1-1-2001

Environmental Analysis of Cores from the Helike Delta, Gulf of Corinth, Greece

S. Soter
American Museum of Natural History

Patricia Blackwelder
University of Miami, <<span class="elink">pblackwe@nova.edu

C. Tziavos
National Center for Marine Research - Greece

D. Katsonopoulou
The Helike Society Poste Restante - Greece

Terri Hood
University of Miami

See next page for additional authors

NSUWorks Citation

S. Soter, Patricia Blackwelder, C. Tziavos, D. Katsonopoulou, Terri Hood, and Carlos A. Alvarez Zarikian. 2001. Environmental Analysis of Cores from the Helike Delta, Gulf of Corinth, Greece .Journal of Coastal Research , (1) : 95 -105. http://nsuworks.nova.edu/occ_facarticles/431.

Authors

Carlos A. Alvarez Zarikian
University of Miami

Journal of Coastal Research	17	1	95–106	West Palm Beach, Florida	Winter 2001

Environmental Analysis of Cores From the Helike Delta, Gulf of Corinth, Greece

S. Soter†, P. Blackwelder‡, C. Tziavos§, D. Katsonopoulou*, T. Hood‡, C. Alvarez-Zarikian‡

†American Museum of Natural History
Department of Astrophysics
Central Park West at 81st Street
New York, NY 10024, U.S.A.

‡Rosensteil School of Marine and Atmospheric Science
University of Miami
Miami, FL 33149, U.S.A.

§National Center for Marine Research
Agios Kosmas
Athens 16604, Greece

*The Helike Society
Poste Restante
25003 Diakopto
Achaia, Greece

ABSTRACT

SOTER, S.; BLACKWELDER, P.; TZIAVOS, C.; KATSONOPOULOU, D; HOOD, T., and ALVAREZ-ZARIKIAN, C., 2001. Environmental analysis of cores from the Helike Delta, Gulf of Corinth, Greece. *Journal of Coastal Research,* 17(1), 95–106. West Palm Beach (Florida), ISSN 0749-0208.

The fan delta southeast of Aigion on the southwest shore of the Gulf of Corinth was the site of ancient Helike, a city destroyed and submerged by an earthquake and seismic sea wave in 373 BC. Bore holes drilled on the Helike Delta yielded numerous ceramic fragments in the upper 12 meters, and a record of changing local environments on the delta during the Holocene period. At about 8 m below present sea level the core profiles show a general upward transition from marine to lacustrine/lagoonal conditions. The transition dates from about 8 kyr BP and is probably due to the deceleration of global sea level rise at the end of the last Ice Age. The deceleration apparently induced an upward and seaward progression of a zone of green clay and silt associated with brackish fauna.

ADDITIONAL INDEX WORDS: *Delta, Greece, microfauna, Holocene, transgression.*

INTRODUCTION

The most prominent flood plain on the southwestern shore of the Gulf of Corinth is a Gilbert-type fan delta formed by the coalesced sediments of three rivers—the Selinous, Kerynites and Vouraikos (Figure 1). We refer to this plain as the Helike Delta, after the principal city of ancient Achaea, which was destroyed by an earthquake and seismic sea wave in 373 BC (MARINATOS, 1960). In the 2nd century AD, Pausanias visited a coastal site still called Helike, about 7 km southeast of Aigion, and reported that the ruined walls of the ancient city were visible in the sea. SOTER and KATSONOPOULOU (1998, 1999) have reviewed the geoarchaeology of the Helike Delta and the search for the lost city.

Although ancient sources described the site of Helike as submerged, modern sonar surveys showed no evidence of a city on or under the seafloor in the area. This suggested that the site now lies on land, under the broad coastal plain. The shoreline has evidently moved seaward since antiquity, due to the progradation of alluvial sediments and the tectonic uplift of the northern Peloponnesos. Accordingly, SOTER and KATSONOPOULOU (1999) carried out a program of bore hole drilling over a large part of the Helike Delta plain, to search for buried ancient occupation horizons.

The present delta lies on the down-thrown block of the Helike Fault, a northward dipping normal fault that marks the contact between the coastal plain and the foothills to the south. The footwall block south of this fault consists of fan deltas of Plio-Pleistocene age, uplifted more than a kilometer, with stratigraphy similar to that of the active Helike Delta (DART *et al.,* 1994). Quaternary subsidence of the hanging wall block has accommodated the deposition of sediments on the active delta, but relic shorelines southeast of the delta suggest that there may have also been episodes of uplift (SOTER, 1998).

Deltas in this region consist of topset beds of subaerial lacustrine/lagoonal and shallow marine deposits, inclined foreset beds of clastic marine deposits forming the prodelta, and bottomset beds of fine-grained marine sediments, all derived from foot wall sources. Rivers and streams erode the uplifting highlands and carry alluvium across the Helike Fault, depositing it on the active delta surface of the hanging wall block.

Tectonic movement has probably subjected the active delta block to differential subsidence, uplift, tilting and retrogressive faulting. Compaction of clay layers may have caused uneven subsidence. Landslides, flood debris flows, earthquake-induced soil liquefaction and seismic sea waves have all left their marks on the delta. High-energy seasonal floods from the three rivers and several streams dominate deposition and erosion of the Helike Delta.

BORE HOLE DRILLING

In 1973 the National Center for Marine Research drilled a bore hole 50 m deep on the beach just north of the Selinous River mouth (S4 in Figure 2). The top 12 m were sand and gravel and the rest consisted of layers of silt or clay alternating with clastics (SCHWARTZ and TZIAVOS, 1979). In 1983, LEONARDS *et al.* (1988) drilled three bore holes near the Ker-

99044 received 30 May 1999; accepted in revision 3 January 2000.

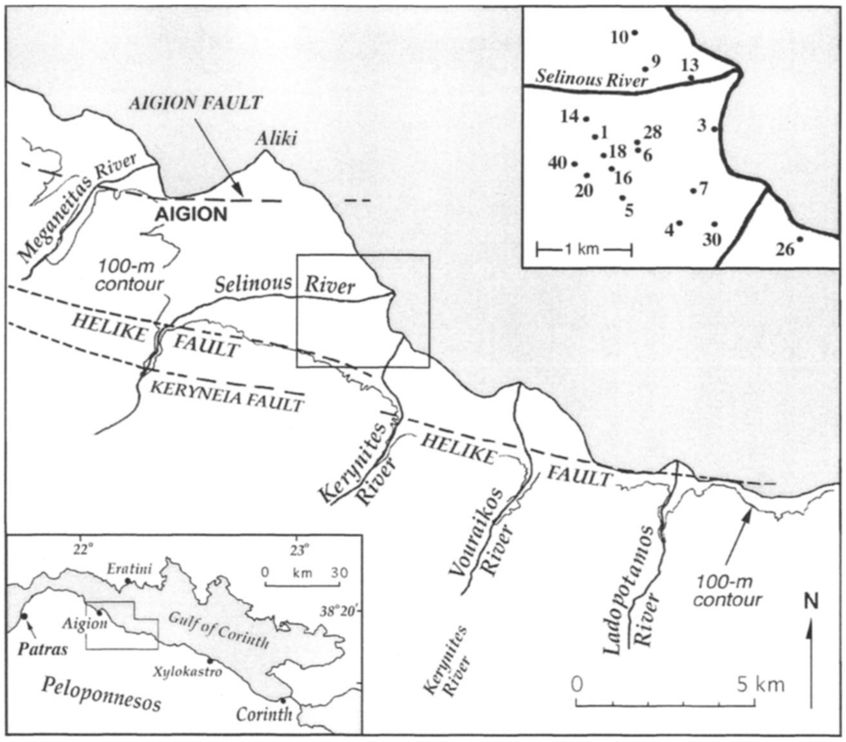


Figure 1. The region of the Helike Delta, southeast of Aigion. Fault names and locations are from Koukouvelas and Doutsos (1996). The inset at upper right shows bore holes with core samples selected for environmental analysis in this paper. Drilling locations are labeled by bore hole number.

ynites River mouth (G1,G2,G3) for a geotechnical investigation. The stratigraphy was similar to that of S4. Based on mechanical tests of these samples, Leonards *et al.* suggested that the subsidence of ancient Helike was caused either by soil liquefaction or mass sliding along inclined clay seams.

During 1991–98, the Helike Project drilled 76 bore holes, mostly on the mid-plain between the Selinous and Kerynites Rivers (see Soter and Katsonopoulou, 1999). We used a rotary drilling rig, with an average core diameter of 10 cm. The average bore hole depth was 45 m for the first 5 holes and 16 m for the remaining 71. Sample recovery was usually better than 75%, but it was never complete, mainly due to the presence of loose sandy aquifers.

The cores showed strata with ceramic fragments, including potsherds, in over half the bore holes, most of them in the upper part of the delta (Figure 2). Most of the ceramic-bearing occupation horizons were found within 12 m of the surface, and above the present sea level. Since Helike was reportedly submerged in the earthquake of 373 BC, the area may subsequently have been uplifted, as suggested by the dating of uplifted rocky shorelines southeast of the delta (Stewart and Vita-Finzi, 1996; Soter, 1998).

The stratigraphy of the delta is extremely heterogeneous. This is not surprising in such a high-energy fan delta environment. Although bore holes drilled within a few hundred meters of one another often showed similar features, we were able to find few detailed correlations, even between cores separated by only a few tens of meters.

Sediments from the Selinous and Kerynites Rivers dominate the lower parts of the plain. Sediments from the stream valley west of the "acropolis" hill have deposited a terrestrial fan delta on the upper part of the plain (Figure 2). This topographic rise, here called the Katourla fan, descends almost symmetrically from its source and merges with the coalesced river deltas at about the 10 m elevation contour.

The Katourla fan is close to its source area and thus cores drilled on it contain mainly coarse clastic debris and few if any marine deposits. Cores drilled at lower elevations contain the full range of sedimentary facies characteristic of an active marine fan delta. These represent braided channels and flood plains, transient lakes and lagoons, barrier beaches and marine foreset beds.

Fragments and traces of ceramics were recovered in core samples from 50 of the 76 bore holes. Most of the bore holes that contained ceramics are within an area of about 2 km^2 between the Selinous and Kerynites Rivers (Figure 2). No ceramics were found in any bore holes drilled north of the Selinous River or seaward of about the 6-m elevation contour. This suggests that the distal part of the delta west of the Kerynites River is relatively young, and that the shoreline in antiquity was near the present 6-m elevation contour. In contrast, every bore hole drilled on the Katourla fan yielded ceramic fragments.

The hundreds of ceramic fragments from cores range in size from small chips up to about 8 cm. Most are archaeologically nondiagnostic. In Figure 2, the term "occupation ho-

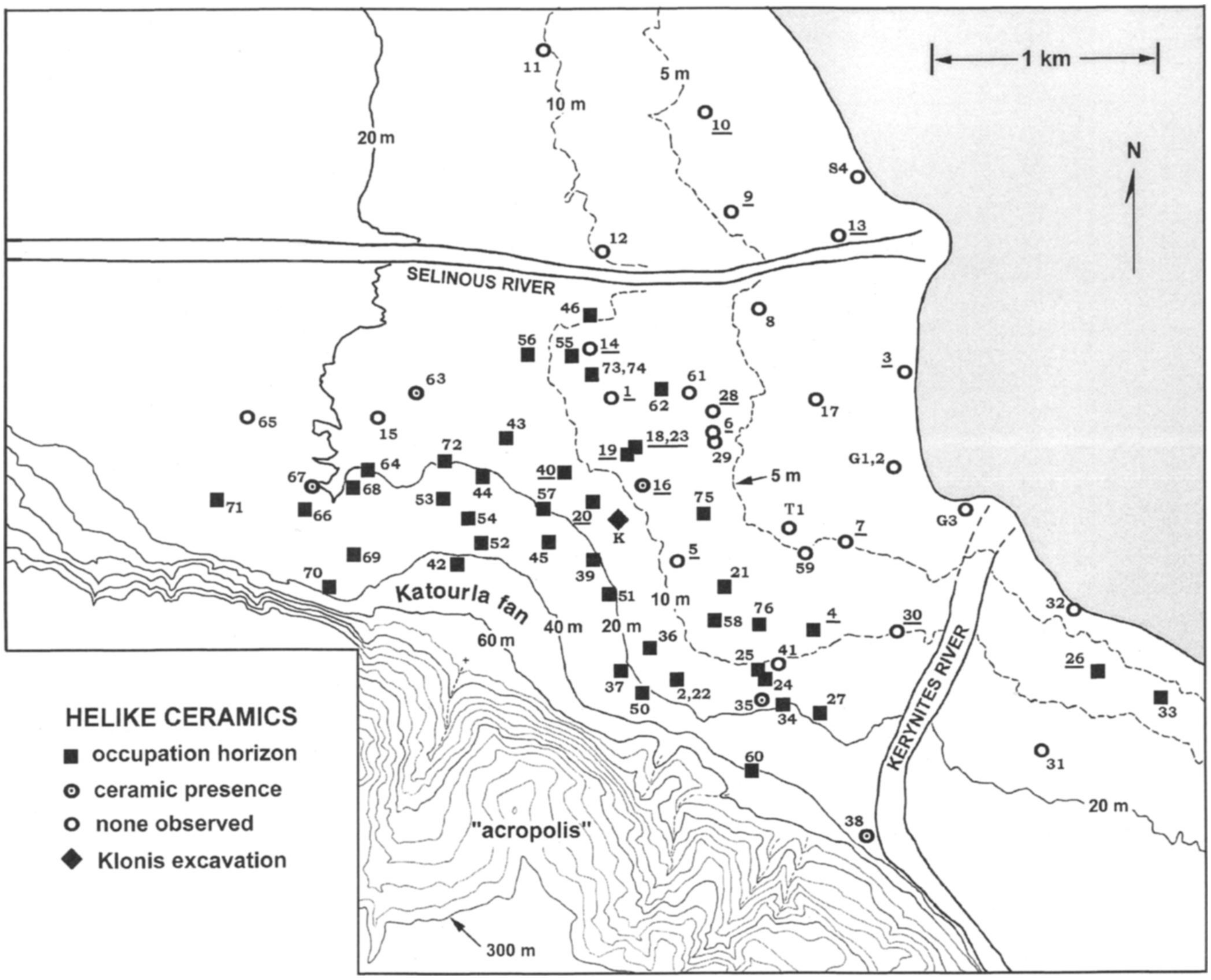


Figure 2. Topographic map of the central Helike search area, with drilling locations identified by bore hole number. The numbered symbols show most of the bore holes B1 to B76 drilled during 1991–1998. Underlined numbers indicate bore holes with core samples analyzed for environment in this paper (*cf.* Fig. 1 inset). Bore holes S4 and G1–3 are described by SCHWARTZ and TZIAVOS (1979) and LEONARDS *et al.* (1988), respectively. The symbol K denotes the Klonis site, where a large Roman building was partly excavated in 1995 (KATSONOPOULOU, 1998; SOTER and KATSONOPOULOU, 1999). Elevation contours are given every 20 meters, plus those at 5 and 10 meters above sea level, from the Greek 1:5000 map. "Occupation horizon" and "ceramic presence" are defined in the text.

rizon" refers to the occurrence of centimeter-size ceramic fragments found in strata of clay, silt, or fine sand. Such fragments were probably deposited by human agency, rather than in flood deposits, since the latter would include gravel and pebbles. The term "ceramic presence" refers to ceramic fragments or traces found in strata containing gravel or pebbles. In this case, flood deposition cannot be excluded.

ANALYSIS OF ENVIRONMENTS

The bore holes sampled sediments from a wide range of ancient deltaic environments, including terrestrial flood plains, fresh water lakes, seasonal ponds, brackish lagoons, beaches, marine delta fronts and prodelta slopes. Environmental analysis of selected core samples was based mainly on the biogenic components within samples, especially microfauna. However, most of the core samples we examined contained no obvious biogenic components. We were able to identify ancient environments with certainty only for the relatively few samples that preserved a rich fossil assemblage.

Most of the biogenic indicators occur in fine-grained strata, deposited in relatively low-energy submerged environments. The core samples with ceramic fragments and/or coarse deposits included few or no biogenic indicators and were probably deposited on a terrestrial flood plain environment or at a river mouth. However, we have not attempted to identify the environmental facies of any sample in the absence of bio-

Table 1. *Bore hole environments.*

No.	D (m)	H (m)	Sediment	Indicators (see notes)	Environment
1A1	8.2	−0.2	gray silty clay	fresh water ostracods (*Can, Iy*)	fresh water
1A3	9.5	−1.5	green silty sand with organics	fresh water ostracods (*Can, Iy*), brackish ostracods (*Cyp*) & brackish to marine forams (*A, E*)	brackish marsh or lagoon
1A4	10.1	−2.1	dark green silty sand, organics	fresh water ostracods, seeds of *Chara sp.*	fresh water
1A5	10.3	−2.3	dark green silty sand, organics	fresh water ostracods, plant fragments	fresh water
1A6	14.7	−6.7	black sand with organics	brackish to marine forams (*A, E*), marine ostracods (*Lo*)	beach to shallow marine
1A7	14.8	−6.8	silt with gravel	brackish to marine forams (*A, E, Q*)	beach to shallow marine
1M39	25.9	−17.9	red-brown clay	abundant fresh water juvenile ostracods, plant-based organics	seasonal pond
1A10	26.0	−18.0	brown clay with organics	fresh water ostracods (*Iy*)	fresh water
1M40	32.3	−24.3	dark gray clay	fresh water ostracod valves, peat	fresh water
3A1	3.0	−2.5	sand & gravel	planktonic & benthonic forams	marine
3W1	14.8	−14.3	sand with silt	sea grass	marine
3A2	16.6	−16.1	sand & fine gravel	brackish to marine forams (*A, E, Q*)	shallow marine
3A4	17.7	−17.2	silty sand with organics	planktonic & benthonic forams	marine
3A6	18.0	−17.5	clay, silt, sand, organics	abundant marine forams & ostracods	marine
3A5	19.6	−19.1	same	small forams (*Q*)	marine
3A8	21.4	−20.9	same	marine forams & ostracods	marine
3A9	23.9	−23.4	same	few forams (*Q*)	marine
3A10	26.5	−26.0	same	marine forams & ostracods, abundant shell fragments	coastal to shallow marine
3A11	27.5	−27.0	same	same	same
3A12	29.4	−28.9	same	same	same
3A14	36.6	−36.1	same	same	same
3A15	38.2	−37.7	clay, clay silt, sandy silt	abundant shells & forams	marine
3A16	41.5	−41.0	same	same	marine
4A2	5.8	2.2	sand, brown silt, gravel	fresh water shells	fresh water
4A7	16.2	−8.2	black sand with silt	abundant plant remains	fresh water
4A8	16.8	−8.8	black silt with organics	abundant brackish to marine forams (*E, A, Q*)	shallow marine
4A9	19.5	−11.5	same	abundant marine forams, ostracods, shell fragments	coastal to shallow marine
4A10	20.7	−12.7	same	abundant marine forams & ostracods	marine
4A12	29.2	−21.2	brown-gray silty sand, silty clay	few forams	marine pro-delta?
4A13	34.5	−26.5	same	marine forams	marine
4A14	34.8	−26.8	clay & silty clay, fine sand layers	marine forams & shell fragments	marine
4A15	35.6	−27.6	same	few forams	shallow marine or lagoon
4A16	37.6	−29.6	brown-black clay, silty clay, layers of fine sand & black silt, organics	few forams	lagoon?
4A17	37.9	−29.9	same	brackish to marine forams (*A, E, Q*) & ostracods (*Cyp*), shell fragments	coastal to shallow marine
4A18	39.0	−31.0	same	similar	same
4A19	40.4	−32.4	black silty sand	similar	same
4A20	43.0	−35.0	same	marine forams & shells	marine
4A21	44.0	−36.0	same	similar to 4A17	coastal to shallow marine
5M41	11.0	−2.3	yellow-brown silty clay with sand, charcoal	fresh water ostracod valves (*Can, Cyp*), abraded mollusc fragments	fresh water
5A2	15.1	−6.4	silty sand with gravel	many forams (*A, E*)	marine
5A3	23.0	−14.3	black silty sand	sparse forams (*E*), rich organics	sheltered coastal area (lagoon?)
5M52	25.0	−16.3	greyish-brown silty sand, well sorted, much charcoal	well-preserved marine forams (*Ap*), variety of seeds, some charred	nearshore marine

Table 1. *Continued.*

No.	D (m)	H (m)	Sediment	Indicators (see notes)	Environment
5A5	27.0	−18.3	black silty sand	few forams (*E, Q*)	coastal marine
5A6	27.5	−18.8	same	forams (*A, E, Q*)	coastal marine
5A7	28.5	−19.8	gray silty clay, organics	same	coastal marine
5A8	32.0	−23.3	silty sand	abundant marine forams & shells	shallow marine
5A9	35.0	−26.3	same	same	shallow marine
6A1	3.8	1.9	black clay	fresh water ostracods (*Iy*)	fresh water
6A2	4.7	1.0	olive green clay	same	fresh water
7W1	7.6	−2.8	fine sand, organics	sea grass	marine
9A1	10.0	−5.3	silt with fine gray sand	marine forams (*C, Cyc, Ec, M, Q, P, R, S*), ostracods (*Car, Lo*), sea grass	marine
10A2	10.5	−6.6	fine brown sand with silt, gray sand lamina	marine forams (*A, C, E, Ec, Q*)	shallow marine
10A3	12.9	−9.0	coarse gray sand, many organics	marine forams (*A, C, E, Ec, R, Q, Sc, T*)	shallow marine
13A1	13.6	−11.6	sand & fine gravel	marine forams (*A, E, Ea, Ec, Q, R, S, T*), ostracods (*Au, Cal, Cyth, Lo, X*)	marine
14A2	7.8	1.8	sand & gray sandy clay	fresh water ostracods (*Can, Iy*)	fresh water
14M11	11.6	−2.0	organic layer with wood & charcoal, above layers with sand and pebbles	land gastropod & fresh water or brackish bivalve shells, benthic foram (*E*)	mixed environment (tsunami?)
16M10	7.7	0.8	brown clay with sand & silt	brackish ostracods (*Cyp, H*), benthic forams (*A*), all badly abraded	reworked assemblage
16A5	9.9	−1.4	brown sand layer in gray clay	fresh water ostracods (*Can, Iy*)	fresh water
16M7	11.0	−2.5	brown sand layer in gray clay, wood, charcoal	fresh water ostracods (*Can, Li*), fresh water green algae	fresh water
18A2	5.6	2.0	olive green clay with silt, some sand, organics	brackish ostracods (*Cypt*)	brackish
19A5	9.3	−1.3	gray silty clay with sand	fresh water ostracods (*Can, Iy*)	fresh water
20A4	11.3	2.2	brown sandy silt, gray-orange areas	brackish ostracods (*Cypt*)	brackish
23M46	8.5	−1.0	sandy silt with clay, well sorted, charcoal fragments	articulated fresh water ostracods (*Can*)	fresh water
23M47	8.9	−1.4	yellow & brown sand, coarsely layered	fresh water ostracod valve	fresh water
23M19	17.1	−9.6	grayish brown silty sand, well sorted	benthic forams (*T*)	marine beach
23M14	18.5	−11.0	black sand, dark clay, charcoal & wood fragments	benthic forams (including *E*), molluscs (bivalves & gastropods), sea urchin spine & crab claw fragments	coastal marine
26M25	5.5	1.1	dary gray brown silty clay, with sand, charcoal	fresh water or brackish snail shell, abraded shell fragments	fresh water or brackish
28M28	3.2	1.8	olive green clay & sandy silt	terrestrial gastropod	terrestrial
30W1	10.9	−0.9	dark grayish brown silty clay	cockle shell (*Cardiidai Cerastoderma Glauca*)	shallow marine
40M1	10.1	2.9	sand with clay	terrestrial snail	terrestrial
40M36	12.4	0.6	sandy clay, ceramic	terrestrial gastropod shell	terrestrial
M54	0.0	0.0	gray clay	fresh water to brackish ostracods (*Cypt, Can, Cys*), marine forams (*E*), abundant molluscs, *Chara sp.*	fresh water to brackish
M55	0.0	0.0	brown-pink clay	fresh water ostracods (*Can*), marine forams (*E*), *Chara sp.*	fresh water to brackish

No. = bore hole number, followed by A for Athens, M for Miami, or W for Washington (location of the analysis), followed by sample number. M54 and M55 are control samples from the contemporary Aliki lagoon.
D(m) = sample depth in meters below surface.
H(m) = elevation in meters relative to present sea level.
INDICATORS = biological inclusions, with following abbreviations for microfauna
ostracoda: *Au* = *Aurila*, *Cal* = *Callistocythere*, *Can* = *Candona*, *Car* = *Carinocythereis*, *Cyp* = *Cyprideis*, *Cypt* = *Cyprideis torosa*, *Cys* = *Cypris sp.*, *Cyth* = *Cythereis*, *H* = *Haplocytheridea*, *Iy* = *Ilyocypris*, *Li* = *Limnocythere*, *Lo* = *Loxoconcha*, *X* = *Xestoleberis communis*
foraminifera: *A* = *Ammonia*, *Ap* = *Ammonia parkinsoniana*, *C* = *Cibicides*, *Cyc* = *Cyclogyra*, *E* = *Elphidium*, *Ea* = *Elphidium adrena*, *Ec* = *Elphidium crispium*, *M* = *Massalina*, *P* = *Planorbulina*, *Q* = *Quinqueloculina*, *R* = *Rosalina*, *S* = *Spiroluculina*, *Sc* = *spiroloculina canaliculata*, *T* = *Triloculina trigonula*

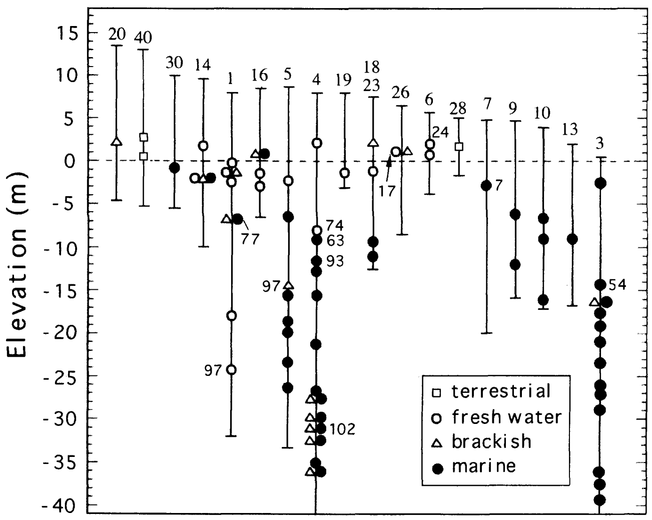


Figure 3. Vertical profiles showing core samples analyzed for deposition environment, based on biogenic indicators. Each profile is labeled at the top by its bore hole number. The profiles are arranged roughly in rank order of surface elevation. The horizontal axis has no scale because the bore holes are located over a broad area. Some profiles include dated samples labeled in hundreds of years before present (from Table 2). "Terrestrial" refers to alluvial flood deposits, "fresh water" to lakes or ponds, "brackish" to lagoonal or near shore facies, and "marine" to the prodelta environment. Samples labeled with more than one symbol represent transitional environments or mixed sediments redeposited from different environments. The profiles for bore holes B18 and B23, drilled only a few meters apart, are combined. Figures 3, 5 and 6 previously appeared in SOTER and KATSONOPOULOU (1999), © John Wiley & Sons, Inc.

genic indicators. Even for samples containing biogenic components, we regard most of the environmental assessments as provisional.

We examined environmental indicators for 71 selected core samples from 19 bore holes and for two control samples from a contemporary lagoon. The locations of those bore holes are shown in Figure 1 (upper right inset) and Figure 2 (underlined). The data are given in Table 1, which includes sample depth (D) below the surface and elevation (H) relative to present sea level, the sediment type, the observed biogenic indicators, and an assessment of the ancient environment of deposition. Each sample is designated by its bore hole number, followed by a letter indicating where the analysis was performed (A for Athens, M for Miami, and W for Washington), and then by a sample number.

Figure 3 summarizes the results of the environmental analysis, with the bore holes ranked in order of surface elevation above mean sea level (MSL). Calibrated radiocarbon ages for selected samples are indicated alongside some profiles, in hundreds of years before present. We have sorted the various environmental assessments into four broad categories, as follows:

(1) "Terrestrial" refers to coarse alluvial sediments deposited on a flood plain in the absence of standing water. This identification is used in only two cases, where we found recognizable terrestrial snail shells.

(2) "Fresh water" refers to sediments deposited in lakes or seasonal ponds. We interpreted the predominantly fresh water ostracods (*Candona, Ilyocypris, Limnocythere*) and fresh water plant fragments as indicators of this environment (Figure 4).

(3) "Brackish" refers generally to lagoonal, beach or near-shore environments. These facies are suggested by the predominantly brackish water ostracods (*Cyprideis torosa* and *Haplocytheridea*) and/or by the presence of both marine and fresh water ostracods. Brackish to marine foraminifera (such as *Elphidium* and *Quinqueloculina*) may also be present.

(4) "Marine" refers here to the prodelta environment, identified by marine ostracods (*Loxoconcha*), marine foraminifera, bivalves and marine detritus such as crab claw and sea urchin fragments.

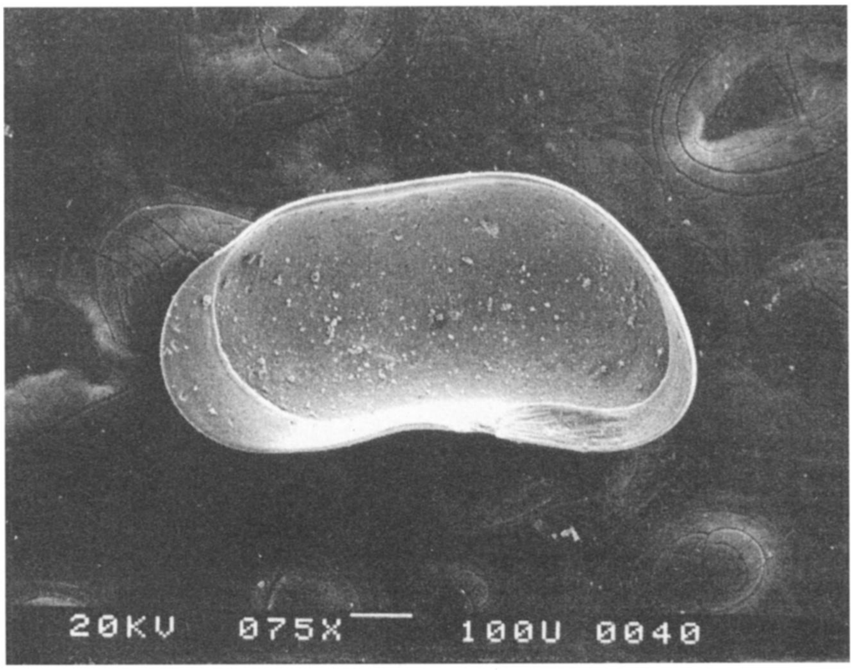
The above categories have some overlap. Many species can tolerate a range of salinities; for example the ostracod *Cypredeis torosa* is found from brackish to marine biotopes (TZIAVOS, 1978). Some core samples represent transition zones, where species from different environments coexist, while others may contain a mixture of reworked sediments originally derived from different environments. Rivers can wash fresh water species into marine environments. Core samples indicated with dual symbols in Figure 3 appear to represent either transition zones or reworked sediments. For example, samples 14M11 and 16M10, found near present sea level (Table 1), contained a mixture of biogenic indicators, representing different environments and showing signs of abrasion. These are evidently reworked deposits, possibly emplaced by a tsunami.

As a test case for a known environment, two control samples were taken from a contemporary brackish deposit in the area, the exposed mud flats of the Aliki lagoon, on the prominent cape northeast of Aigion (Figure 1). This spring-fed lagoon is protected from the sea only by a low sand barrier. Control sample M53 consisted of gray clay, with abundant fresh water ostracods (*Candona*) and generally brackish ostracods (*Cyprideis torosa*), together with brackish to marine forams (*Elphidium*), mollusks, and abundant fragments of *Chara* sp. (a fresh to brackish water plant). Control sample M54 consisted of reddish brown clay, with *Candona, Elphidium,* some gastropods, and *Chara*. If these samples had been found in a bore hole core, we would have assigned them, based on the criteria discussed above, to a lagoonal environment, as is indeed the case.

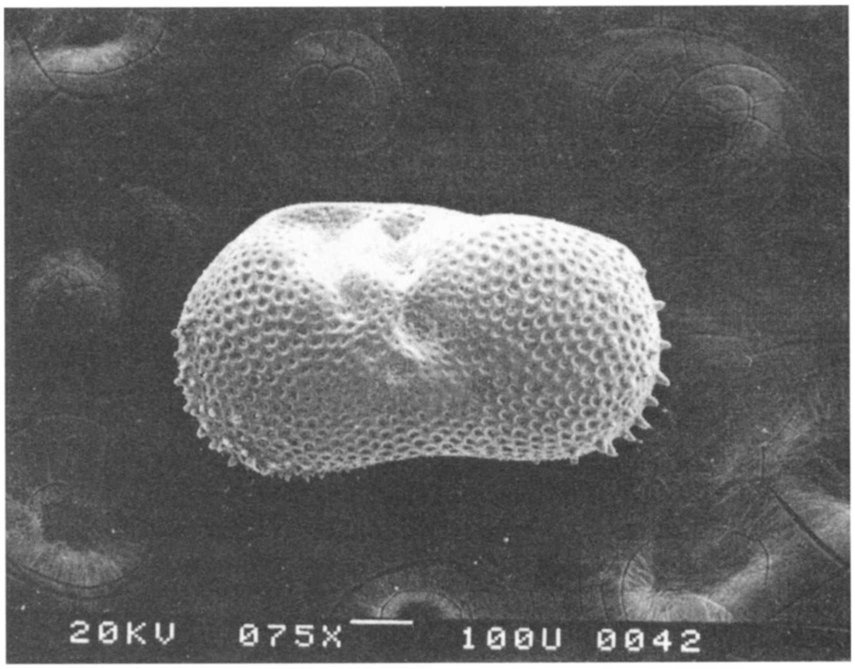
Five bore holes (B1–5) were more than 40 m deep. Bore holes B1, B4 and B5 were located in the mid-plain at 8 to 9 m above sea level, and all contained indicators characteristic of marine, brackish and fresh water facies (Figure 5). Bore hole B2, located at 16 m elevation near the Helike Fault, yielded no brackish or marine indicators at any depth, while B3, located near the shore, contained only marine or brackish indicators.

Core samples with indicators of a brackish environment were presumably deposited at or near sea level. In bore hole B18, we found typically brackish ostracods (*Cyprideis torosa*) in a layer of sandy green silt and clay (18A2) between two ceramic horizons (Figure 6). To date, this is the only case of a brackish deposit overlying ceramics that we have recognized. Many of the bore holes contained layers of olive green

Fresh water ostracods, sample 16M7



Candona sp.



Ilyocypris sp.

Figure 4. Scanning electron micrograph of typically fresh water ostracods in sample 16M7 from bore hole B16 at a depth of 2.5 m below present mean sea level. Electron Microscopy Laboratory, RSMAS, University of Miami.

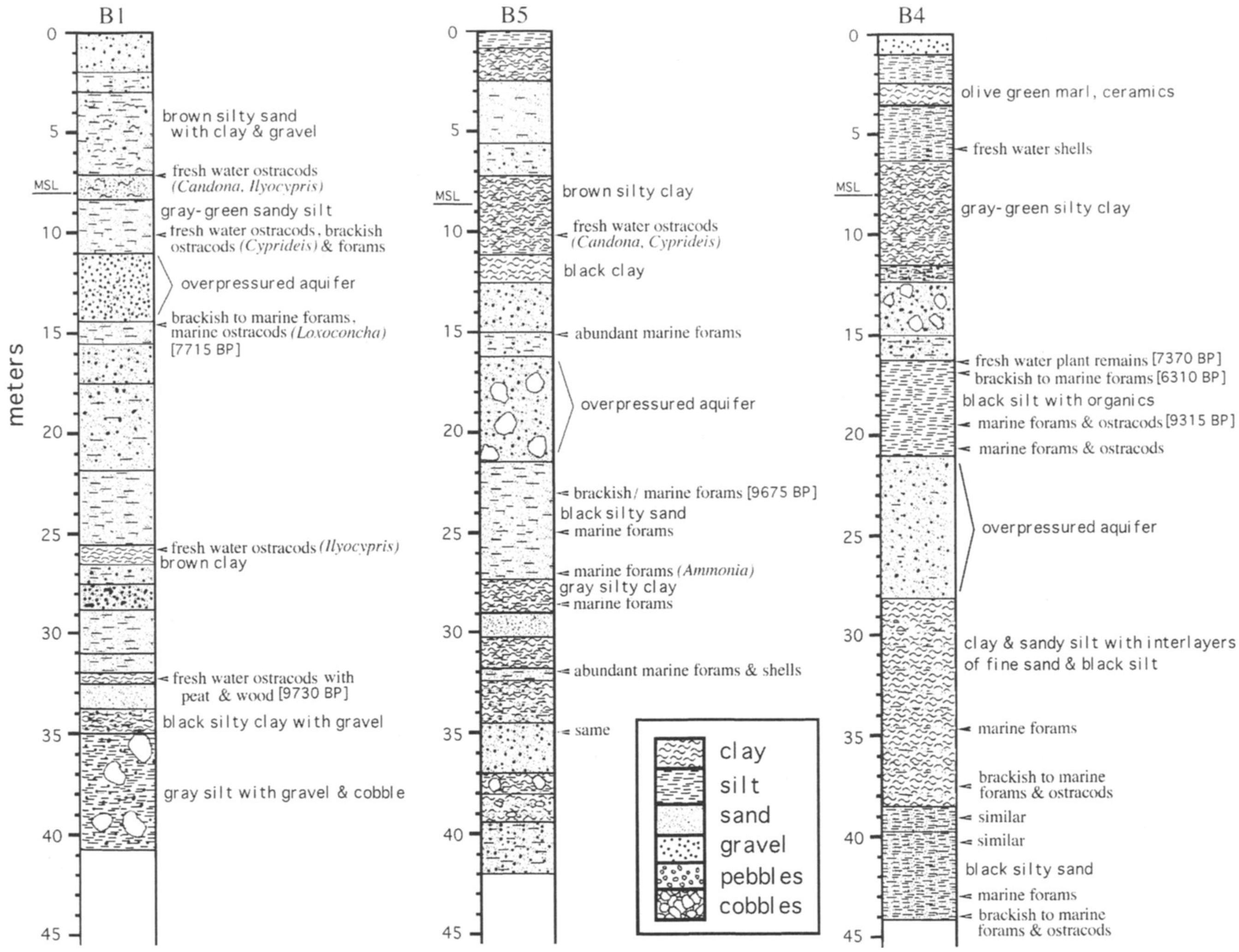


Figure 5. Stratigraphic profiles of bore holes B1, B5, and B4, all drilled in the mid-plain with surface elevations from 8 to 9 m. Radiocarbon dates are shown in brackets (from Table 2).

or gleyed clay or silt, as shown in the profiles of Figure 7. Some of these strata contain or are close to faunal indicators of a brackish environment.

The upper parts of the cores in Figure 3 show predominantly terrestrial and fresh water facies, while most of the samples deeper than about 8 m below the present MSL represent marine facies. The transition represents a major change in the evolution of the delta.

Preliminary analysis of bore holes drilled in 1998 suggests the presence of an ancient lake in the upper part of the plain on the western side of Katourla fan. Three bore holes B66–68, all drilled at 21–22 m surface elevation (Figure 2), contained only clay, silt or fine sand in their upper 7–8 m, together with fragments or traces of ceramics, some of them apparently *in situ.* While maps dating back to 1700 AD show no lakes here, it is significant that the traditional local name for this area is *oi limnes* ("the lakes").

AGE-DEPTH RELATIONS

To investigate the relation of age and depth in the sediments of the Helike Delta, we used three methods to date samples: stylistic identification of diagnostic ceramic fragments, luminescence dating of nondiagnostic ceramic fragments, and radiocarbon dating of wood, sea grass and organic silt and clay. The data are plotted in Figure 8 as a function of depth in meters and age in thousands of years.

Some of the many ceramic fragments found in the bore holes could be dated by stylistic criteria (KATSONOPOULOU, 1998). They are indicated by open triangles in Figure 8. Several nondiagnostic ceramic fragments were dated by optically stimulated luminescence (LIRITZIS *et al.,* 1997). These data are shown as solid triangles.

MANIATIS *et al.* (1996) obtained radiocarbon dates for Helike bore hole samples of organic fragments (wood, peat, sea

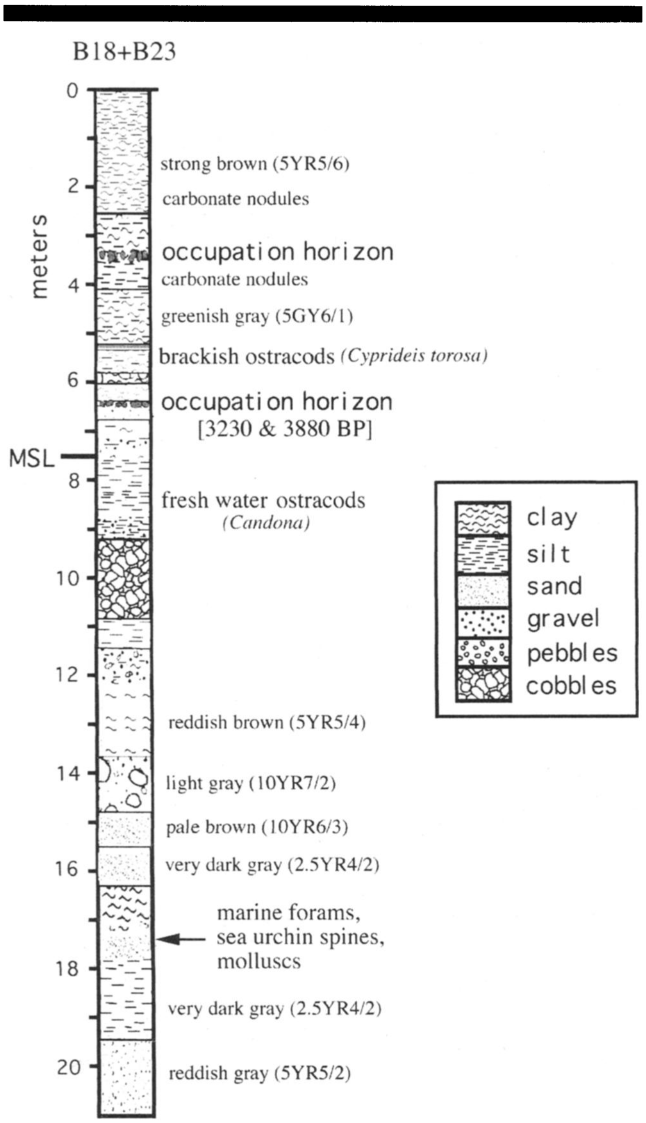


Figure 6. Composite profile of bore holes B18 and B23, drilled a few meters apart, showing a brackish green clay layer between ceramic occupation horizons at 3.3 and 6.5 m below ground in B18. The lower ceramics yielded two luminescence dates (LIRITZIS *et al.* 1997).

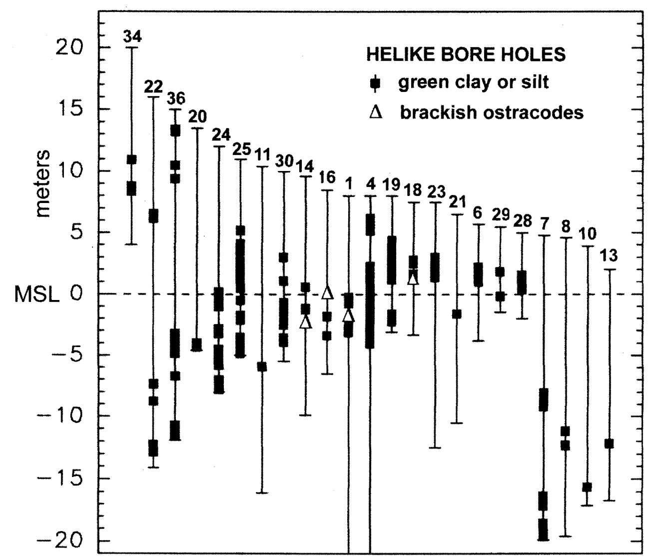


Figure 7. Profiles of borings containing olive green or gleyed clay or silt, with brackish indicators.

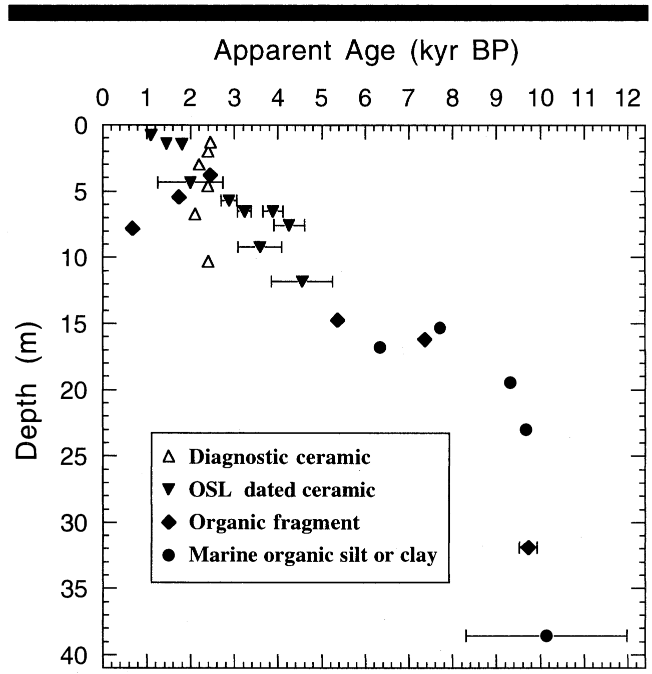


Figure 8. Apparent ages of dated samples in thousands of years before present (1950 AD), versus depth below the surface in meters. Open triangles represent diagnostic ceramic fragments, solid triangles are luminescence-dated ceramics, solid diamonds are radiocarbon dates of organic fragments, and solid circles are radiocarbon dates of marine organic silt or clay.

grass, etc.) and of amorphous organic carbon (AOC) in black silt or clay. The radiocarbon dates for organic fragments and marine AOC samples (identified as such by their microfauna) are plotted in Figure 8 as solid diamonds and circles, respectively. Those data are generally consistent with the broad age-depth trend obtained for the ceramic fragments.

Most of the fresh water AOC samples from the cores yielded anomalously old radiocarbon ages (SOTER and KATSONOPOULOU, 1999). They appear to be unreliable as a class, and are not included here. SOTER (1998) suggested that their anomalous ages reflect the uptake by fresh water aquatic plankton of radioactively "dead" carbon derived from the prevailing limestone of the region (*cf.* MACDONALD *et al.*, 1991).

In contrast, the AOC from marine sediment deposits in the Helike cores yielded acceptable radiocarbon ages, requiring

Table 2. *Radiocarbon ages.*

No.	D(m)	H(m)	Environment	Dated Sample	Cal Age BP	Lab Number
1A7	14.8	−6.8	beach to shallow marine	AOC at 15.3 m	7715 ± 35	Dem-191
1M40	32.3	−24.3	fresh water	wood at 31.9 m	9732 ± 202	Dem-185
3W1	14.8	−14.3	marine	sea grass	5465 ± 105	Dem-188
4A7	16.2	−8.2	fresh water	wood	7365 ± 150	Dem-187
4A8	16.8	−8.8	shallow marine	AOC	6340 ± 50	HD-16126
				sea grass	6280 ± 90	Dem-283
4A9	19.5	−11.5	coastal to shallow marine	AOC	9315 ± 65	Dem-192
4A18	39.0	−31.0	same	AOC	10,150 ± 1840	Dem-186
5A3	23.0	−14.3	sheltered coastal area (lagoon?)	AOC	9675 ± 135	Dem-198
6A1	3.8	1.9	fresh water	rootlets	2410 ± 62	Dem-375
7W1	7.6	−2.8	marine	sea grass	680 ± 25	Beta-72211
26M25	5.5	1.1	fresh water or brackish	plant stern	1739 ± 130	AA-15022

No. = bore hole number, followed by A for Athens, M for Miami, and W for Washington, followed by sample number.
D(m) = sample depth in meters below surface, H(m) = sample elevation in meters relative to present sea level.
AOC = amorphous organic carbon in silt or clay.
Cal Age BP = calibrated radiocarbon age before present (Maniatis *et al.*, 1996; Soter and Katsonopoulou, 1999).
Lab Number: AA = University of Arizona, Beta = Beta Analytic, Dem = Demokritos, HD = Heidelberg.

only a correction for the marine reservoir effect. Heezen *et al.* (1966) sampled surface water from the Gulf of Corinth in 1956 and found that its radiocarbon age was about 380 years older than the average age of North Atlantic surface water (itself about 400 years). They attributed this anomalous reservoir effect to dead carbon washed into the restricted Gulf of Corinth basin from the surrounding limestone mountains. We have used a reservoir correction factor $\Delta R = 380$ years in calibrating all the radiocarbon ages for marine organics (Soter, 1998).

Most of the points in Figure 8 define a broad linear trend of increasing age with depth. The scatter is not large, considering that the samples came from bore holes drilled in various parts of the delta with different surface elevations and sedimentation histories. Table 2 lists the radiocarbon ages found for marine AOC and organic fragments in sediments with environments evaluated in Table 1. Figure 3 shows the elevations of these dated samples.

DISCUSSION AND CONCLUSIONS

Figure 8 shows that the main age-depth trend was nearly linear for the last 8 kyr, with a slope of about 2.5 m/kyr, and in earlier times the slope was about ten times steeper. The change in deposition rate occurs in bore holes at roughly 8 m below present sea level, where the sediments in several cores shift from marine to overlying fresh water deposits (Figure 3).

This change on the Helike Delta was apparently part of a global pattern. Stanley and Warne (1994) showed that marine deltas throughout the world began prograding rapidly between about 9500 and 7400 cal yr BP, due to deceleration in the rate of global sea level rise with the end of the last Ice Age. When sea-level rise was rapid, the subaerial delta was smaller than today. However, with deceleration of sea level rise, the same sediment supply would have produced a rapid progradation of the delta front.

The deeper layers of bore holes B4 and B5 yielded only marine and shallow marine indicators (Figure 5), which suggests that the shoreline oscillated across the area of B4 and B5 until about 7 kyr ago, after which a subaerial delta was established there (Figure 9). In contrast, the deeper layers of bore hole B1 yielded only fresh water indicators, suggesting that the delta of the Selinous River was subaerial near B1 during most of the same period.

After Classical Helike was submerged by the earthquake of 373 BC, marine or brackish sediments should have been deposited over the site, at least until such time as the area again became a subaerial delta. In one bore hole (B18) we found a brackish deposit overlying a ceramic layer, but in that case the ceramics appear to have OSL dates from the Bronze Age (Figure 6). The area around B18 was evidently an occupied site in the 2nd millennium BC, and was later covered by a lagoon. We note that B18 lies on the seaward fringe of the region defined by occupation horizons (Figure 2). We have not yet identified any other cases of marine or brackish sediments overlying an occupation horizon.

Perhaps only the parts of Helike lying at lower elevations (seaward of the present 10-m elevation contour) were actually submerged by subsidence, while most of the ceramic horizons represent the upper parts of the city. By this hypothesis, the subsidence of the delta would have drowned only the harbor town and other low-lying areas. If this explanation is correct, then ancient accounts suggesting that the entire city was submerged may have been exaggerated. It is also possible that the submergence only lasted a few hundred years before tectonic uplift again raised the site above sea level (Soter, 1998). In that case, only a thin layer of marine sediment would have been deposited, and this may have been removed by erosion after subsequent uplift.

Core samples with microfaunal indicators of a brackish environment were presumably deposited at or near sea level. The strata of green and gleyed clay associated with brackish indicators in cores samples found near present sea level probably indicate stagnant, near-shore lagoonal facies. They show a trend in which their absolute depth decreases with decreasing surface elevation of the bore hole (Figure 7). This may

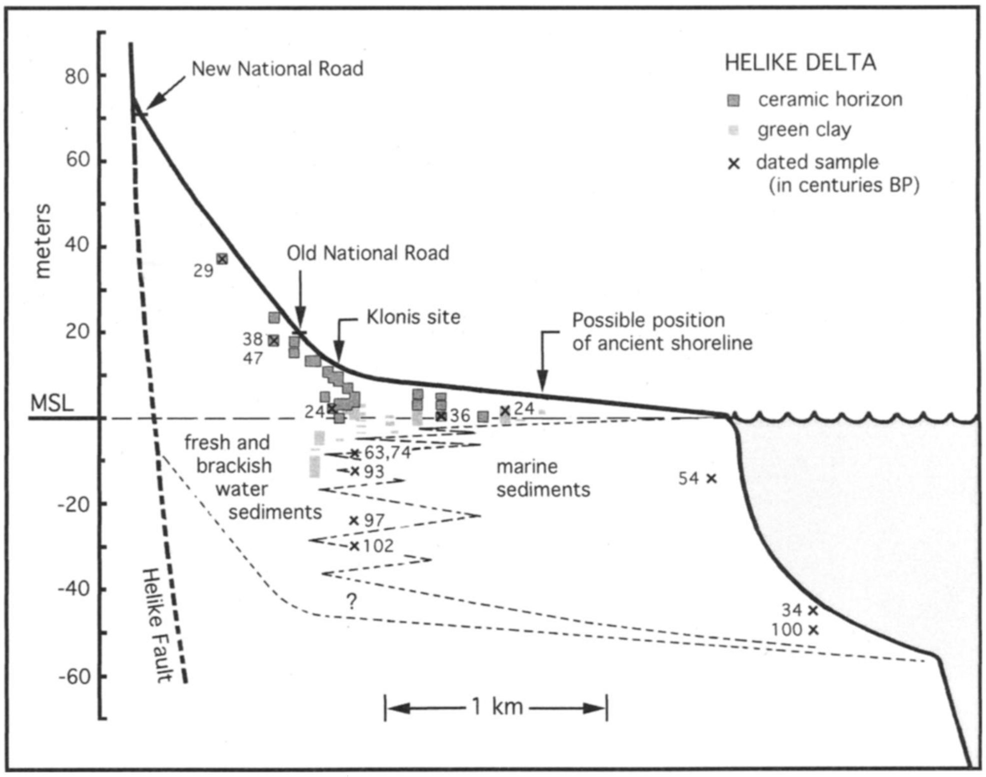


Figure 9. Schematic profile of the Helike Delta. The ceramic horizons occur mostly above the present mean sea level (MSL). The green clay strata often occur below the ceramic horizons, and generally reflect a brackish environment. Dated samples are labeled in hundreds of years before present. The ages of the two seafloor samples are based on data from SCHWARTZ and TZIAVOS (1979).

reflect a progradation of lagoonal facies with rising sea level during the Holocene. These strata also extend seaward only up to the boundary corresponding to about the present 6-m surface elevation contour. The shoreline may have been near this boundary in Classical times. No occupation horizons were found in any bore holes drilled seaward of this boundary.

Figure 9 summarizes the bore hole analyses in a schematic profile of the Helike Delta, which combines ceramic, environment and dating results.

ACKNOWLEDGMENTS

The Helike Project is conducted under the auspices of the American School of Classical Studies at Athens. The Tria Epsilon Group of Companies (Hellenic Bottling Company) contributed important financial support. For their assistance with the sample retrieval, we thank Maria Argyropoulou, Katerina Bichta, Alexandra Georgiou, Alexis Liogas, Eirini Maganioti, Dimitra Papantoni and Annie Trikka. We also thank P. Karanikolas for a preliminary analysis of cores B1–B5, and J. Norris and T. Waller of the Smithsonian Institution for examining two biological specimens. For their help in other important ways, we wish to thank Demetrius Schilardi, Elias Sotiropoulos, Elias Papaioannou, Susan George, John C. Kraft and Daniel Jean Stanley.

LITERATURE CITED

DART, C.J.; COLLIER, R.E.L.; GAWTHORPE, R.L.; KELLER, J.V.A., and NICHOLS, G., 1994. Sequence stratigraphy of (?)Pliocene-Quaternary synrift, Gilbert-type fan deltas, northern Peloponnesos, Greece. *Marine and Petroleum Geology,* 11, 545–560.

HEEZEN, B.C.; EWING, M., and JOHNSON, G.L., 1966. The Gulf of Corinth floor. *Deep-Sea Research,* 13, 381–411.

KATSONOPOULOU, D., 1998. The first excavation at Helike: Klonis field. A preliminary report [in Greek]. *In:* KATSONOPOULOU, D.; SOTER, S., and SCHILDARDI, D. (eds.), *Ancient Helike and Aigialeia.* Athens: The Helike Society, pp. 31–66.

KOUKOUVELAS, I.K. and DOUTSOS, T.T., 1996. Implications of structural segmentation during earthquakes: the 1995 Egion earthquake, Gulf of Corinth, Greece. *Journal of Structural Geology,* 18, 1381–1388.

LEONARDS, G.A.; SOTIROPOULOS, E.S., and KAVVADAS, M.J., 1988. Helice: the lost town of ancient Greece. *In: Engineering Geology of Ancient Works, Monuments and Historical Sites* (MARINOS, P.G. and KOUKIS, G.C. eds.). Rotterdam: Balkema, pp. 1307–1313.

MACDONALD, G.M.; BEUKENS, R.P., and KIESER, W.E., 1991. Radiocarbon dating of limnic sediments: a comparative analysis and discussion. *Ecology,* 72, 1150–1155.

MANIATIS, Y.; FACORELLIS, Y.; SOTER, S.; KATSONOPOULOU, D., and KROMER, B., 1996. Locating horizons with ^{14}C sediment dating: the case of the lost city of Helike. *Radiocarbon,* 37, 931–942.

MARINATOS, S., 1960. Helice: a submerged town of Classical Greece. *Archaeology,* 13, 186–193.

SCHWARTZ, M.L. and TZIAVOS, C., 1979. Geology in the search for ancient Helike. *J. Field Archaeology,* 6, 243–252.

SOTER, S., 1998. Holocene uplift and subsidence of the Helike Delta, Gulf of Corinth, Greece. *In:* Stewart, I. and Vita-Finzi, C. (eds.), *Coastal Tectonics,* Spec. Pub. Geol. Soc. London 146, 41–56.

Soter, S. and Katsonopoulou, D., 1998. The search for ancient Helike, 1988–1995: geological, sonar and bore hole studies. *In:* Katsonopoulou, D.; Soter, S., and Schildardi, D. (eds.), *Ancient Helike and Aigialeia.* Athens: The Helike Society, pp. 67–116.

Soter, S. and Katsonopoulou, D., 1999. Occupation horizons found in the search for the ancient Greek city of Helike. *Geoarchaeology,* 14, 531–563.

Stanley, D.J. and Warne, A.G., 1994. Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. *Science,* 265, 228–231.

Stewart, I. and Vita-Finzi, C., 1996. Coastal uplift on active normal faults: the Eliki Fault, Greece. *Geophys. Res. Lett.,* 23, 1853–1856.

Tziavos, C., 1978. Distribution of recent foraminifera and ostracoda from the Sperchios River delta and Maliakos Gulf, Greece. *Thalassographica,* 2(1), 57–81.