphed for each sample.

Microprobe Analyses: The relative amounts of shell calcium and magnesium in a species of ostracode were found by microprobing the carapace. The microprobe technique described by Teeter (1986) was utilized in this study. The euryhaline ostracode Loxoconcha rhomboidea was chosen for the laboratory experiments. The ostracodes were removed from sub-samples of Core 12 (3.23-3.28 m, 3.70-3.73 m, 3.90-3.93 m) and Core 20 (3.40 m, 3.88

m, 4.40 m, 4.80-4.84 m). They were washed in distilled water and put into a 30% H<sub>2</sub>O<sub>2</sub> solution for 30 minutes to oxidize any organic matter on the carapace. The carapaces were dried and placed concave up on a glass slide with double-faced tape. A copper sleeve (1/4 inch outside diameter by 1/4 inch height) was positioned on the double-faced tape over the ostracodes. The glass slide (containing ostracodes and sleeves) was heated slightly on a warming plate, and Hillquist Thin Section Epoxy was poured into the sleeves. The air bubbles in the epoxy were forced to the surface by heating the slide slightly a second time. They and the bubbles adjacent to and inside the ostracode valves were removed with a fine dissecting needle.

After the epoxy cooled, the sleeves were removed from the glass slide and placed in a microprobe sample holder. The brass holder, designed by Quick (University of Akron), contains five holes into which the copper sleeves fit. The surfaces with the ostracodes were hand polished with grits ranging in size from 1000 um to .05 um. The brass holder and sleeves were put into an ultrasonic water bath for 30 minutes after polishing with each grit size. The ostracodes were prevented from being ground too far by repeated observation under a binocular microscope; this was particularly necessary in the later stages of polishing. After being ground, the ostracodes appeared elliptically shaped, as a transect was cut through the carapace. Before microprobing, the sleeve holder and sleeves were carbon-coated.

Samples were taken to the University of Wisconsin, Madison for microprobing. The samples were probed for Ca and Mg at 15 kV and  $4 \times 10^{-9}$  amps. Each ostracode valve was probed three times medially. Analytical results for magnesium and calcium are expressed as atomic ratios (Mg/Ca) for the ostracodes, and can be found in Table 3.

## RESULTS

### Faunal Analyses

Micropaleontologic analyses of samples from surficial sediment and drill core involved the identification of ostracode species, an estimation of the faunal density, and a quantitative analysis of the relative abundance of species in the samples (diversity). These parameters formed the basis for the reconstruction of the paleoenvironments.

The modern ostracode assemblages from the surficial sediment samples were used to define the biocoenoses of the different environments. Similar assemblages were found in the drill cores. Since the ostracodes from the drill cores were extremely well preserved, biocoenoses (representing their modern counterparts) and their respective environments were easily defined. The thanatocoenose assemblages were considered to be those distinguished by abraded valves.

The initial step in the reconstruction of the paleoenvironments was to observe the assemblages representing the modern harbor environments. Four different faunal assemblages were distinguished (Table I). The different assemblages were based on data from Jouirou (1982) and Mansouri-Menaouar (1979), who found certain ostracode assemblages were indicative of particular geographic areas in the coastal environments of the Carthage region. Although each assemblage is defined by ostracodes particular to one environment, one must realize that there is overlap between the assemblages. For instance, C. torosa is found to be the sole ostracode in Assemblage IV. Since it is a euryhaline ostracode however, it is also found in all of the other assemblages, although not in the same proportions. Hence some care must be taken in the interpretation of the data.

The first assemblage consists entirely of a polyspecific population of ostracodes containing from 10 to 15 individual species. The majority of the individuals in this assemblage include Loxoconcha rhomboidea, Aurila convexa, Carinocythereis sp., Actinocythereis sp., Cytheridea sp., and Hemicytherura sp.. This assemblage also includes many different benthic detrital feeders. The second assemblage contains primarily L. rhomboidea, Aurila convexa, and Leptocythere fabaeformis; minor abundances of C. torosa, L. elliptica and Xestoleberis sp. may occur. The third assemblage contains primarily C. torosa and Loxoconcha elliptica, with a minor occurrence of Xestoleberis sp.. The fourth assemblage consists entirely of a monospecific population of Cyprideis torosa.

The distribution of each assemblage is governed by a number of factors including the nature of the substrate and the mode of nutrition (Mansouri-Menaouar, 1979). For example, many benthic ostracodes prefer a particular type of substrate. Cyprideis torosa has an affinity for a muddy substrate because it is a benthic detrital feeder and gets its nutrients from the organic matter in the clay. Certain species of Loxoconcha also prefer a finer grained substrate, although their distribution is not as dependent upon the substrate as that of C. torosa. Many of the neritic benthic marine ostracodes, Aurila convexa and Carinocythereis carinata, for example, are found in association with coarser substrates (Benson, 1985).

The mode of nutrition of individual species is also useful in determining the different environments in which the ostracodes live. Loxoconcha elliptica, L. rhomboidea, Aurila convexa, and Carinocythereis carinata are phytal ostracodes; they live on or at the base of sea grasses and algae. Many of the phytal ostracodes live in association with the very common sea grass Posidonia oceanica. Posidonia oceanica is an endemic Mediterranean species that lives in clear shallow waters with salinities from 32-42 ppt (Thornton, 1980).

The presence of plants such as Posidonia is a very important factor in the distribution of phytal ostracodes and may explain their lack of dependence upon the substrate. Cyprideis torosa is a benthic detrital feeder. It is restricted in distribution to muddy substrates. The majority of species representing a marine assemblage are detrital feeders or are phytal ostracodes (Benson, 1985).

ASSEMBLAGE	PRIMARY OSTRACODE FAUNA	ENVIRONMENT
I	<u>Loxoconcha rhomboidea</u> <u>Aurila convexa</u> <u>Carinocythereis</u> sp. <u>Actinocythereis</u> sp. <u>Cytheridea</u> sp. <u>Hemicytherura</u> sp. <u>Costa</u> sp. <u>Heterocythereis</u> sp. <u>Cushmanoidea elongata</u> <u>Callistocythere</u> sp. benthic detrital feeders	normal marine
II	<u>L. rhomboidea</u> <u>Aurila convexa</u> <u>Leptocythere fabaeformis</u> <u>Cyprideis torosa</u> <u>Loxoconcha elliptica</u> <u>Xestoleberis</u> sp.	open lagoon or bay with direct marine influence. <u>L. fab.</u> may mark beginning of gradual restriction
III	<u>Cyprideis torosa</u> <u>Loxoconcha elliptica</u> <u>Xestoleberis</u> sp.	slightly restricted lagoon or bay
IV	<u>C. torosa</u>	hypersaline lagoon
V	no ostracodes	sabkha

Table 1. Ostracode assemblages and their related environments

The environments of the four ostracode assemblages, based on their modern distributions, are outlined in Table I.

Assemblage I: The ostracodes in Assemblage I are nearly all detrital feeders and are associated with coarse substrates. Assemblage I is indicative of a shallow marine (neritic) environment.

Assemblage II: Assemblage II contains many marine ostracodes similar to those of Assemblage I, however A. convexa occurs in greater numbers, and Xestoleberis sp. and Leptocythere fabaeformis are introduced. Jouirou (1982) suggests that the species in this assemblage are located at the limit or boundary of a marine domain, where physical and chemical parameters fluctuate significantly. He also suggests that the appearance of Leptocythere marks the start of the gradual restriction of an open lagoon or bay. Mansouri-Menaouar (1979) found that L. fabaeformis is indicative of an increase in the sulfate concentration in the environment. The evidence presented by Jouirou and Mansouri-Menaouar, as well as the ostracode assemblage, suggests that Assemblage II may be indicative of an open lagoon or bay.

Assemblage III: Assemblage III, containing L. elliptica and C. torosa, with or without Xestoleberis, represents an environment more restricted than Assemblage II. The ostracodes within Assemblage III are associated with an environment that has a slightly higher salinity than Assemblage II. This environment may have represented the final stages in the restriction of a lagoon. The presence of L. elliptica indicates that plants must have been present, which suggests that the environment was not extremely hypersaline.

Assemblage IV: Assemblage IV is composed of 100% C. torosa. C. torosa prefers a muddy substrate, indicating an environment with little or no large clastic influx. The absence of phytal ostracodes, as well as any other species, may indicate a hypersaline environment.

Assemblage V: Assemblage V is defined by the absence of ostracodes and by the presence of gypsum and/or pyrite. That environment is thought to represent a supratidal sabkha.

The faunal assemblages of the ostracodes from the surficial samples correlate with the sediments of those assemblages. The samples that contain ostracode assemblages that are restricted from marine influence, Assemblage IV for example, characteristically contain larger amounts of mud and silt-sized sediments. The samples containing ostracodes indicative of marine influence (Assemblage II) contain silty clay and slightly sandy clay-sized sediments. The samples containing ostracode assemblages associated with strictly marine environments (Assemblage I) are characterized by even larger amounts of sand-sized sediments.

Surficial sediments: Ostracodes were removed from surficial sediments that were collected from both Punic harbors, the Lake of Tunis, and the Mediterranean coast east of the harbors (figures 5 and 6). The faunal densities of each sample vary greatly and appear to be related to the different ostracode assemblages (Table II). Sample 1a, from the circular harbor, was collected in water 30 cm deep. The source of the water in the circular harbor is artificial, and is pumped into the harbor from the Mediterranean Sea. Consequently, the faunal assemblage is characteristic of Assemblage I (marine). The assemblage contained A. convexa (36%), L. rhomboidea (23%), Heterocythereis sp. (15%), Hemicytherura (9%), Actinocythereis sp. (7%), Cytheridea sp. (6%), and Cushmanoidea elongata (4%). The faunal density is 84 individuals per 20 g of sediment. Sample 2a, from the rectangular harbor, is representative of Assemblage III (restricted lagoon). The sample consisted 94% C. torosa and 6% L. elliptica (out of 100 individuals). The faunal density is over 100 individuals per 20 g of sediment. Sample 3a represents Assemblage I (the open marine

environment) from the Mediterranean Sea east of the Punic harbors. The faunal assemblage is strictly marine (L. rhomboidea (34%), Aurila convexa (26%), Heterocythereis sp. (11%), Actinocythereis sp. (10%), Cushmanoidea elongata (7%), Carinocythereis sp. (6%), and Callistocythere sp. (6%)). The faunal density is 86 individuals per 20 g of sediment.

The surficial samples from the Lake of Tunis were collected from an embayment in the northeastern corner of the lake (figure 6). Sample 4a represents a highly polluted, stressed environment (Rapp, pers. comm.). It contained an assemblage of ostracodes corresponding to Assemblage II (open lagoon or bay containing individuals of L. rhomboidea (45%), A. convexa (17%), L. elliptica (13%), Xestoleberis sp. (11%), C. torosa (10%), Leptocythere fabaeformis (4%)). The faunal density is 96 individuals per 20 g of sediment. This area may also have had seawater pumped into it, because the faunal densities appear to be high for a polluted environment. Sample 4b was collected from the shoreline of the open lake in 10 cm of water. Only one species of ostracode was found: C. torosa. The monospecific assemblage corresponds with Assemblage IV (hypersaline). The faunal density is over 100 individuals per 20 g sample.

Detailed maps of the faunal distribution of the harbors and Lake of Tunis cannot yet be constructed with accuracy due to an insufficient number of samples and their lack of geographic distribution.

Core samples: Ostracodes removed from the core samples were analyzed with similar methods. Approximately 100 valves were removed and identified from each sediment sample. The core samples contained nearly identical ostracode species and assemblages as the modern surficial samples.



The fauna in the core samples was usually very diversified and often represented more than one faunal assemblage. It was unusual to find all the ostracodes in a sample corresponding to one faunal assemblage. More often, the samples contained representatives of two or more assemblages--one of which usually dominated the sample. The assemblage which composed greater than 50% of the sample was designated as the primary assemblage for that sample. The others were designated as secondary. If the sample contained two assemblages of similar proportions, each assemblage was addressed as a primary assemblage. The paleoenvironmental interpretation was defined as being transitional between those primary assemblages. When the sample contained large proportions of euryhaline ostracodes (ostracodes found in more than one assemblage), "key" or marker ostracodes aided in the identification of the primary assemblage. For example, if a sample contained a large number of Loxoconcha rhomboidea and there was question as to whether Assemblage I or II was primary, marker ostracodes helped. If there were a high number of ornate ostracodes in the sample (Actinocythereis sp. or Carinocythereis sp., for example), normal marine conditions were inferred (Benson, 1985). If the species Leptocythere fabaeformis was present, a transitional marine environment was inferred (Jouirou, 1979). Differences between Assemblage II and III were defined by the presence of Leptocythere fabaeformis (for the designation of Assemblage II) and more than 10% C. torosa for designating Assemblage III. The primary assemblages are described in detail in the text. It was the primary assemblages upon which the reconstruction of the harbors was based. A complete faunal list of each core sample can be found in Appendix I.

Core 7: The sediments at the base (5.65 meters) contain an assemblage predominantly of open lagoon/bay ostracodes (Assemblage II: Aurila convexa(33%), L. rhomboidea (34%), Leptocythere fabaeformis (15%), and Xestoleberis sp. (6%). The large numbers of the phytal species L. rhomboidea and the presence of A. convexa indicate very

little restriction from open marine conditions. The faunal density is over 100 individuals in 20 g of sediment. The ostracodes from the horizon 5.10-5.15 meters indicate a greater marine influence. The sediments contain a similar faunal assemblage to that of 5.65 meters, however the number of individual species differs greatly. The number of L. rhomboidea individuals increases from 34% (5.65 meters) to 77% in the sediments from 5.10-5.15 meters. Individuals of A. convexa decrease from 33% (5.65 meters) to less than 2% of the individuals from the sample at 5.10-5.15 meters. The faunal density of the sample from the horizon 5.10-5.15 meters is 83 individuals per 20 g of sediment.

The stratigraphic horizons from 4.05 meters through the interval between 3.22-3.28 meters are all represented by assemblages from normal marine salinities (Assemblage I). The assemblages consist primarily of Hemicythura sp., Actinocythereis sp., L. rhomboidea, and Cytheridea sp.. The faunal densities of the samples from the 3.88 meter, 3.41 meter, and 3.22-3.28 meter horizons all contain greater than 100 individuals per 20 g of sediment. The faunal density of the sample from 4.05 meters is 98 individuals per 20 g of sediment.

A dramatic change in the ostracode population occurs above the 3.22 meter horizon. In the stratigraphic interval from 2.90-3.00 meters the faunal assemblage is composed entirely of C. torosa. This is indicative of a very restricted environment, possibly a hypersaline lagoon (Assemblage IV). The faunal density is over 100 individuals per 20 g of sediment. The sediments at 2.78-2.82 meters contain no ostracodes and have substantial amounts of gypsum; indicative of a supratidal sabkha (Assemblage V from Table I).

Core 11: As with Core 7, the fauna at the base (4.24 meters) contains an assemblage predominantly of normal marine ostracodes (Assemblage I: Hemicytherura sp. (34%), L. rhomboidea (27%), and Actinocythereis sp. (12%)). The decreased abundance of L. rhomboidea in the sample indicates the possibility of some restriction (Assemblage II), however, the dominance of Hemicytherura and Actinocythereis signifies that the environment was primarily open marine. The faunal density is 83 individuals per 20 g of sediment. The ostracodes representative of the horizon at 3.84 meters are also indicative of marine conditions (Assemblage I: Actinocythereis sp. (47%), Hemicytherura sp. (29%), L. rhomboidea (23%)). Actinocythereis sp. and Hemicytherura are generally more robust in form and may indicate a coarser substrate and more turbulent environments. This factor as well as a lower faunal density (56 individuals) suggests that the paleoenvironment was probably nearshore marine.

Individuals in the remaining samples from Core 11 (excluding 1.15 meters) are very sporadic and all represent hypersaline conditions (Assemblage IV). The sediment sample from 3.34-3.39 meters contains 9 individuals, all of which are C. torosa. The interval from 3.15-3.21 meters is similar: 11 individuals of C. torosa. The faunal densities for the intervals between 2.72-2.79 and 2.19-2.24 meters are over 100 individuals (of C. torosa). The faunal density in the horizon 2.30-2.35 is 49 individuals. The uppermost section of the core, 1.15 meters, consists primarily of Assemblage II (open lagoon/bay). This signifies an increase in the water circulation between the previous horizon and that at 1.15 meters. The fauna consists primarily of Hemicytherura sp. (39%), L. rhomboidea (20%), and Leptocythere fabaeformis (13%). Leptocythere fabaeformis in a sample indicates changing environmental conditions, usually between more saline and normal marine environments (Jouirou, 1982).

Core 1: Core 1, from the northeast corner of the rectangular harbor, contains at its base a very restricted fauna indicative of a hypersaline lagoon. The stratigraphic horizon at 7.3 meters, has over 100 individuals of C. torosa. The sediments at 6.1 meters contains an assemblage indicative of both Assemblage II and I. The sample contains marine ostracodes such as Cushmanoidea elongata (4%), Cytherida sp. (4%), Hemicytherura sp. (30%), and L. rhomboidea (17%), as well as containing Xestoleberis sp. (26%), A. convexa (7%), and L. elliptica (4%) which are indicative of a slightly restricted environment. The faunal density is 23 individuals. The ostracode assemblages again change dramatically, at 3.8 meters the population indicates a reversion to a hypersaline lagoon (Assemblage IV: C. torosa). The faunal density is 17 individuals in 20 g of sediment. At 3.6 meters the assemblage is monospecific, containing only Cyprinotus salinus. This particular species was not encountered in any of the other drill cores. C. salinus is primarily a freshwater or brackish water ostracode (Benson, 1985) although Carbonel (1980) found that monospecific associations of C. salinus from the sabkha of Ariana were accompanied by the crystallization of authigenic gypsum. Mansouri-Manaouar (1979) also noted that the beginning of sulphate precipitation in the lagoon of Ghar-el-Melh was marked by the coexistence of C. torosa and C. salinus. Therefore, the horizon 3.60 meters containing over 100 individuals of C. salinus may indicate the beginning of gypsum precipitation in a very restricted hypersaline basin rather than a brackish or fresh water environment. The sediments from the horizon at 2.40 meters contain substantial amounts of authigenic gypsum and no ostracodes, indicating the existence of a supratidal sabkha environment.

Core 12: The sediments at the base (3.90 meters) contained an assemblage predominantly of open lagoon/bay ostracodes ( Assemblage II: Xestoleberis sp. (11%), A. convexa (30%), and L. rhomboidea (33%). The faunal density is 27 individuals. From the core interval 3.70-3.73 meters, the assemblage is typical of a shallow marine environment

(Assemblage I). L. rhomboidea comprises 81% of the individuals. The faunal density is 68 individuals in 20 g of sediment. The ostracodes in the stratigraphic horizon between 3.50 and 3.53 meters are also representative of shallow marine waters (Assemblage I). The faunal density is only 9 individuals, all of which are the robust Hemicytherura sp. The horizon between 3.25 and 3.28 meters also contains few individuals (11 total) representative of both Assemblages II and III (L. rhomboidea (50%), C. torosa and L. elliptica (40%)). The faunal assemblage appears to reflect the initial stages in the development of a restricted lagoonal environment.

The faunal density of the stratigraphic interval between 2.70 and 2.73 meters is 10 individuals per 20 g of sediment, all of the individuals are C. torosa. This monospecific assemblage is indicative of a restricted hypersaline environment. There are no ostracodes in the horizon between 2.39 and 2.42 meters, however there is a substantial amount of gypsum in that horizon which probably contributes to the absence of fauna. This horizon represents a supratidal sabkha. The horizon overlying the gypsum layer (2.20-2.28 meters) contains over 100 individuals (high faunal density) of C. torosa. This is followed by a horizon containing more gypsum. The beds containing C. torosa may represent fluctuating marine inundation, in which an influx of water persisted in the sabkha long enough for an ostracode population to grow. The source of the water may have been from periodic storm surges.

Core 14: Core 14 was drilled south of the rectangular harbor. The sediments at 5.70 meters depth contain an assemblage indicative of the slight restriction of an open marine embayment. The assemblage is composed of approximately 70% marine ostracodes (L. rhomboidea (50%), C. elongata (12%), Trachyleberis sp.(9%)) representing Assemblage I, as well as 20% from an open lagoon or bay representing Assemblage II (Xestoleberis

(13%) and A. convexa (7%). The faunal density is 32 individuals per 20 g of sediment. At 5.00 meters, the population correlates with Assemblages II and III (restriction of an open lagoon/bay). L. rhomboidea (16%), A. convexa (6%), and Leptocythere sp. (5%) comprise over 20% of the individuals. However, C. torosa and L. elliptica comprise the majority of the assemblage (over 50%). The faunal density is moderately high (82 individuals). This horizon is followed by a unit (at 4.03 meters) that contains a bispecific assemblage indicative of a slightly restricted lagoon (Assemblage III: C. torosa (91%) and L. elliptica (9%)). The sample contains over 100 individuals. There are no ostracodes in the horizons from 3.90 or 2.90 meters depth, which may reflect the presence of a supratidal sabkha. The horizon at 2.50 meters contains over 100 individuals, all of which were C. torosa (Assemblage IV: restricted lagoon).

Core 20: Core 20 was drilled south of Core 14 in the Bay of Kram. The sediments at the base (4.80-4.84 meters) contain an ostracode assemblage indicative of both marine and open lagoon/bay environments (Assemblage I and II: L. rhomboidea (37%), Xestoleberis sp. (16%), L. elliptica (11%), and minor amounts of other marine ostracodes (figure 9)). The faunal density is low; only 39 individuals in 20 g of sediment. The stratigraphic horizon at 4.40 meters also contains ostracodes representing Assemblages II and I. Assemblage II (open lagoon/bay) appears to be more influential as 48% of the individuals are Xestoleberis sp. and L. elliptica. The faunal density is moderately high; 87 individuals per 20 g of sediment. The sediments from the stratigraphic horizon at 3.88 meters contained ostracodes representative of a partially restricted lagoon (Assemblage III: Xestoleberis sp. (33%) and L. elliptica (66%)). The faunal density was low: 6 individuals. The uppermost samples horizon in Core 20 (3.40 meters) contained a faunal assemblage indicative of marine waters (Assemblage I). The faunal density was moderately high (71 individuals). Over 50% of the individuals were the phytal ostracode L. rhomboidea.

### Sediment Analyses

Sediment analyses not only confirmed the paleoenvironments described from the ostracode assemblages, but provided additional information in portions of the core where ostracods were absent. The sand/silt/clay ratios, in particular, were valuable in determining the progression of environment from open marine to lagoon and sabkha. The samples were analyzed under the premise that samples containing large amounts of sand represented high energy conditions (finer material winnowed away by strong current action). Samples containing a large amount of clays represent low energy conditions. Those samples containing greater than 5% gravel are exceptions. Most of the gravel-sized particles were composed of gypsum crystals which indicate a very restricted environment. The sediment analyses data are presented in Table II.

The interpretations of sediment data are presented in terms of the relative ages of the sediments. The ages were determined for two stratigraphic horizons within the Punic harbors. Organic material from the 3.33-3.35 meter horizon in Core 12 was dated by  $^{14}\text{C}$ :  $2270 \pm 110$  Y.B.P. A  $^{14}\text{C}$  date of material from the 2.16-2.22 meter horizon in Core 20 indicates an age of  $970 \pm 80$  Y.B.P. These dates allow limited correlation of the units. The environments of deposition are described in terms of four different stages in the development of the harbors, based on the age dates. The time "stages" will correlate to 1) pre-2270 Y.B.P., 2)  $2270 \pm 110$  Y.B.P., and 3) 2270 to 970 Y.B.P., and 4) post-970 Y.B.P.

The samples representing the lowest units of the drill cores (pre-2270 Y.B.P.) from Cores 14 and 20 contain evidence to suggest that a lagoon existed from the rectangular harbor southward (including Core 20). The evidence lies in the roughly equal sand/silt/clay ratios which indicate a low energy restricted environment. The presence of the lagoon

<u>DEPTH (m)</u>	<u>% GRAVEL</u>	<u>% SAND</u>	<u>% SILT</u>	<u>% CLAY</u>
Core 1:2.45-2.50	36	48	13	3
Core 7:2.71-2.78	38	31	0	21
3.22-3.28	4	49	25	22
3.41	0	35	28	37
3.98	0	37	32	31
4.05	4	42	22	32
5.10-5.15	40	14	16	30
5.65	24	26	20	30
Core 11:1.15	0	56	36	8
2.19-2.24	7	71	10	12
2.30-2.35	0	8	34	58
2.49-2.54	1	31	29	39
2.72-2.79	1	22	38	39
3.15-3.21	0	3	40	57
3.34-3.39	0	9	34	57
3.84	20	53	21	6
4.24	0	69	24	7
Core 12:0.20-0.30	0	97	1	2
1.70-1.73	0	66	14	20
2.25-2.28	0	19	10	71
2.39-2.42				
3.25-3.28	1	48	25	26
3.50-3.53	10	47	27	16
3.70-3.73	2	33	33	32
3.90-3.93	0	21	47	32
Core 14:2.50	3	46	30	20
2.90	0	51	30	19
3.90	0	12	54	34
4.03	5	20	25	50
5.00	1	38	28	33
5.70	2	89	9	5
Core 20:2.36-2.40	2	93	4	1
3.80-3.82	0	91	7	2
3.88	1	94	5	0
4.16-4.20	17	73	5	5
4.40	15	30	26	29
4.80-4.83	13	35	30	22

Table II. Sediment analyses data from Cores 1, 6, 11, 12, 14, and 20

would indicate that barrier must have separated the harbor area from the Mediterranean Sea. The barrier was probably in the form of a spit that extended southward from the Cape Bon peninsula. The large amount of sand-sized sediment (84%) in the basal unit of Core 14 (5.70 meters) might have been the result of an opening in the barrier/spit east of Core



14. The opening may have provided an inlet for coarse clastic material and an outlet for fine sediments winnowed from the lagoon. The influx of the sand-sized materials also might have resulted from storm surges when clastic material was swept over the barrier/spit into the adjacent lagoon (Reinson, 1984; Blatt et al., 1980). Raban (1985) suggests that this area was the probable location of an entrance into the rectangular harbor during the Phoenician occupation.

The second stage in the evolution of the harbors occurred approximately 2270 ± 110 Y.B.P. The sediment analyses provide evidence to suggest that a number of local changes in geomorphology occurred during that time. For example, the circular harbor contains sedimentological evidence suggesting that there was substantial marine influence locally. Sediments from the basal portion of Core 7 in the circular harbor contain roughly equal amounts of sand/silt/clay, indicating a partially restricted lagoonal environment. The amount of sand increases slightly (to appx. 40%) near the horizon at 4.05 meters suggesting a slight increase in the amount of marine influence. Core 11 (3.84 meters) contains roughly 50% sand-sized sediment in the basal portion. Coarse clastic material is more abundant in the basal samples from the circular harbor. The trend towards larger amounts of sand-sized particles in the Cores 7 and 11 indicates that the sediments may be reflecting more stable environment with progressively more marine influence, rather than periodic storm-surge, washover, or eolian influx of clastic material. The influence might have been the result of an opening in the barrier/spit east of the circular harbor. Whether the opening was an artificially dredged entrance into the circular harbor is not known.

During the same time, the rectangular harbor (Core 12) and the area south of the harbor (Core 14) underwent a regressional stage. The lagoonal environment (roughly equal amounts of sand, silt, and clay) changed into a very restricted environment with very little

coarse sediment influx. The amount of clay in the lagoon increases to over 50% in some instances. The precipitation of gypsum occurs in the middle sections of Core 12 and Core 14 (3.15 and 3.90 meters, respectively). The sediments from Core 20 contain evidence to indicate the the environment in that region was probably a beach or swash zone (greater than 90% sand).

The third stage in the harbor evolution is marked by a period of little to no marine influence. This stage corresponds roughly to a time period between 2270 and 970 Y.B.P., which correlates with the time of Roman Carthage. The sediments in the circular harbor indicate that a lagoon with a minor marine influence existed initially, and that the marine influence decreased with time. The decrease in marine influence might indicate a gradual closing of the channel that led from the circular harbor to the Mediterranean Sea. The sediments from Core 12 in the rectangular harbor contain increasing amounts of gypsum (qualitative) suggesting that the rate of evaporation was exceeding the amount of water influx into the harbor. The core from the area south of the rectangular harbor (Core 14) contains no evidence for a lagoon, only gypsum, suggesting the formation of a coastal sabkha. The absence of any lagoonal sediments suggests that the area south of the rectangular harbor was restricted both from the rectangular harbor and the Mediterranean Sea. Core 20 contains greater than 90% sand, indicating that the area was probably a beach or swash zone.

The minor regression that left the harbors relatively isolated from the Mediterranean Sea may have been the result of the Roman deforestation of the Medjerda River basin. The large amount of sediment picked up by longshore currents probably deposited in the barrier/spit system south of the Cape Bon peninsula. The rapid deposition of large amounts of clastic material could easily have resulted in the gradual closing of channels between the

barrier islands or of canals dredged into the harbor area. The deposition of the sediment more than likely resulted in the physical isolation and subsequent fill-in of the Carthaginian harbors.

The final stage in the evolution appears to have been a major regression that left both of the harbors stranded from any marine influence. The regression formed supratidal evaporite sequences indicative of coastal sabkhas. The presence of gypsum and the absence of biota in the circular and the rectangular harbor areas, as well as in the sediments above 2.90 meters in Core 14 act as conclusive evidence for the formation of the sabkha.

Figures 8 and 9 are schematic diagrams of the evolution of the Punic harbors based on sediment data.

#### Microprobe Analyses

Ostracodes are known to incorporate significant amounts of magnesium into their carapace. It is not clearly understood whether the fluctuation of the magnesium content is related more to genetics or environment. Studies completed by Chivas et al. (1986), Cadot et al. (1972), and Teeter (personal communication) established that individual species concentrate different amounts of magnesium, implying genetics plays an important role. Other studies have suggested that environment is an important factor in the distribution of magnesium. Chave (1954), Lowenstam (1954), Cadot et al. (1972, 1975), Durazze (1975), Schifano (1982), and Chivas et al. (1983) found the magnesium content in an ostracode carapace to be temperature dependent, implying the importance of environment in the distribution of magnesium. Teeter (personal communication) and Chivas et al. (1986) have found that magnesium content is related to salinity. Teeter documented a negative

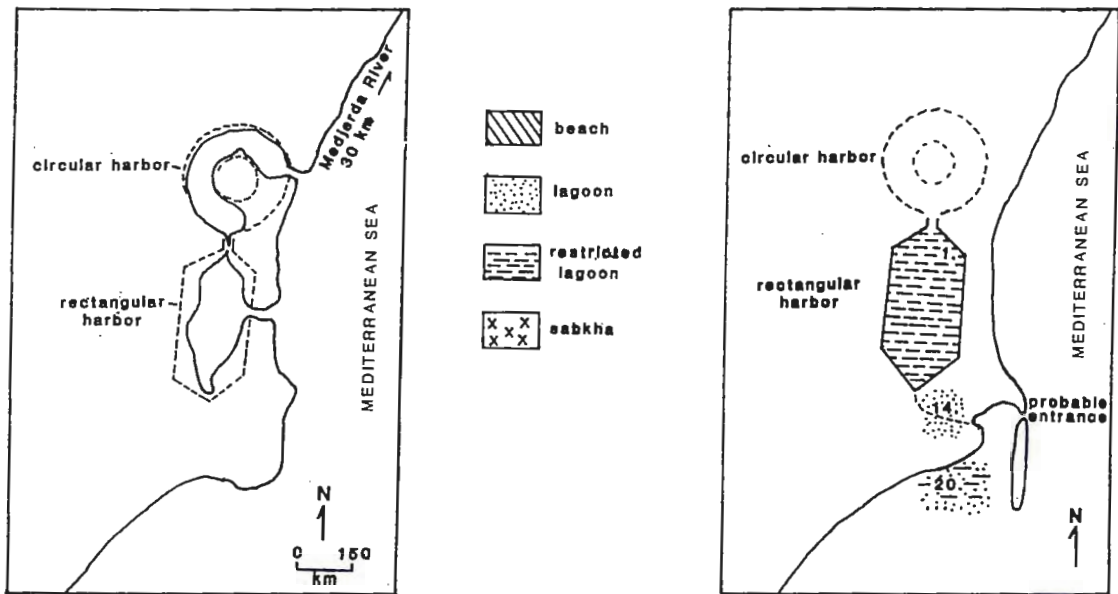


Figure 8. Speculative time-sequence diagrams of the evolution of the harbors.

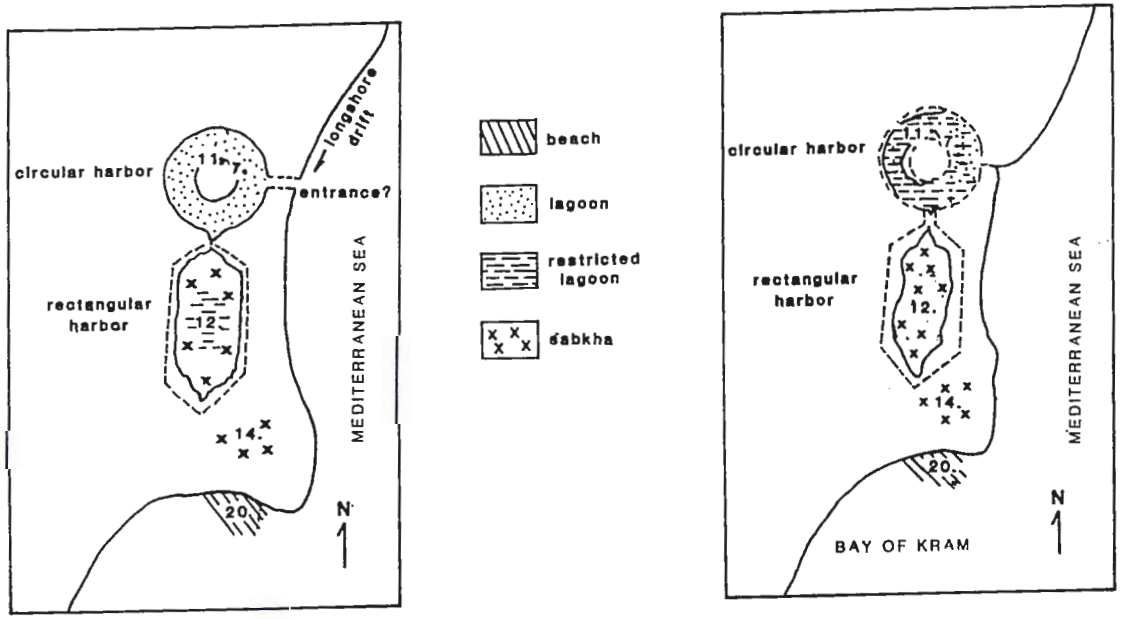


Figure 9. Speculative time-sequence diagram of the evolution of the Punic harbors.

correlation between the magnesium content in an ostracode carapace and salinity, while Chivas et al. found a positive correlation.

In this study, Teeter's method was followed with the intent of determining if the data from the Mg/Ca ratios correlated with the faunal and sedimentological data. The method described by him involved microprobing the ostracode carapace for calcium and magnesium and then determining a Mg/Ca ratio. That ratio should vary inversely with the salinity of the water in which the ostracodes lived, if Teeter's views are true.

Teeter's hypothesis is based on the availability of calcium and magnesium in marine waters and the preferential incorporation of those ions into the ostracode carapace. Under normal salinities, ostracodes tend to incorporate Ca ions over Mg ions. The ratio between Mg and Ca ions in modern seawater is approximately 5:1. At salinities higher than normal marine (35 ppt), the availability of calcium ions for the carapace structure is high because more calcium ions are present. Therefore, very little magnesium is incorporated into the carapace structure at higher salinities. However, as the salinity decreases, so does the availability of the calcium. At some point, magnesium will be substituted for some calcium simply because the calcium level is low. This "availability problem" results in a measurable magnesium change in the ostracode carapace that is tied directly to fluctuations in the salinity. Teeter has used his hypotheses with success in the saline lakes of San Salvador, Bahamas.

The analytical results for magnesium and calcium are expressed as atomic ratios (Mg/Ca) and can be found in Table III. Ostracodes from 3.93 to 3.23 meters in Core 12 (from the rectangular harbor) showed increasing Mg/Ca ratios (figure 10). According to Teeter, an increase in the magnesium content suggests a decrease in salinity. The

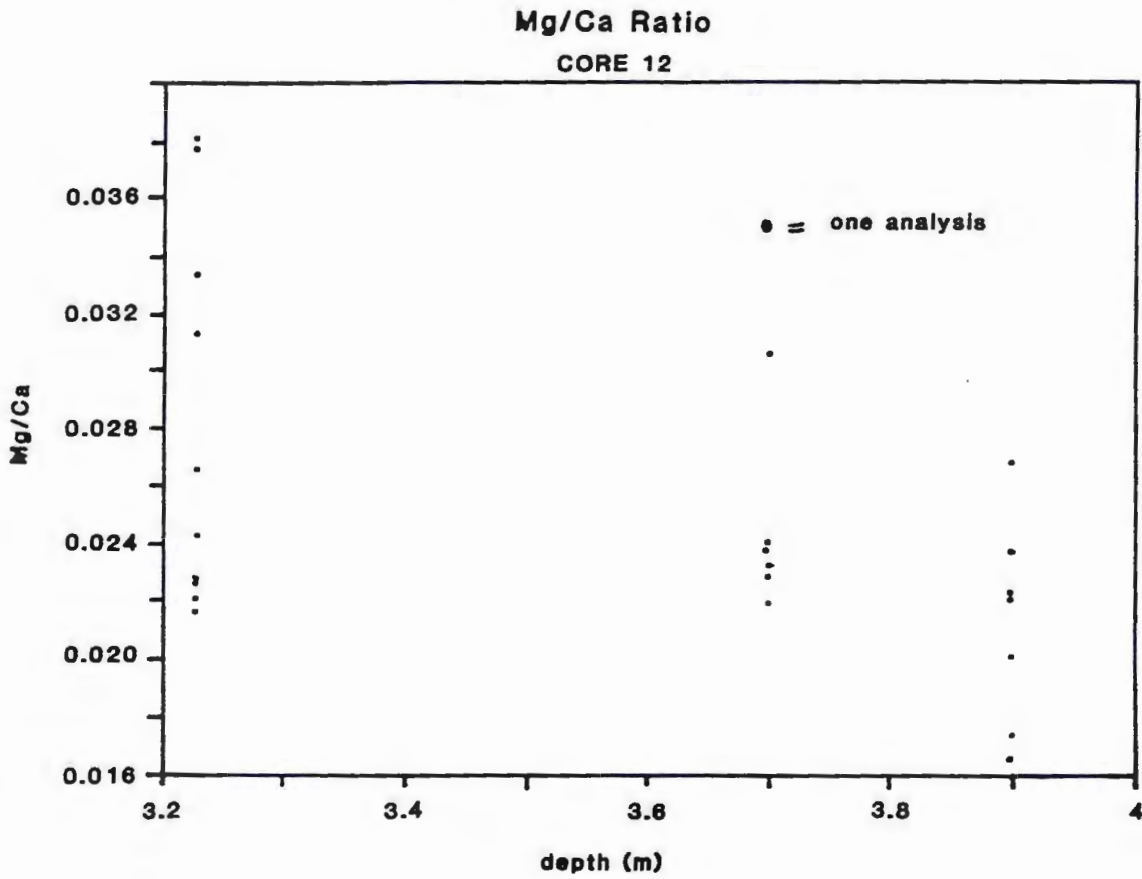


Figure 10. Mg/Ca ratios of ostracode carapaces from Core 12.

ostracode faunal assemblages from the same horizons in Core 12 suggest that the opposite is true, as do the sediment analyses. The faunal assemblages indicate that the salinity increases rather than decreases as the microprobe analyses indicate. The sediment analyses completed on the sediments from Core 12 contain a sequence that fines upward, also indicating restriction (which may correlate with increasing salinity).

The microprobe results from Core 12 correlate better with the hypothesis of Chivas et al. (1986). Unfortunately, their experiment was completed on ostracode carapaces from saline lakes in which the Mg/Ca ratio differed greatly from the 5:1 Mg/Ca ratio of normal marine waters. Their work may not be applicable to this study.

The Mg/Ca ratios of ostracode shells from Core 20 indicate both increasing and decreasing trends in the paleosalinity. The data from the stratigraphic horizons 4.80 and 4.40 meters suggest that the environment became more saline. The Mg/Ca ratios of ostracodes from the interval between 4.40 and 3.40 indicate an environment that was progressively less saline (figure 10). The ostracode faunal assemblages corresponding to the sediments in Core 20 suggest that the salinity fluctuated very little. Most of the ostracodes are representative of normal marine conditions. The sediment analyses also support a normal marine environment: above 4.40 meters, the sediment samples contain over 75% sand-sized particles, which may indicate the formation of a beach or swash zone.

The microprobe results were inconsistent and this may be due to a number of reasons. The variability in results of the technique was relatively large, possibly as a consequence of both mechanical and technical error. Irregularities on the surface of the polished ostracode sections caused uneven dispersal of the electron beam, also resulting in inconsistent data. Often the beam volatilized CO<sub>2</sub> from the crystal structure of the



DEPTH	Wt% MgO	Wt% CaO	MgO/CaO (Wt %)
Hole 12			
3.90-3.93	1.21	54.22	0.022
	1.11	49.87	0.022
	0.8	48.19	0.017
	0.96	47.67	0.020
	1.38	51.37	0.027
	1.19	49.98	0.024
	1.02	58.5	0.017
	1.17	58.15	0.020
3.23-3.28	1.28	56.41	0.023
	1.9	49.95	0.038
	1.22	53.66	0.023
	1.73	55.39	0.031
	1.33	54.76	0.024
	1.55	58.26	0.027
	2.13	56.31	0.038
	1.74	52.17	0.033
	1.27	57.35	0.022
	1.23	56.9	0.022
3.70-3.73	1.33	57.86	0.023
	1.2	54.68	0.022
	1.75	57.2	0.031
	1.2	49.92	0.024
	1.18	50.78	0.023
Hole 20			ERR
3.40	1.71	53.5	0.032
	0.93	53.84	0.017
	2.96	53.94	0.055
	1.27	55.61	0.023
	1.5	54.84	0.027
	1.82	55.8	0.033
	1.89	56.11	0.034
	1.79	52.28	0.034
4.40	0.84	49.99	0.017
	1.19	54.79	0.022
	0.82	58.14	0.014
3.88	1.48	57.87	0.026
	1.24	57.98	0.021
	1.1	54.61	0.020
	1.26	58.45	0.022
	1.74	57.88	0.030
	1.98	56.35	0.035
	1.62	49.21	0.033
4.80-4.84	1.62	55.15	0.029
	1.18	53.35	0.022

Table III. Microprobe analyses for Cores 12 and 20 (the data are given in weight percent).

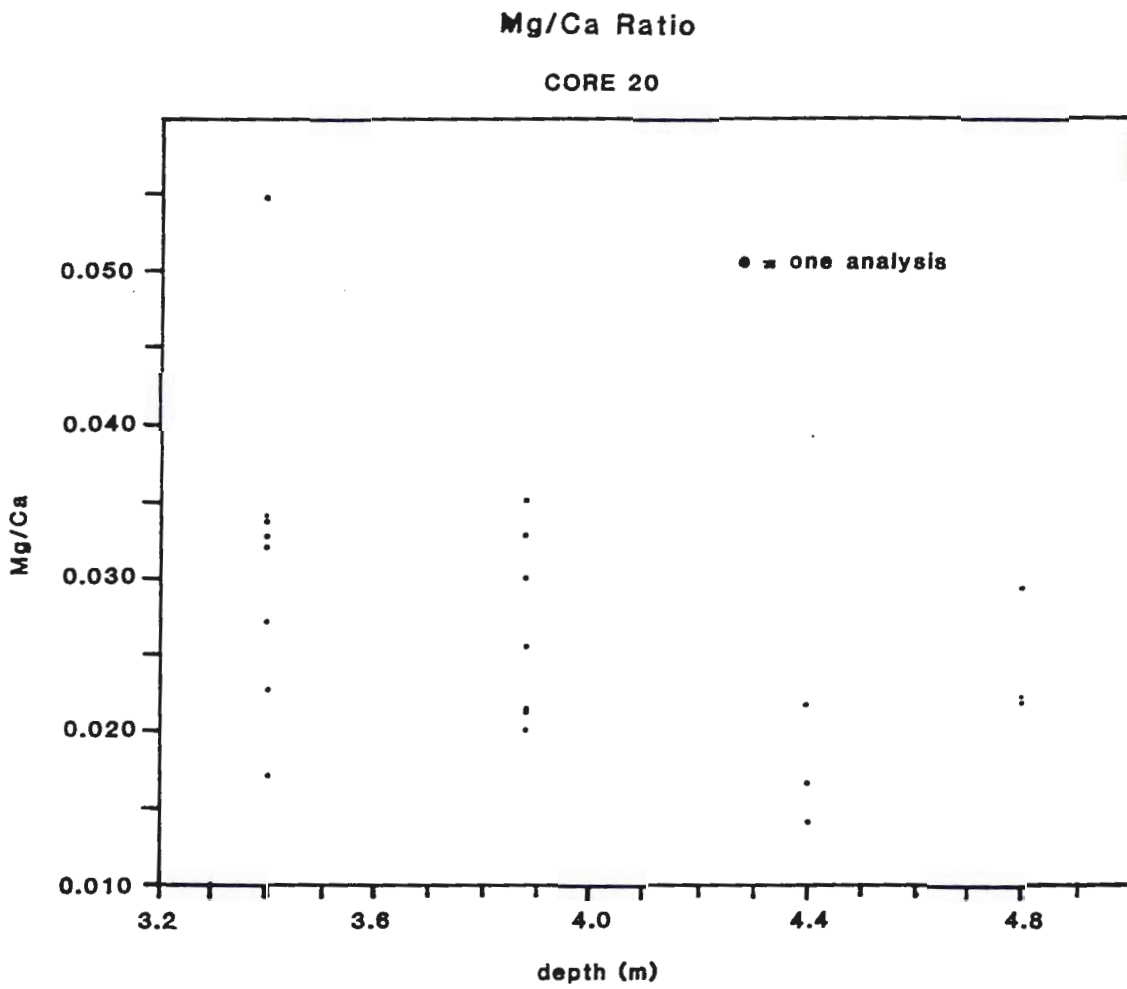


Figure 11. Mg/Ca ratios of ostracode carapaces from Core 20.

carapace, thereby increasing the amounts of elemental Ca and Mg in the sample reading.

A second interpretation of the inconsistency of magnesium content may be due to genetic differences in individual species of ostracodes. Dodd (1965) detected a so-called "species effect" in the magnesium concentration in Mytilus species (bivalves). He found that different Mytilus species concentrated varying amounts of magnesium in their shell. Cadot et al. (1972) found that variations in the magnesium content of an ostracode carapace is dependent on the species of the ostracode rather than on the genus of the ostracode as Chave (1954) suggested. Teeter's study of San Salvadorian ostracodes also found that magnesium concentrated in different amounts within a species population. Only one species was used in this experiment in order to simplify the results. Unfortunately, the absence of a broad data base of magnesium "norms" for individual species prohibits correlation of Mg/Ca ratios in Loxoconcha rhomboidea from this study with similar ostracode microprobe studies.

Finally, diagenetic effects may account for the inconsistency in the microprobe results. Unfortunately, little is known about the diagenetic alterations in biogenic calcite and aragonite and how they may affect paleosalinity studies. Studies by Pilkey and Goodell (1964) suggest that the magnesium content is lower in fossil molluscs than in Recent mollusc shells of the same species, when the shells are equilibrated with fresh water. They feel that the difference may be a result of the early phases of diagenesis. Curtis and Krinsley (1965) found that Mg/Ca ratio changes in populations of individual gastropod species are indicative of diagenetic alteration. They suggested that the variance in the chemical composition of shells within a population is a direct measure of whether or not the shells are in equilibrium with the environment. Unfortunately, similar studies have not been conducted on ostracode populations. Walls et al. (1977) illustrated the effects of

dissolution and release of magnesium in relation to calcium in biogenic calcite (mollusc). They found that the release of ions, particularly magnesium, from calcite is an early phase of diagenesis resulting in the equilibration of the shells with the surrounding chemical environment.

Unfortunately, there is an absence of data relative to the solubility of magnesium in ostracode carapaces. Most of the studies completed on biogenic calcite and aragonite have indicated that the early stages of diagenesis in fossil skeletal material considerably alters the original magnesium concentration. This may invalidate many of the paleoecological interpretations based on trace element studies.

To summarize, neither Teeter's or Chivas' work can be affirmed by this study, although the latter is in closer accord with the faunal and sedimentologic work completed on the Carthage samples. More fundamental work must be accomplished before conclusive results can be obtained for paleoenvironmental reconstructions using trace element studies. Initially the polishing and microprobe technique must be refined. Second, studies concerning the cause of species-specific variation in magnesium content must be completed. Once understood, a database containing the magnesium concentrations of individual species can be constructed. The quantitative information regarding magnesium concentrations may aid in determining whether or not individuals have been altered during the early stages of diagenesis.

## DISCUSSION

The paleoenvironmental reconstructions of the Punic harbors were accomplished using ostracode faunal assemblages as well as by using sediment analyses data. Microprobe analyses of the ostracode carapaces from Cores 12 and 20 have also been completed in an attempt to determine relative paleosalinities based on Mg/Ca ratios of the carapaces; those results are inconclusive. The magnesium content of samples from Core 12 increased toward the surface, suggesting a diminishing salinity over time, in the sense of Teeter. The faunal assemblages from Core 12 suggested the opposite to be true: salinity increased with a decrease in depth. The magnesium content of the ostracodes from Core 20 varied with each section of the drill core, thus no distinctive trend was apparent. Since the microprobe results were inconclusive, the reconstructions are based solely on the ostracode and sediment data.

The geographic isolation of the harbors within the study area results in each location changing independently through time. This results in a number of problems, particularly relating to sedimentation rate. Since the lagoons are influenced heavily by both marine and anthropogenic factors and because they alter independently, their sedimentation rates are very different. This causes difficulty when trying to correlate drill cores throughout the field area. A gypsum bed does occur in three of the six drill cores. This horizon may be suitable as a stratigraphic marker bed, although the unit would not be a time stratigraphic unit, which is needed for this reconstruction. Another factor to be considered for the gypsum unit is that human influence probably was a major factor in its dissynchronous deposition. Since material from the gypsum bed has not been age-dated, and because the unit is not laterally extensive (i.e. does not occur in each drill core), the unit cannot be regarded as one synchronous depositional event. Therefore, the gypsum bed will not be used as a stratigraphic marker.

Due to the difficulty in finding an adequate time line, the paleogeographic summary was developed by treating each geographic area as a single unit. A broad summary for each general area will be followed by a brief discussion regarding human influence in the evolution of the harbors.

Circular harbor: The evolution of the circular harbor occurs in three stages. Ostracode assemblages and sediment analyses from Cores 7 and 11 suggest that the first stage consisted of a lagoonal environment that was heavily influenced by marine waters. The ostracode assemblages primarily consist of these genera: Aurila, Loxoconcha, and Leptocythere. Sediment analyses from the base of Core 7 (from 5.65 to 3.98 meters) and from the base of Core 11 (4.24 to 3.84 meters) show roughly equal amounts of sand, silt, and clay indicating an open lagoon (no major influx of large or small clastic input). Core 11 (4.24 and 3.84 meters) contains more sand, however the core was drilled near the eastern margin of the lagoon and the increased amount of sand may represent evidence of marine currents. If there was an opening in the lagoon near the location of Core 11, then the marine currents could have winnowed some of the fine sediments away in the proximity of the opening and could also have provided an influx for some of the marine fauna found in the ostracode assemblages in Core 11.

The first stage lagoon or bay was probably formed in a back barrier region. As the barrier or spit continued to prograde, the lagoon gradually became more restricted from marine influence. The second stage in the evolution of the circular harbor was the isolation and restriction of the lagoon. Scattered grains of gypsum and pyrite occur in Core 7 and Core 11, and portions of both cores contain monospecific assemblages of ostracodes (Core 7, 2.90-3.00; Core 11, 2.72-2.79 and 2.49-2.54 meters). The monospecific assemblages as well as the gypsum and pyrite crystals indicate a very harsh biological environment.

Both the sediments and the ostracodes were from very specific environments and indicate a very restricted lagoon evolving into a supratidal sabkha. The severe restriction of the lagoon probably stemmed from the closing of the barrier channel. It is plausible that the opening in the barrier was gradually closed by increasing longshore drift due to the Roman deforestation.

The final stage in the evolution of the circular harbor is represented by a small re-invasion of marine waters. A marine assemblage of ostracodes occurs at horizon 1.15 meters in Core 11. The sediment analysis from that horizon contains a sand, silt, clay ratio of 56/36/8. Since this unit only occurs in Core 11, it may represent human influence. Specifically, the marine invasion may have been a result of dredging the harbor or canals leading into the harbor. A direct marine influence would explain the 56% sand in the sediment sample as well as the ostracodes of Assemblage I (marine) found within that horizon.

Rectangular harbor: The evolution of the rectangular harbor can be described by four stages. The first stage is represented by a very restricted lagoon and this is indicated by the monospecific ostracode population (*C. torosa*) in the basal portion of Core 1 (7.30 meters). The second stage was marine influenced, as indicated by a polyspecific ostracode population from Core 1 (6.10 meters depth) and Core 12 (3.90-3.93, 3.70-3.73, and 3.50-3.53 meter intervals) containing species indicative of both marine and lagoonal environments. The sediment analyses of the three intervals between 3.90 and 3.53 meters depth (Core 12) have roughly equal amounts of sand, silt, and clay. The second stage probably represented an open lagoon or bay with direct marine influence. A <sup>14</sup>C age date for the horizon at 3.33 meters in Core 12 indicates that material from that particular bed is 2270 ± 110 Y.B.P., which roughly correlates with the time of Punic Carthage.

Stage three represents a series of sub-stages indicative of the gradual restriction of the open lagoon or bay. The ostracode assemblages consist of L. rhomboidea, L. fabaeformis, and C. torosa. The presence of L. fabaeformis in Core 12 (3.25-3.28 meters depth) dictates the beginning of the restriction (Jouirou 1982). By the depth 2.70-2.72, 90% of the ostracode population in Core 12 is C. torosa (indicating a very restricted environment). The sediments contain scattered grains of gypsum in Core 12 (3.25-3.28). By the time of the deposition of the horizon in Core 12 at 2.39 to 2.42 meters, the lagoon was so restricted, sulphates and sulphides were precipitating (sulphates probably above the sediment-water interface and sulphides within the sediments). That horizon contains no ostracodes and is indicative of the formation of a supratidal sabkha (stage four). This final stage is also accompanied by a monospecific population of Cyprinotus salinus in Core 1 (3.60 meters depth). This ostracode is tolerant of sulphate-precipitating environments (Mansouri-Menaouar, 1979; Carbonel, 1980). The presence of this ostracode may mark the beginning of the formation of an extensive supratidal salt flat.

Probable entrance: The ostracodes and sediments taken from Core 14 suggest four different stages in the evolution of the so called 'probable entrance' to the harbors. The first stage (5.70 meters depth) is represented by a marine ostracode assemblage including the genera Loxoconcha, Hemicytherida, and Cytherida. The sediment sample from the same horizon contained over 80% sand. The marine influence may have resulted from the migration of the barrier seaward of the probable entrance; whether the opening was natural or was a dredged entrance into the harbors is not known. This environment changed gradually into a slightly restricted lagoon (stage two), as indicated by the ostracodes C. torosa and L. elliptica in the samples from 5.00 and 4.03 meter depths. The sediment samples from the same depths contain roughly equal amounts of sand, silt and clay - again suggesting a somewhat restricted environment.



The slightly restricted lagoon of stage two evolved gradually into a very restricted hypersaline lagoon or sabkha (stage three). This stage is characterized by the absence of fauna (3.90 and 2.90 meters depth) and the presence of gypsum and pyrite. The sabkha stage was followed by some re-entry of marine waters and the development of a restricted lagoon (2.50 meters in Core 14). The ostracode assemblage (from 2.50 meters) of the lagoon contain 96% C. torosa - indicating a restriction. None of the samples from Core 14 were age dated, which causes problems in trying to correlate the samples with anthropogenic events. It seems possible that the marine and open lagoonal environments near the base of the core may represent an opening, perhaps due to the migration of a barrier. This channel may have been a man-made entrance into the lagoon complex, as Raban (1985) suggested, or a natural channel in the barrier system.

Core 20: The evolution of the area south of the harbors can be described in three stages. The first stage is from an open lagoon to a transitional marine environment; ostracode assemblages from the lower core (4.80 meters depth) are indicative of both environments (Leptocythere, L. elliptica, L. rhomboidea, Xestoleberis). The sediments contain roughly equal amounts of sand, silt and clay. The second stage (4.40 and 4.16-4.20 meters depth) is an open lagoon with considerably more marine influence than the first stage as indicated by many more normal marine ostracode species (L. rhomboidea and Xestoleberis), as well as more sand (up to 73%). The final stage in the evolution is an open marine environment characterized primarily by an assemblage of neritic benthic and phytal ostracodes (Aurila, L. rhomboidea, Cushmanoidea, and Hemicytherura in the sample from 3.40 meters depth). Sediment samples containing greater than 90% sand-sized particles indicate the presence of a beach or swash zone. A <sup>14</sup>C age date was obtained from organic matter in the horizon 2.16 meters. The material was dated to be 970 ± 80 Y.B.P. This date correlates with the post-Roman occupation of Carthage.

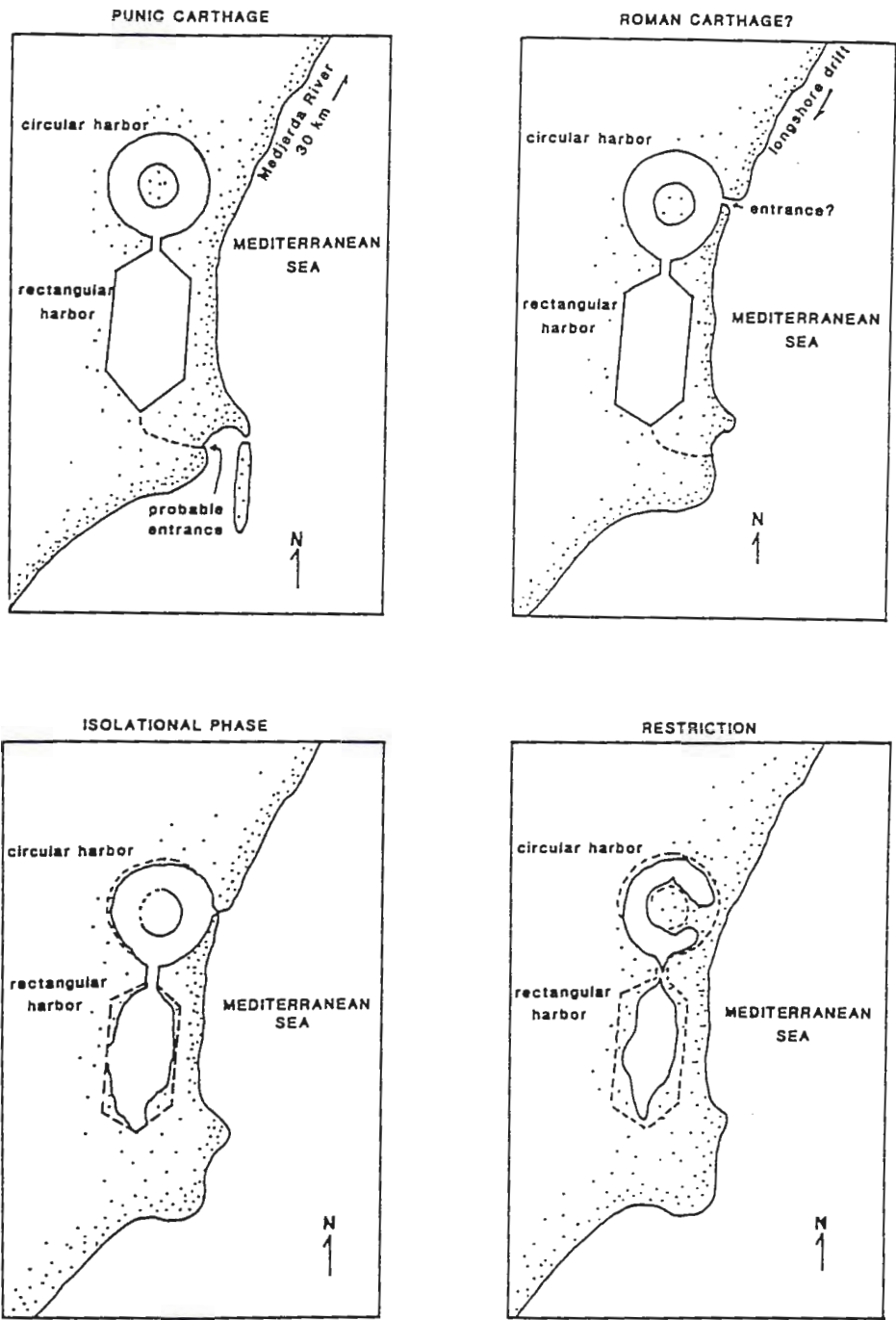


Figure 12. Speculative diagrams of the evolution of the harbors; a) harbors during time of Punic Carthage, b) Roman Carthage, c and d) isolation and restriction of harbors from the Mediterranean from longshore drift

Broad paleogeographical reconstructions of the Carthaginian harbors are shown in Figure 12. It appears as though both the circular harbor and the area south of the rectangular harbor were connected at one point in time to the Mediterranean Sea. Paleontological and sedimentologic evidence suggest that the area south of the rectangular harbor was probably connected to the sea before the circular harbor was connected. The region underwent a phase in which the lagoons were isolated and restricted from the sea. This phase may have been the result of longshore drift, in which case the entrances into the harbors (via break in the barrier or via man-made canal) were gradually closed. The increased longshore drift may have been a consequence of the Roman deforestation of the Medjerda River basin.

SYSTEMATIC DESCRIPTIONS

(Benson, 1985)

Phylum ARTHROPODA

Class CRUSTACEA

Subclass OSTRACODA Latreille, 1806

Order PODOCOPIDA Muller, 1894

Suborder PODOCOPINA Sars, 1866

Superfamily Cytheracea Baird, 1850

Family Cytherideidae Sars, 1925

Subfamily Cytherideinae Sars, 1925

Genus Cytheridea Bosquet, 1852

Cytheridea sp. Bosquet, 1852

Pl.

Carapace.- Thick shelled carapace, subquadrangular in dorsal view; anterior obliquely rounded, posterior oblique, bluntly pointed near venter, both ends denticulate. Merodont hinge. Adductor muscle scars in vertical row of 4 with large distinct and smaller less distinct antennal scar.

Cyprideis torosa Jones, 1850

Pl.

Carapace.- Oval shaped. Hinge entomodont, LV has crenulate anterior socket consisting of 15 pits, postjacent short high crenulate ridge merging into shallow furrow, and short posterior crenulate socket with about 6 pits. Adductor scars in row on 4, above which are 3 small scars (v-shaped antennal scar in front of top of row and mandibular scars near ventral margin).

Family CYTHERURIDAE Muller, 1894

Genus Hemicytherura Elofson, 1941

Hemicytherura sp. Elofson, 1941

Pl.

Carapace.- Small carapace, anterior margin rounded but pointed in dorsal view, posterior margin with subdorsal caudal process; ornamentation consists of pits and reticulations. Adductor muscle scars consist of 4 in a vertical row with 1 anterior to them. RV has 2 terminal tooth plates with intervening furrow.

Family HEMICYTHERIDAE Puri, 1953

Genus Aurila Pokorny, 1955

Aurila convexa Baird, 1850

Pl.

Carapace.- Almond-shaped carapace, rounded in front, pointed behind; pitted surface. Holamphidont hinge; adductor muscle scars variable.

Family LEPTOCYTHERIDAE Hanai, 1957

Genus Lepthcythere Sars, 1925

Lepthcythere cf. fabaeformis Muller, 1894

Pl.

Carapace.- Elongate; surface smooth to punctate. Hinge modified entomodont, more than 2 anterior terminal teeth of median hinge element of LV enlarged. Adductor muscle scars in vertical row with single heart-shaped scar in front.

Family LOXOCONCHIDAE Sars, 1925

Genus Loxoconcha Sars, 1866

Loxoconcha elliptica Brady, 1868

Pl.

Carapace.- Almond-shaped carapace with straight dorsal margin. Surface pitted or reticulate. Hinge gongylo-donty, middle element crenulate. Adductor muscle scars 4, antennal scar crescent-shaped, mandibular scar oval.

L. rhomboidea Fischer, 1855

Pl.

Carapace.- Same as L. elliptica, except venter surface sinuous.

Family TRACHYLEBERIDIDAE Sylvester-Bradley, 1948

Genus Actinocythereis Puri, 1953

Actinocythereis sp. Puri, 1953

Pl.

Carapace.- Holamphidont hinge; ornament like Costa but ridges broken up into spines (ornamentation dominated by 3 subparallel ridges with median ridge parallel to length). 4 adductor muscle scars in vertical row, V-shaped antennal scar opens upward.

Genus Carinocythereis Ruggieri, 1956

Carinocythereis carinata Roemer, 1838

Pl.

Carapace.- Hinge holamphidont tending to hemiamphidont; duplicature narrow; ornamentation includes ridges, spines and reticulations similar to Trachyleberis. Muscle scar pattern vertical row of 4, U-shaped scar or pair of oval antennal scars within pit immediately in front of adductor scars.

Family XESTOLEBERIDIDAE Sars, 1928

Genus Xestoleberis Sars 1866

Xestoleberis sp. Sars, 1866

Pl.

Carapace.- Carapace ovate, LV larger than RV. Merodont hinge with elongate cusps in RV. Marginal areas narrow. Adductor scars in vertical row of 4, arrowhead-shaped antennal scar in front and 2 mandibular scars below in front.

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PLATES

PLATE 1

Association IV: Cyprideis torosa Jones

Fig. 1. Left valve exterior, X110.

Fig. 2. Right valve interior, adductor muscle scars in vertical row, V-shaped antennal scar in front of top of row, mandibular scar in front of bottom of row and 2nd mandibular scar near vertral margin. X130.

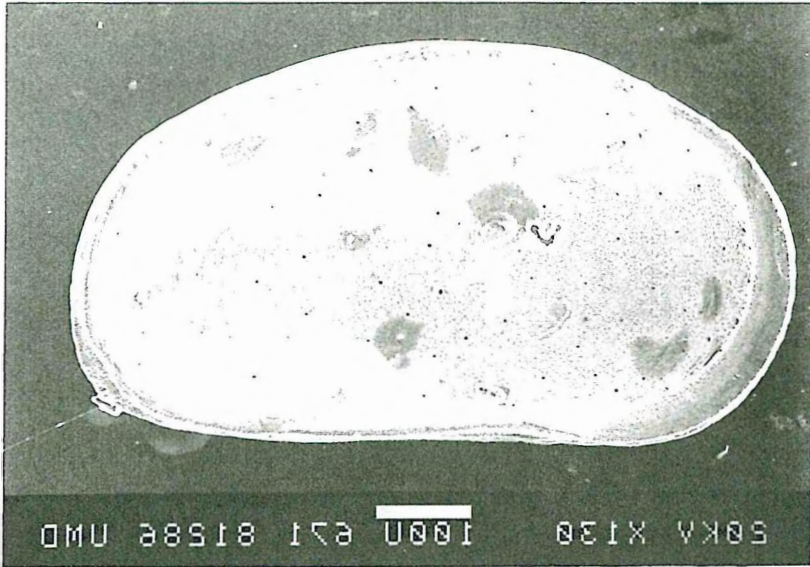
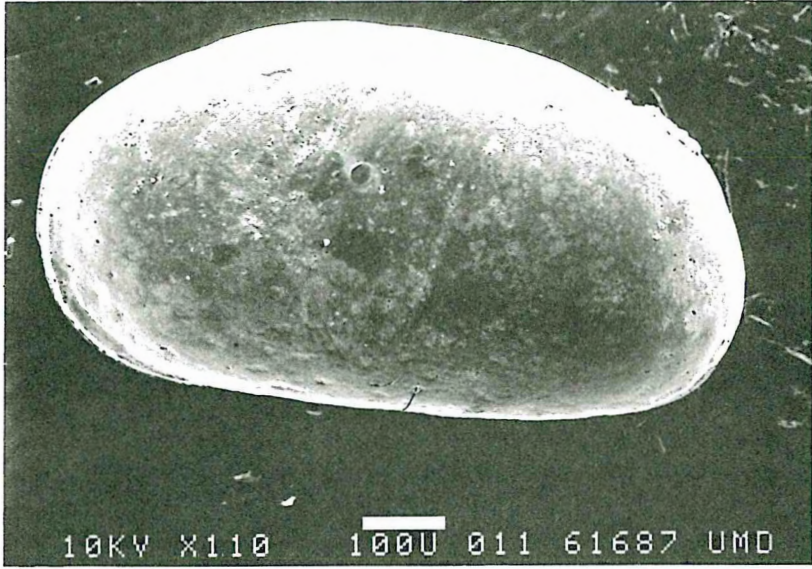


PLATE 2

Association III: Loxoconcha elliptica Brady  
Xestoleberis sp. Sars  
C. torosa Jones

Fig. 1. Loxoconcha elliptica Brady, right valve exterior.  
X120.

Fig. 2. Xestoleberis sp. Sars, left valve exterior.  
X100.



PLATE 3

Association II: Aurila convexa Baird  
Loxoconcha rhomboidea Fischer  
Leptocythere cf. fabaeformis Muller  
X. sp. Sars  
L. elliptica Brady  
C. torosa Jones

Fig. 1. Aurila convexa Baird, left valve. X140.



PLATE 4

Fig. 1. Loxoconcha rhomboidea Fischer, left valve exterior. X140.

Fig. 2. Leptocythere fabaeformis Muller, left valve exterior. X100.





PLATE 5

Association I: Carinocythereis carinata Roemer

Hemicytherura sp. Elofson

Actinocythereis sp. Puri

Cytherida sp. Bosquet

A. convexa Baird

L. rhomboidea Fischer

Fig. 1. Carinocythereis carinata Roemer, right valve exterior. X100.

Fig. 2. Hemicytherura sp. Elofson, right valve exterior. X200.

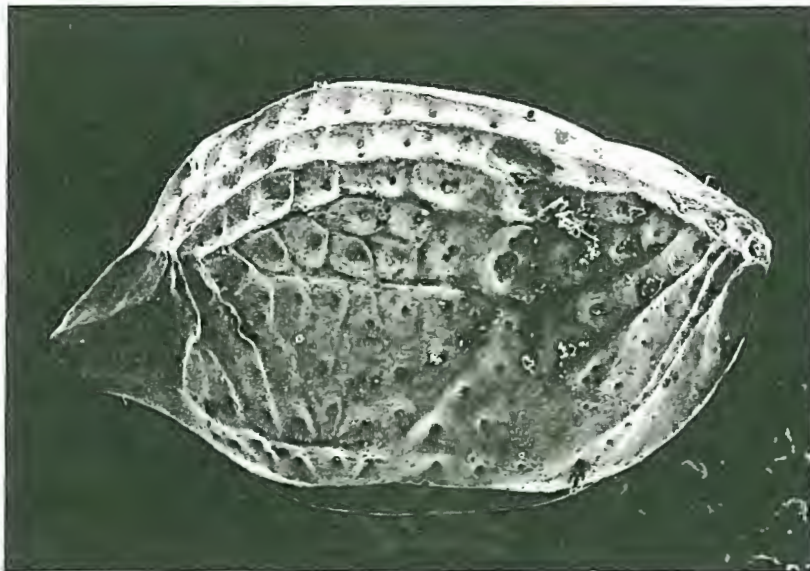
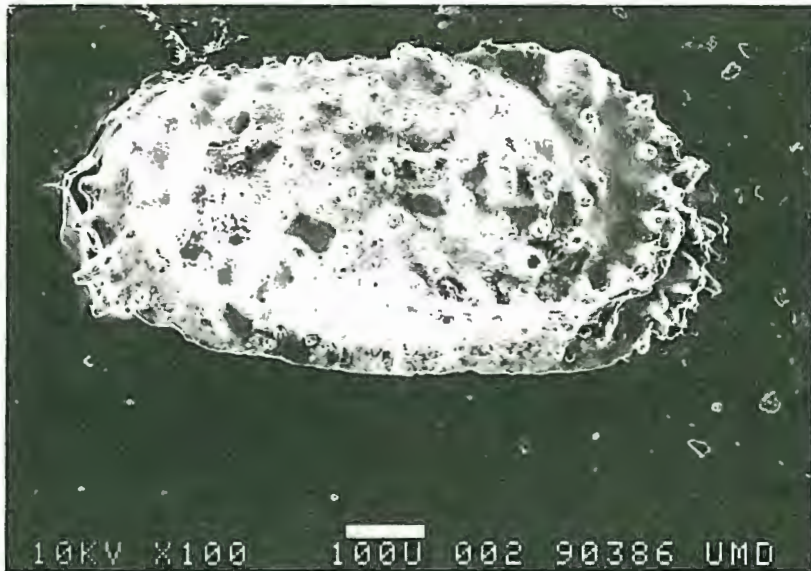


PLATE 6

Fig. 1. Actinocythereis sp. Puri, right valve exterior.  
X100.

Fig. 2. Cytheridea sp. Bosquet, left valve exterior.  
X100.

