Occupation Horizons Found in the Search for the Ancient Greek City of Helike

Steven Soter[1] and Dora Katsonopoulou[2]

[1]*American Museum of Natural History, Department of Astrophysics, Central Park West at 81st Street, New York, NewYork 10024*
[2]*The Helike Society, 2 Metropoleos Street, Aigion 25100, Greece*

In 373 B.C. an earthquake and seismic sea wave destroyed and submerged Helike, the principal Greek city on the southwestern shore of the Gulf of Corinth. Our sonar survey of the seafloor in the area where ancient sources located Helike, southeast of Aigion, showed no evidence of a submerged city. We concluded that the site must now lie in the alluvial deposits of the adjacent coastal plain. Accordingly, we used bore hole drilling and geophysical techniques to look for buried occupation horizons on land. The bore hole cores yielded numerous ceramic fragments and remains of walls, ranging from near the surface to about 15 m deep, concentrated in an area of some 2 km^2 on the upper part of the delta between the Selinous and Kerynites Rivers. Ceramic and organic samples from the cores yielded ages ranging from Byzantine to Early Helladic times. A shallow auger hole brought to light a superb fragment of an architectural terracotta statue from an Archaic building, ca. 600 B.C. Near the center of the ceramic-bearing area, we discovered by magnetometry a large Roman building and began its excavation. It may belong to a Roman settlement that Pausanias visited at the site of Classical Helike. The deeper layers of the excavation yielded black-glazed vase fragments from the 5th century B.C. and potsherds from Protogeometric and Mycenaean times. The overall results suggest that most of the Roman to Classical horizons lie within about 6 m of the surface, whereas Bronze Age horizons range down to 15 m. While we have yet to determine by excavation whether the occupation horizons include the center of a city, this area appears to be a strong candidate for the site of ancient Helike. © 1999 John Wiley & Sons, Inc.

INTRODUCTION

On a winter night in 373 B.C., a catastrophic earthquake and seismic sea wave destroyed and submerged Helike, the principal city in Achaea, on the southwest shore of the Gulf of Corinth. The entire population reportedly perished. In the 2nd century A.D., Pausanias (7.24.5) visited a coastal site called Helike, 40 stadia (about 7 km) southeast of Aigion (Figure 1), and reported that the ruined walls of the ancient city were still visible in the sea. Later all traces of the site were lost. The historical background of the search for Helike was reviewed by Marinatos (1960).

Helike could be unique among Greek cities if the submergence removed a large part of the site from later human intervention. The ruins may not have been salvaged, quarried, looted, or altered by subsequent occupation. The site of Helike could thus provide a relatively undisturbed "time capsule" from the Classical Era.

Geoarchaeology: An International Journal, Vol. 14, No. 6, 531–563 (1999)

CCC 0883-6353/99/060531-33

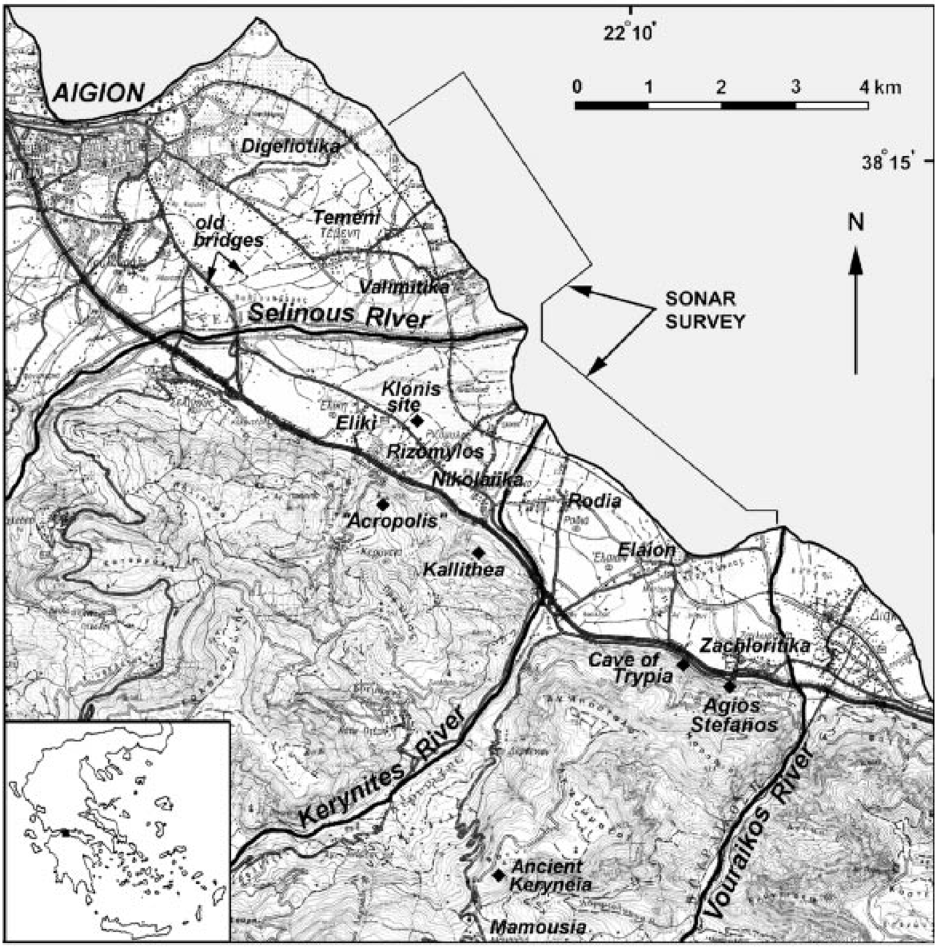

Figure 1. The environs of the Helike search area, including our 1988 sonar survey. The solid diamonds represent ancient sites. Adapted from the Greek 1:50,000 map.

Since Helike was reportedly submerged by the earthquake, previous search efforts concentrated in the sea (Demangel, 1951; Dontas, 1952). From 1966 to 1974, Edgerton (1973, 1981) and colleagues conducted a series of subbottom and sidescan sonar investigations northeast of the Selinous River mouth. They found an unusual sonar target below the seafloor under 42 m of water, which appeared to suggest the presence of ruins (Edgerton and Throckmorton, 1979). Three offshore holes were drilled to investigate the target, but the results were inconclusive (Schwartz and Tziavos, 1979).

To resolve the question of whether the site of Helike lay in the sea or on land, in 1988 the Helike Project carried out a systematic sidescan and subbottom sonar survey of 8 km^2 of the seafloor (Figure 1) northwest of the Vouraikos River mouth (Soter and Katsonopoulou, 1998a). We observed striking geological evidence of earthquakes, but, with few exceptions, including a submerged structure that resembles an ancient harbor mole at Elaion, we found no indications of a city on or under the seafloor. We concluded that the site of Helike probably now lies on land, under the broad coastal plain (Figure 2). The shoreline had evidently moved seaward since antiquity, due to the deposition of alluvial sediments and tectonic uplift of the coastal region. Accordingly we carried out a program of bore hole drilling over a large part of the coastal plain, to search for buried ancient occupation horizons on land. This led to the discovery of ceramic-bearing occupation horizons concentrated in the area between the Selinous and Kerynites Rivers. We also carried out a magnetometry survey which led to the excavation of a large Roman building at the Klonis site in the same area.

THE GEOLOGICAL SETTING

Tectonics

The Gulf of Corinth occupies an asymmetric crustal rift (Ori, 1989), which is migrating northward as the northern Peloponnesos is uplifted. Rows of normal extension faults mark the southwestern part of the rift zone (Dart et al., 1994; Doutsos and Poulimenos, 1992). The principal faults dip to the north and define a tilted set of crustal blocks. The major onshore element of the system is the Helike Fault (Koukouvelas and Doutsos, 1996; Mouyaris et al., 1992; Poulimenos, 1993; Stewart, 1996; Stewart and Vita-Finzi, 1996). It marks the abrupt change of slope between the delta plain and the mountains of Achaea to the south (Figures 2 and 3). During the migration of the rift zone, seismic activity has shifted northward and is now concentrated in the Helike and Aigion Faults, and perhaps in other faults under the Gulf (Bernard et al., 1998).

The western Gulf of Corinth is one of the most seismically active areas in Greece, having suffered destructive earthquakes in 1748, 1817, 1861, 1888, and 1995 (Ambraseys and Jackson, 1997). The earthquake of 1861 ruptured the Helike Fault. Schmidt (1862, 1875) found that it formed a scarp extending for 13 km near the base of the foothills and that the entire plain subsided by about 2 m, submerging a coastal strip up to 200 m wide (Figure 4). He also found the distal part of the delta covered with fissures and sand volcanoes (Figure 5). Schmidt suggested that a similar event, but of greater magnitude, had destroyed ancient Helike in the same area. The Aigion earthquake of June 15, 1995 (M 6.2) also resulted in soil liquefaction and coastal subsidence (Lekkas et al., 1996; Papatheodorou and Ferentinos, 1996). In addition, it was associated with anomalous precursory phenomena (Soter, 1999).

The highlands south of the Helike Fault consist of a sequence of coarse-grained Plio-Pleistocene fan deltas, composed predominantly of limestone conglomerates, uplifted by tectonism and incised by the antecedent rivers (Seger and Alexander,

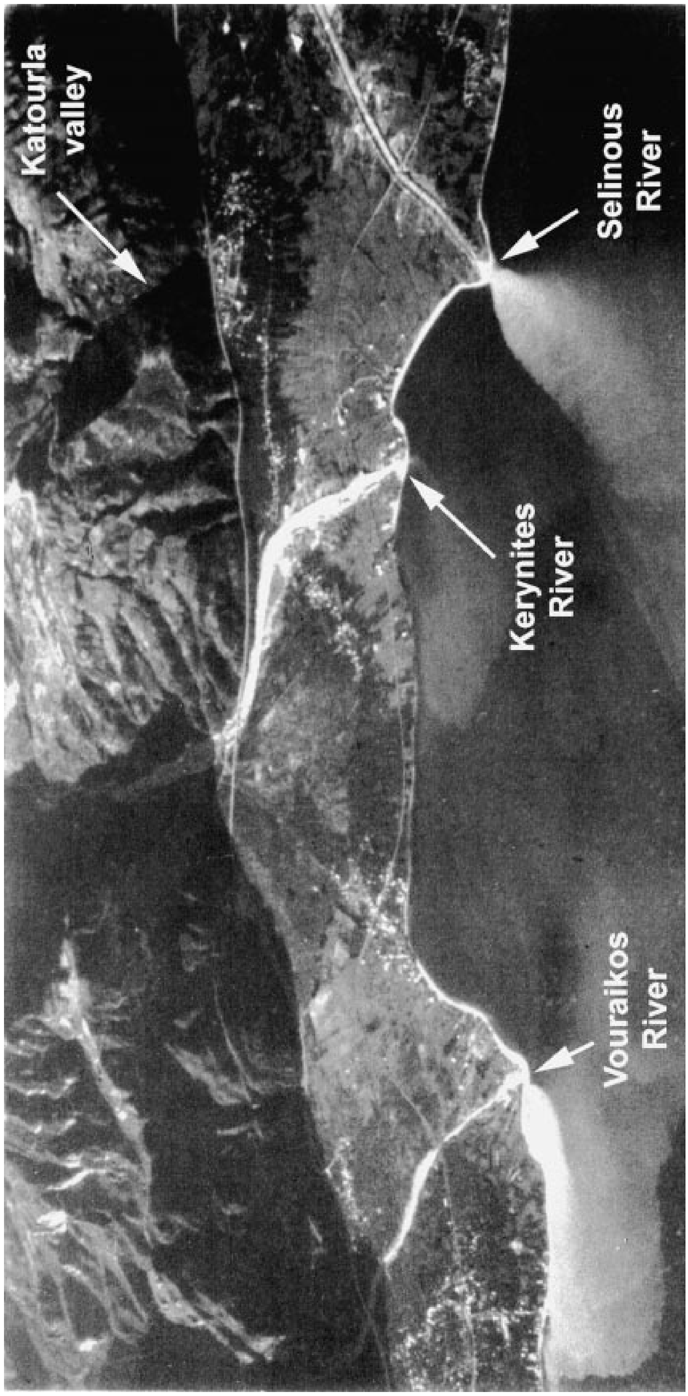

Figure 2. Oblique aerial photograph of the Helike Delta, looking southwest, taken by Robert Stieglitz in December 1979. The distance between the Vouraikos and Selinous River mouths is 4.5 km.

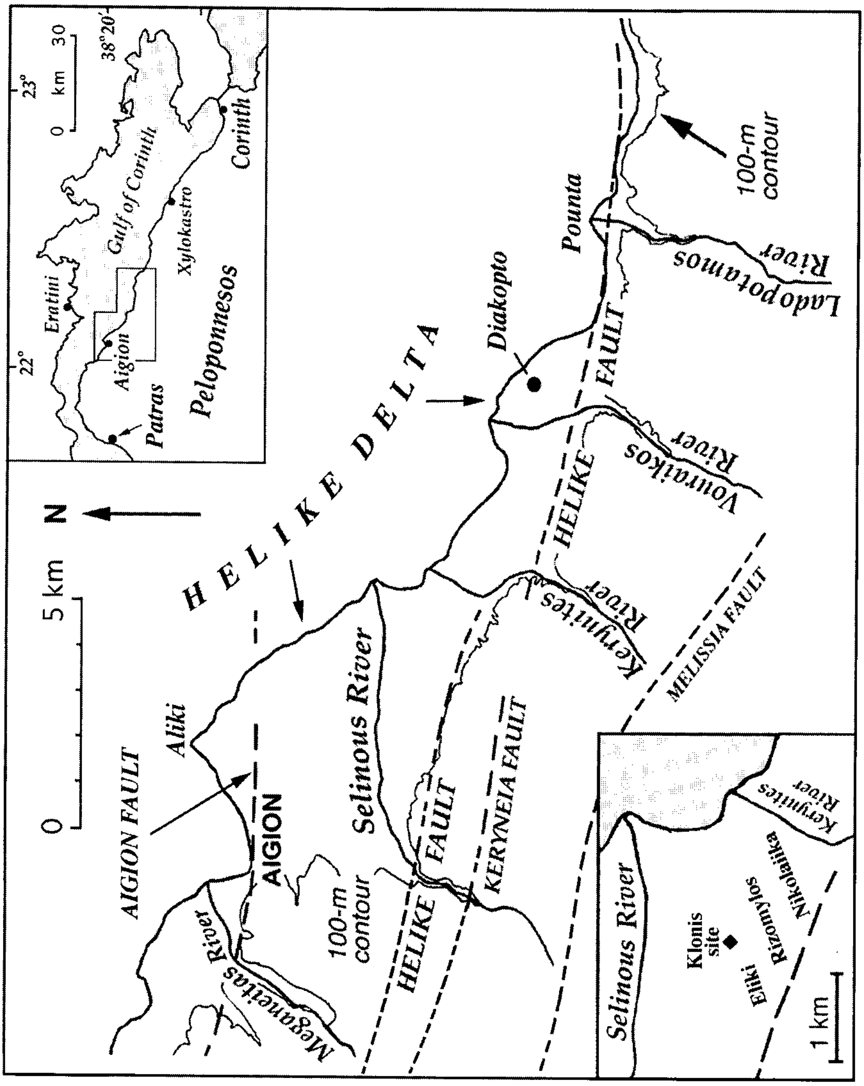

Figure 3. The Helike Delta, and the principal tectonic faults in Aigialeia. The positions and names of the faults are from Koukouvelas and Doutsos (1996).

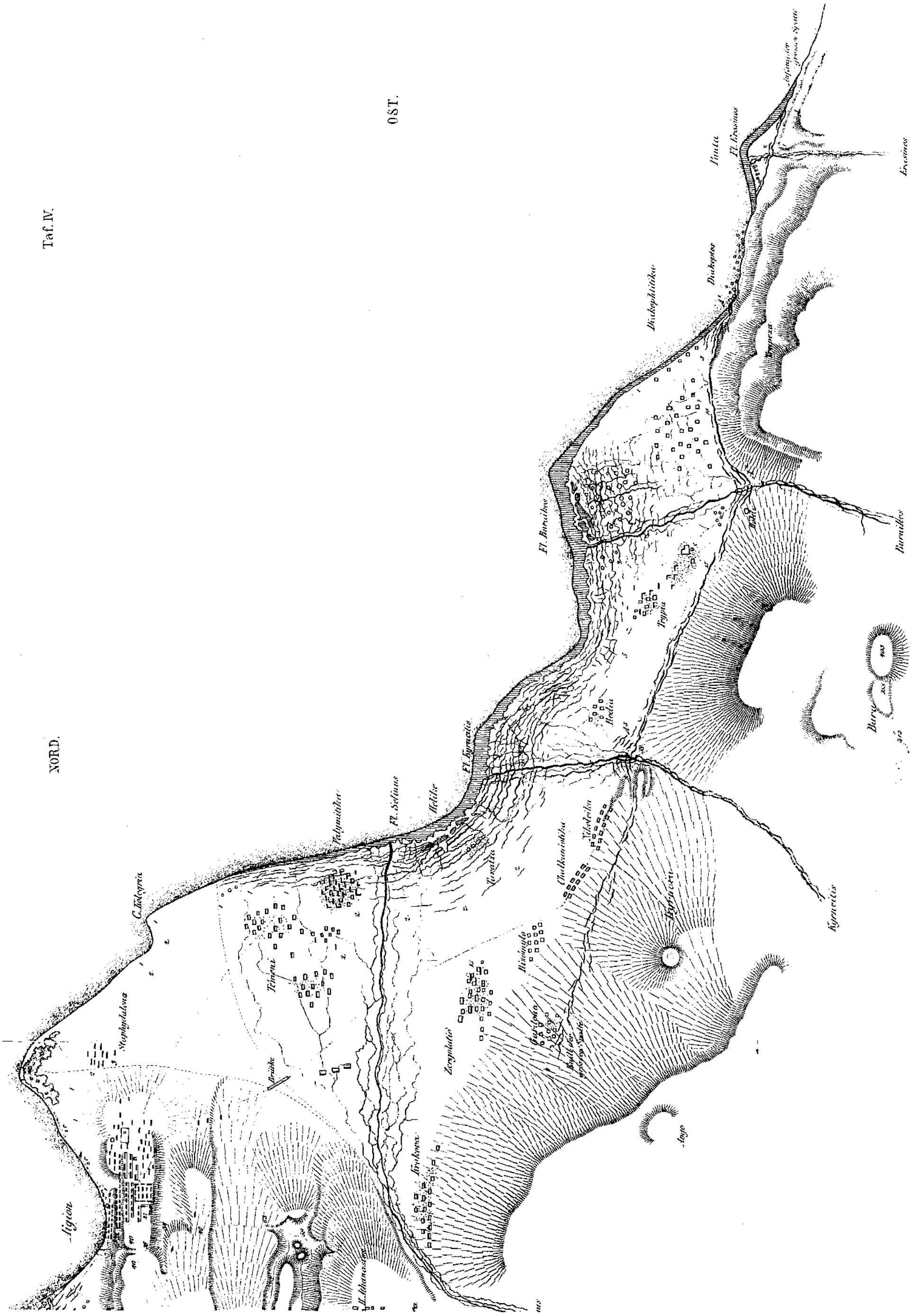

Figure 4. Schmidt's map of the Helike Delta, drawn a month after the earthquake of December 1861 (Schmidt, 1875). A fault scarp extends along the base of the hills from Pounta to Gardena (modern Keryneia). The shaded fringe by the shore represents the area submerged by the earthquake. Extensive fissuring occurred all along the shore, and sand blows (open circles) were concentrated on the delta of the Vouraikos River.

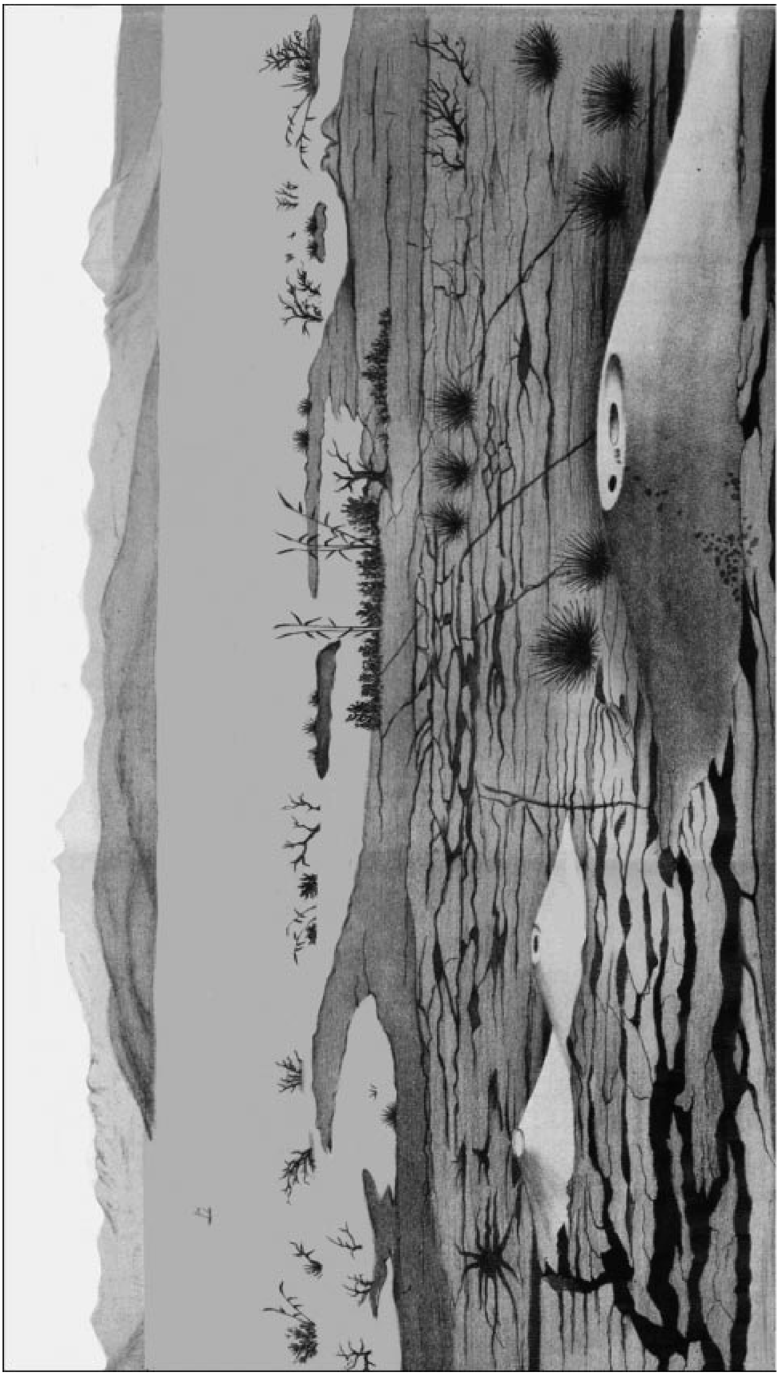

Figure 5. Submerged shore near the mouth of the Vouraikos River, as it appeared a month after the earthquake of December 1861 (Schmidt, 1875), with multiple fissures, sand volcanoes, and submerged bushes and olive trees. The sand volcano at lower right is about 20 m in diameter. The view looks ENE across the Gulf of Corinth, with the bay of Itea at upper left.

1993). These sequences are very similar to the active delta of the present coastal plain (Dart et al., 1994). A dated series of coastal terraces west of Corinth shows that uplift of the northern Peloponnesos has occurred through the late Quaternary (Armijo et al., 1996; Keraudren et al., 1995). A sequence of raised marine notches on the rocky shores east of the Helike Delta shows the uplift continuing through the Holocene. Using radiocarbon ages of shells from these notches, Stewart and Vita-Finzi (1996) and Stewart (1996) estimated the Holocene rate of tectonic uplift of the foot wall of the Helike Fault to be about 1.5 mm/yr. Applying an improved eustatic–isostatic sea level model, Soter (1998) estimated the average Holocene uplift rate to be about 2.4 mm/yr. He also found evidence for an abrupt footwall uplift probably due to the earthquake of 373 B.C.

Stratigraphy

The search for Helike is focused on the coastal alluvial plain southeast of Aigion. This plain, here called the Helike Delta, is a coalesced Gilbert-type fan delta, built from sediments deposited by the rivers Selinous, Kerynites, and Vouraikos. It lies on the hanging wall of the Helike Fault. Long-term subsidence of the delta has accommodated the deposition of younger sediments, but there have evidently been periods of net uplift of the delta as well.

The subaerial delta has varied over time in a complex manner, reflecting changes in the sediment supply (influenced in turn by changes in climate and land use) and in local sea level. Hardy et al. (1994) developed a computer model to show how such factors control the growth of fault-bounded coarse-grained fan deltas, with specific reference to this area.

The Helike Delta contains 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 (Figure 6). Rivers and streams erode the uplifting highlands and carry alluvium across the Helike Fault, depositing it on the delta surface of the hanging wall block. The position of the shoreline can shift rapidly. A house built on the shore between the Selinous and Kerynites Rivers in the 1890s is now about 350 m from the sea.

Tectonic movement of the delta block has probably subjected it to differential subsidence, uplift, tilting, and retrogressive faulting. Compaction of clay layers may have caused uneven subsidence. Landslides, flood debris flows, seismogenic soil liquefaction, and seismic sea waves have all probably left their marks on the delta. Abandoned Roman and Turkish bridges show that the rivers of the Helike Delta have frequently changed course on an historical time scale (Katsonopoulou, 1998a; Soter and Katsonopoulou, 1998a).

High-energy seasonal floods from the three rivers and several torrents dominate deposition and erosion of the Helike Delta. The rivers drain an aggregate watershed area of about 650 km^2 (Seger and Alexander, 1993). The environment of the modern delta has been shaped by overbank flooding, braided channels, and clastic splays.

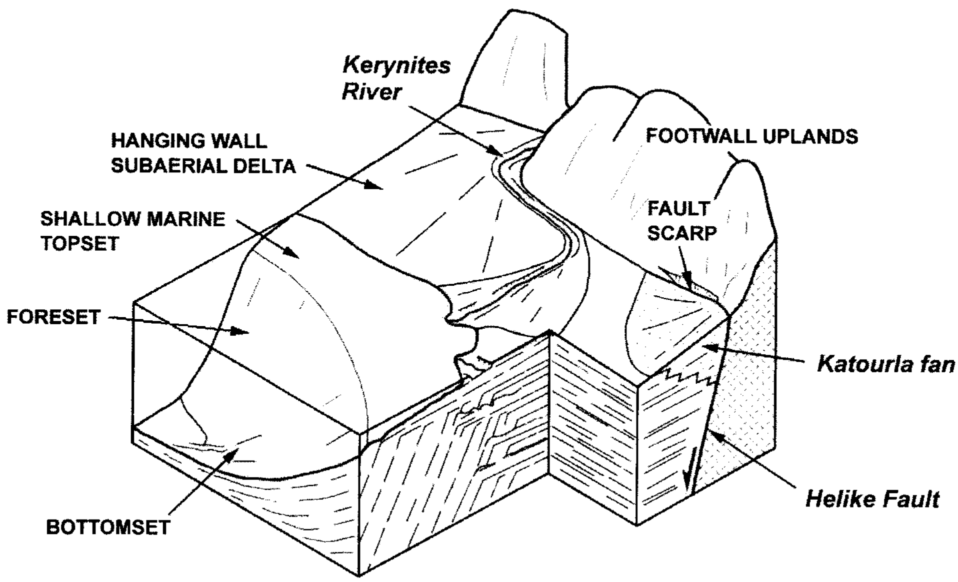

Figure 6. Schematic cutaway, adapted from Dart et al. (1994), showing the geological structure of the Helike Delta.

The resulting deltaic deposits are expected to show lateral heterogeneity on the scale of meters.

The Earthquake of 373 B.C.

The ancient sources mention submergence of the land and an enormous wave from the sea. According to Strabo (8.7.2), Helike was

> wiped out by a wave from the sea. For the sea was raised by an earthquake and it flooded Helike and the sanctuary of Helikonian Poseidon. . . . And Eratosthenes says that he himself saw the place, and that the ferrymen were saying that a bronze Poseidon stood erect in the strait, holding in one hand a hippocamp, which was dangerous to those fishing with nets. And Herakleides says the disaster occurred at night in his time and, although the city was twelve stadia from the sea, this whole district together with the city was covered; and two thousand men who had been sent by the Achaeans were unable to recover the dead. . . .

Diodoros (15.48) wrote that

> the disaster came at night, so that . . . the majority who were caught in the ruined houses were annihilated, and when day came some dashed from the houses and, when they thought they had escaped the danger, met with a greater and still more incredible disaster. For the sea and the wave rose to a vast height, and as a result all the inhabitants together with their land were inundated and disappeared.

Aelian (*On Animals* 11.9) wrote that

> an earthquake occurred at night; the city subsided; an immense wave flooded and Helike disappeared, while ten Spartan vessels which happened to be at anchor were lost together with the city. . . .

According to Pausanias (7.24.12),

> the sea surged against a great part of the land and encircled the whole of Helike. And the flood so covered the grove of Poseidon that only the tops of the trees remained visible. Because when the god suddenly quaked, the sea advanced together with the earthquake, and the wave dragged down Helike with all its people.

From these accounts we extract the following information on the timing of events:

Strabo—earthquake with flooding and sea wave at night
Diodoros—earthquake at night, followed by flooding and sea wave at dawn
Aelian—earthquake at night, followed by subsidence and flood wave
Pausanias—earthquake together with flood and wave

Pausanias suggests that the wave struck together with the earthquake. However, Diodoros has the wave arriving "as day returned," presumably some hours after the nocturnal earthquake. Such a time lag would be unusual but not impossible. Ground liquefaction due to an initial seismic shock could have weakened and destabilized much of the delta. Strong aftershocks, occurring even a few hours later, may then have triggered subsidence with flooding of the delta as well as a massive submarine landslide, which in turn could have produced the seismic sea wave. Such a sequence might account for the time delay between the initial earthquake and the wave implied by Diodoros.

The length of the Helike Fault (about 40 km) suggests that its largest earthquake will not exceed a magnitude of about 7 (Doutsos and Poulimenos, 1992). Such an earthquake would not by itself cause a tsunami of the magnitude reported in antiquity. Leonards et al. (1988) suggested that the Helike earthquake triggered a submarine landslide, which in turn produced the tsunami. Several cases are known of powerful tsunamis following earthquakes of intermediate magnitude. For example, the $M = 7.0$ earthquake that struck Papua New Guinea on July 17, 1998 was followed by a wave with a vertical runup exceeding 10 m. This tsunami may have been triggered by a seismogenic submarine landslide (Kawata et al., 1999) or by a coseismic eruption of a mud volcano (Davies, 1999).

The remark by Pausanias that the sea covered the grove of Poseidon almost to the treetops suggests that the sanctuary was on low-lying ground that subsided by a few meters. Pausanias also says that the flood "encircled" Helike, which suggests that part of the city was on higher ground than the sanctuary and perhaps remained above sea level. However, Strabo, citing Herakleides, a contemporary of the events, says that the whole city and the district between it and the shore (a distance of 2 km) were “covered” (by the water) and that the neighboring people were unable to recover any bodies. This suggests that the ruins lay under several meters of water.

BORE HOLE DRILLING

Previous Results

In 1973 the Greek agency IOKAE (now ΕΚΘΕ, the National Center for Marine Research) drilled three offshore bore holes to investigate Edgerton’s sonar target, which lay under water 42 m deep, about 1400 m north of the Selinous River mouth. The offshore cores sampled two layers of clayey marine silt (with shells and coral) alternating with layers of sand and gravel (Schwartz and Tziavos, 1979). Samples from the upper silt layer (about 3 m below the seafloor) yielded a calibrated radiocarbon date of 1410 ± 290 B.C., and samples from the lower silt layer (5–9 m deep) yielded dates of 7750 ± 200 and 8635 ± 615 B.C. (We calibrated these dates using a marine reservoir correction factor of $\Delta R = 380$ years, as discussed later.)

IOKAE drilled a fourth bore hole, 50 m deep, on the beach just north of the Selinous River mouth (S4 in Figure 7). The top 12 m was 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 on land near the shore west of the Kerynites River mouth (G1, G2, G3 in Figure 7) for a geotechnical investigation of potential seismic ground failure in the area. The stratigraphy was very similar to that of S4, with clastics dominant in the top 10 m, followed by layers of silt or soft plastic clay alternating with layers of sand or gravel. 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.

Helike Project Results

During 1991–1997 we drilled 60 bore holes within an area of about 20 km^2 on the Helike Delta. Most of the holes were concentrated on the midplain between the Selinous and Kerynites Rivers, but the search also extended to Zachloritika in the southeast, to Temeni in the northwest, and from the shore to the base of the foothills.

We used a rotary drilling rig, with an average core diameter of about 10 cm. The average depth was about 20 m. Sample recovery was usually better than 75%, but it was never complete, mainly due to the presence of unconsolidated sandy aquifers. Whenever it was possible to extrude coherent sediment units from the drill barrel, we split them longitudinally to record and sample the stratigraphy.

The principal goals of the drilling were to find ancient occupation horizons in the search area and to determine their ages as a function of depth. We found strata with ceramic fragments in about half the bore holes, most of them in the upper part of the delta between the Selinous and Kerynites Rivers. Five bore holes also

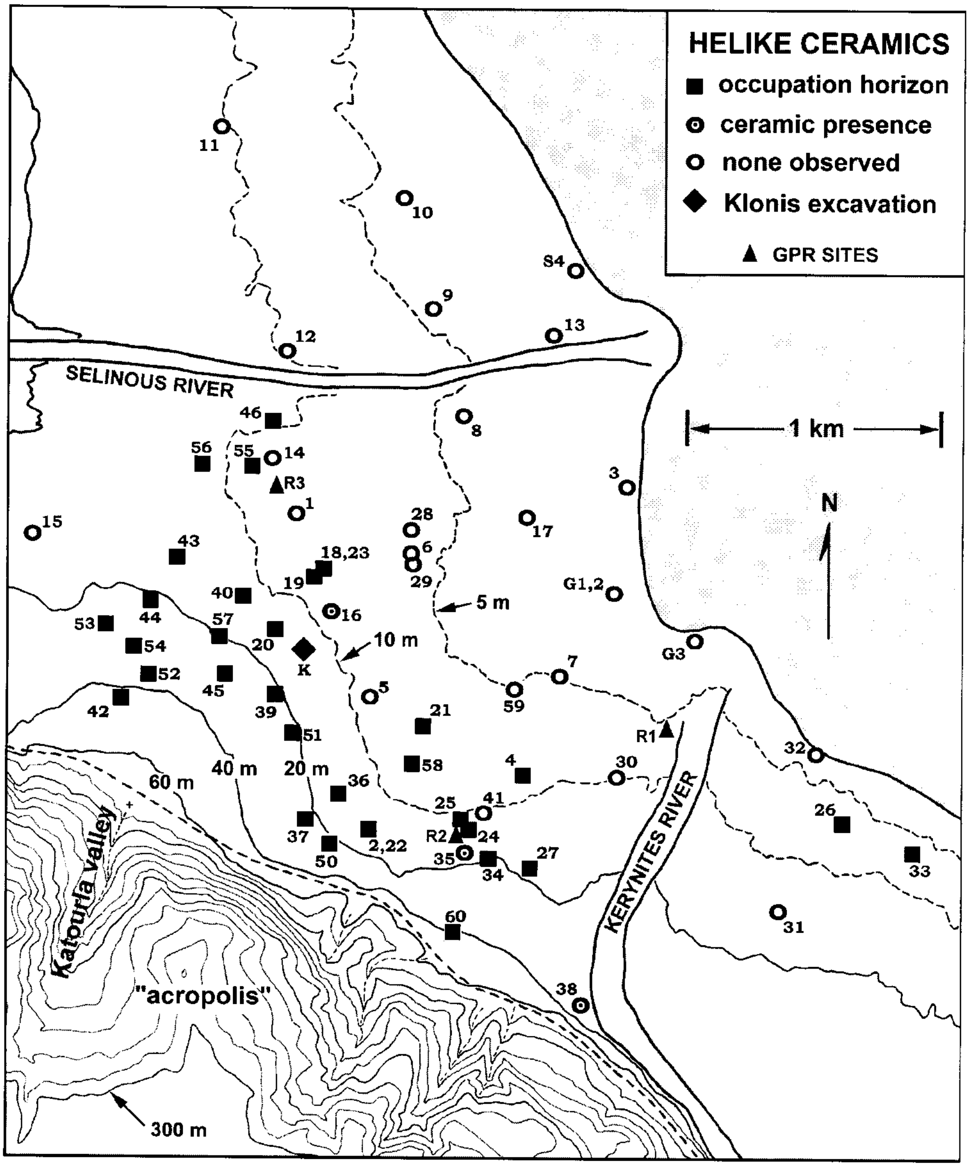

Figure 7. Topographic map of the central Helike search area, with drilling locations identified by bore hole number. The numbered symbols show locations of bore holes B1–B46 and B50–B60, drilled during 1991–1997. (Bore holes B47–B49 were drilled to the southeast in Zachloritika and Trypia and are not shown here; they yielded no evidence of occupation.) Bore hole S4 was drilled by IOKAE in 1973 (Schwartz and Tziavos, 1979) and bore holes G1–G3 were drilled in 1983 by Leonards et al. (1988). The diamond labeled "K" locates the Klonis excavation site. The triangles R1–R3 show the sites of ground penetrating radar surveys made in 1996 (Kutrubes et al., 1996). The heavy dashed line shows the New National Road, which nearly traces the Helike Fault. Elevation contours are given every 20 m, plus those at 5 and 10 m above sea level, from the Greek 1:5000 map. The terms "occupation horizon" and "ceramic presence" are defined in the text.

yielded the debris of ancient walls, in the form of cobbles partly encrusted with clay mortar.

We drilled the first five bore holes (B1–B5) more than 40-m deep. Bore hole B2 was located near the Helike Fault at 16 m surface elevation. B3 was on the shore and closely resembled S4 and G1–G3 in its stratigraphy. Bore holes B1, B5, and B4 (listed here from north to south) were all located in the midplain at surface elevations of 8–9 m above MSL (Figure 7). In drilling those three holes, we found overpressured aquifers at depth intervals of 11–14, 16–21, and 21–28 m, respectively (Figure 8). The water forced sand and gravel up into the drill stem by as much as 5 m, severely retarding the drilling operation. These aquifers consisted of sand and gravel layers capped by strata containing relatively impermeable silt. These conditions render the midplain vulnerable to failure due to soil liquefaction during earthquakes, as suggested by Leonards et al. (1988).

The cores show that the stratigraphy of the delta is extremely heterogeneous. This is not surprising in such a high-energy fan delta environment. Until artificial levees were built on the river banks about 50 years ago to control the winter floods, much of the delta surface was a patchwork of fine and coarse deposits, dominated by shifting distributaries. The ancient deposits below the surface reflect the same disorder. Although bore holes drilled within a few hundred meters of one another often showed similar stratigraphy, we found little in the way of detailed correlation even between cores separated by only a few tens of meters. For this reason, detailed comparison of stratigraphy between bore hole profiles is not particularly revealing.

However, we can impose some minimal order on the chaotic stratigraphy by distinguishing the main sources of sediment supply to the delta. Sediments from the Selinous and Kerynites Rivers dominate the lower parts of the plain. Sediments from the Katourla stream valley, west of the "acropolis" hill, have deposited a terrestrial fan delta on the upper part of the plain (evident in Figure 7). This topographic rise, here called the Katourla Fan, descends almost symmetrically from an apex about 75 m above sea level and merges with the coalesced river deltas at about the 10 m elevation contour.

The Katourla Fan is closer to its source area than the river deltas and thus contains more coarse clastic debris and few if any marine deposits. Cores drilled at lower elevations, where the rivers dominate, contain the range of sedimentary facies characteristic of an active marine fan delta. These represent braided channels and flood plains, fresh water lakes, seasonal ponds and brackish lagoons, barrier beaches, and marine foreset beds.

Ceramics

We recovered ceramic fragments, potsherds, and traces of ceramics in core samples from 36 of the 60 bore holes, shown in Figure 7. Most of the bore holes that contained ceramics fall within an elliptical area of about 2 km^2, in the contemporary villages of Eliki, Rizomylos, and Nikolaiika (cf. Figure 1). With two exceptions, all

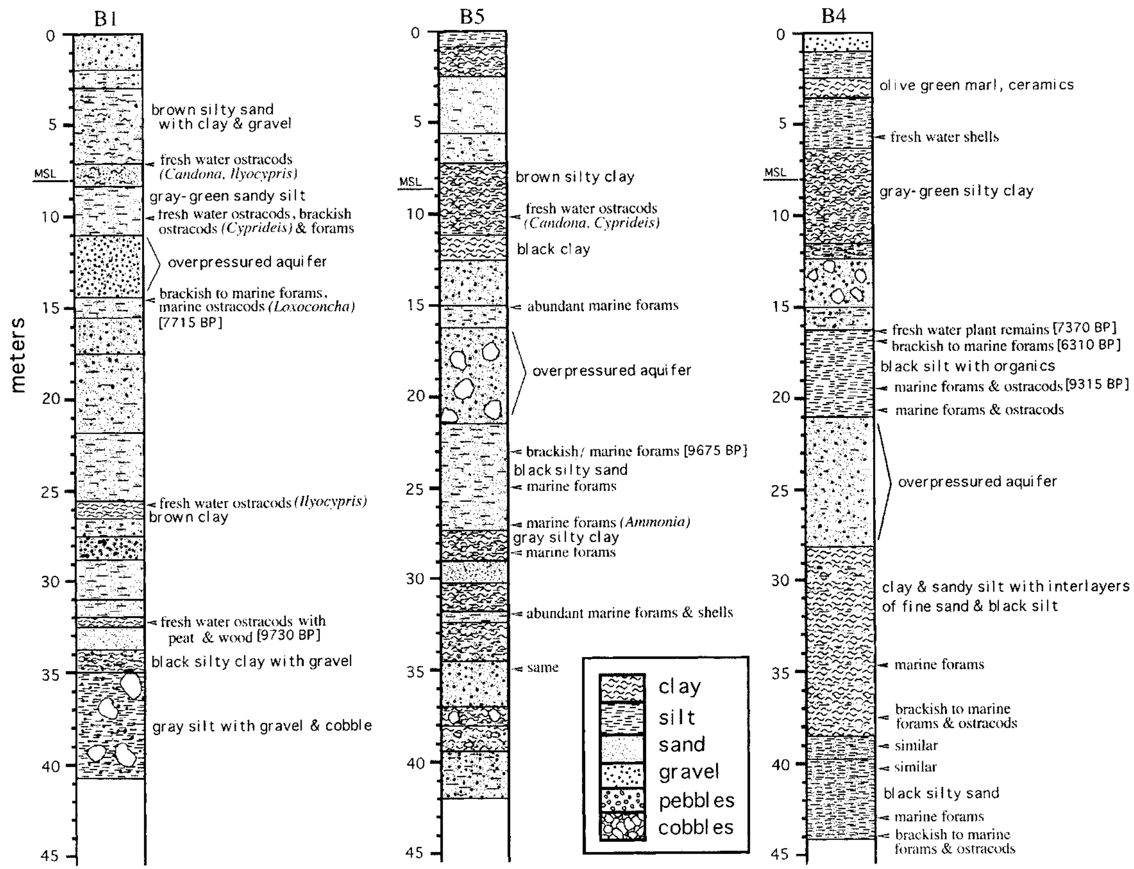

Figure 8. Stratigraphic profiles of bore holes B1, B5, and B4, all drilled in the midplain with surface elevations from 8 to 9 m. Biogenic indicators of environmental facies are from Soter et al. (1999). Radiocarbon ages in brackets are from Table III.

the bore holes with ceramics are at least 1.5 km from the present shore. The exceptions (B26 and B33) are in Rodia, east of the Kerynites River, and both showed the same distinctive ceramic-bearing horizon at about 5 m depth.

We found no ceramics in bore holes drilled either north of the Selinous River or seaward of the railway line, which runs near the 5-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 railway line. In contrast, every bore hole drilled on the Katourla Fan yielded ceramic fragments. This area lies at the foot of the so-called "acropolis" hill of Agios Georgios, where many antiquities have been found (Soter and Katsonopoulou, 1998b).

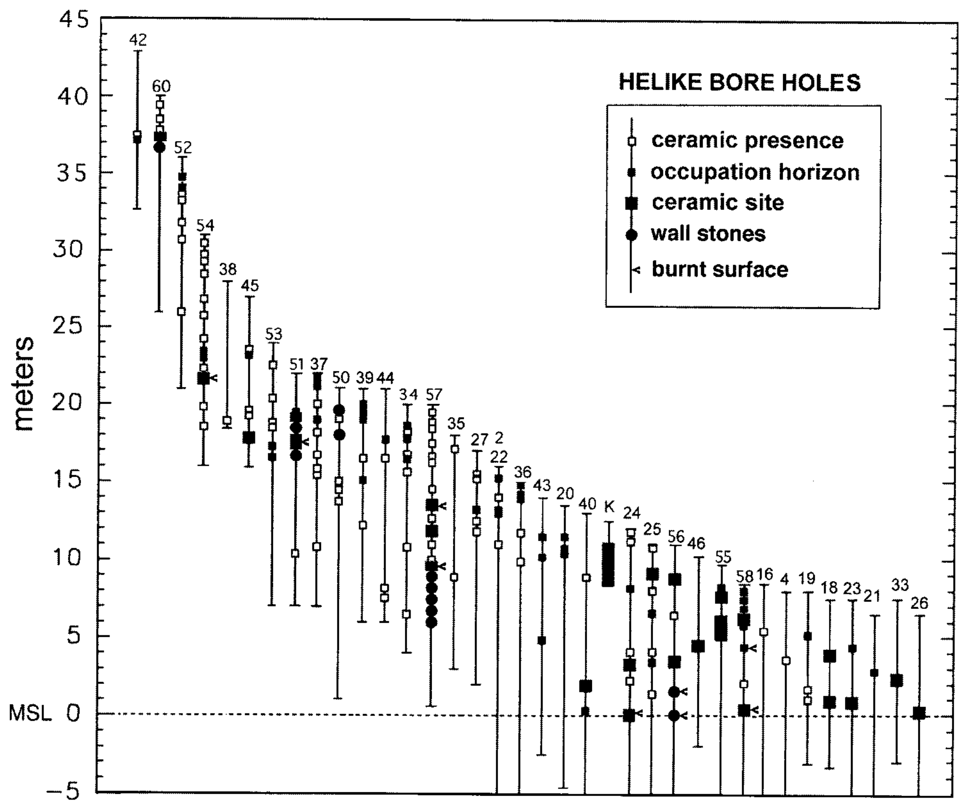

Figure 9. Vertical profiles of all bore holes that yielded ceramics, displayed horizontally in rank order of local surface elevation above mean sea level (MSL). The horizontal axis has no scale, because the bore holes are dispersed over a broad area. The surface is at the top of each column, which is labeled by bore hole number. "K" is the Klonis excavation site. The text defines "ceramic presence" and "occupation horizon." Some bore holes yielded the remains of ancient walls, in the form of river cobbles partly encrusted with clay mortar and sometimes associated with fragments of ceramics or plaster. Some ceramic fragments and stones showed burnt surfaces.

Figure 9 shows the profiles of all the bore holes in which we found ceramics, in rank order of decreasing surface elevation above mean sea level (MSL), and labeled by bore hole number. The hundreds of ceramic fragments from the cores range in size from small chips up to sherds of about 8 cm. Most of them are archaeologically nondiagnostic. We have sorted the ceramic occurrences into two categories:

1. "Ceramic presence": We use this term to refer either to an isolated ceramic fragment (centimeter scale) found in sediment containing gravel, or to ceramic chips or traces (millimeter scale) found in any sediment (including clay, silt, or sand). While many ceramics in this class were probably deposited by floods, their mere existence suggests that a site may lie "upstream" from the bore hole.
2. "Occupation horizon": We often found centimeter-sized ceramic fragments in strata of fine-grained sediment (clay, silt, or sand). Ceramic fragments deposited by a flood are generally accompanied by gravel and pebbles of comparable size. But centimeter-sized ceramic fragments found in a stratum containing only fine-grained sediments were probably deposited by human agency, rather than by flooding (C. Tziavos, personal communication, 1993). Ceramics in this category represent an occupation horizon, defined here as a buried surface contemporary with and in the vicinity of an archaeological site. However, the location of an occupation horizon in a bore hole does not always correspond to an inhabited site. For example, a few of these ceramic fragments may have been discarded in the fields with other rubbish in antiquity, and would thus reflect the broad anthropogenic "halo" around an inhabited site, rather than the site itself (Bintliff and Snodgrass, 1991).

However, in many cores we found occupation horizons containing two or more centimeter-sized ceramic fragments from different parent objects, often together with other anthropogenic indicators (charcoal, cobbles partly encrusted with clay mortar, traces of lime plaster, burnt rock, and soil inclusions of unusual color). In these cases we can assume that the horizon represents an inhabited site ("ceramic site" in Figure 9). These categories cannot always be clearly distinguished in bore hole cores, and some of our designations in Figure 9 are provisional.

Almost all the evidence of ancient occupation was found within the upper 15 m of the bore holes and above the present sea level. However, in B2 and B22, located only a few meters apart, we found ceramic fragments and traces at depths of 22–23 m (or 6–7 m below MSL). Some bore holes contained multiple ceramic horizons at many depths, as is seen for example in B24 (Figure 10), with six levels of ceramics. This bore hole was drilled in a part of Nikolaiika where drill core and geophysical evidence suggests a concentration of ancient habitation.

In five bore holes (B50, 51, 56, 57, 60), we found cobbles partly encrusted with clay mortar, probably from ancient walls (Figure 9). In some cases we found them in core segments together with fragments of ceramic and plaster. Bore hole B57, located just below the Old National Road in Eliki, yielded such wall stones in almost every core sample from the interval between 10.7 and 14.7 m. In six bore holes

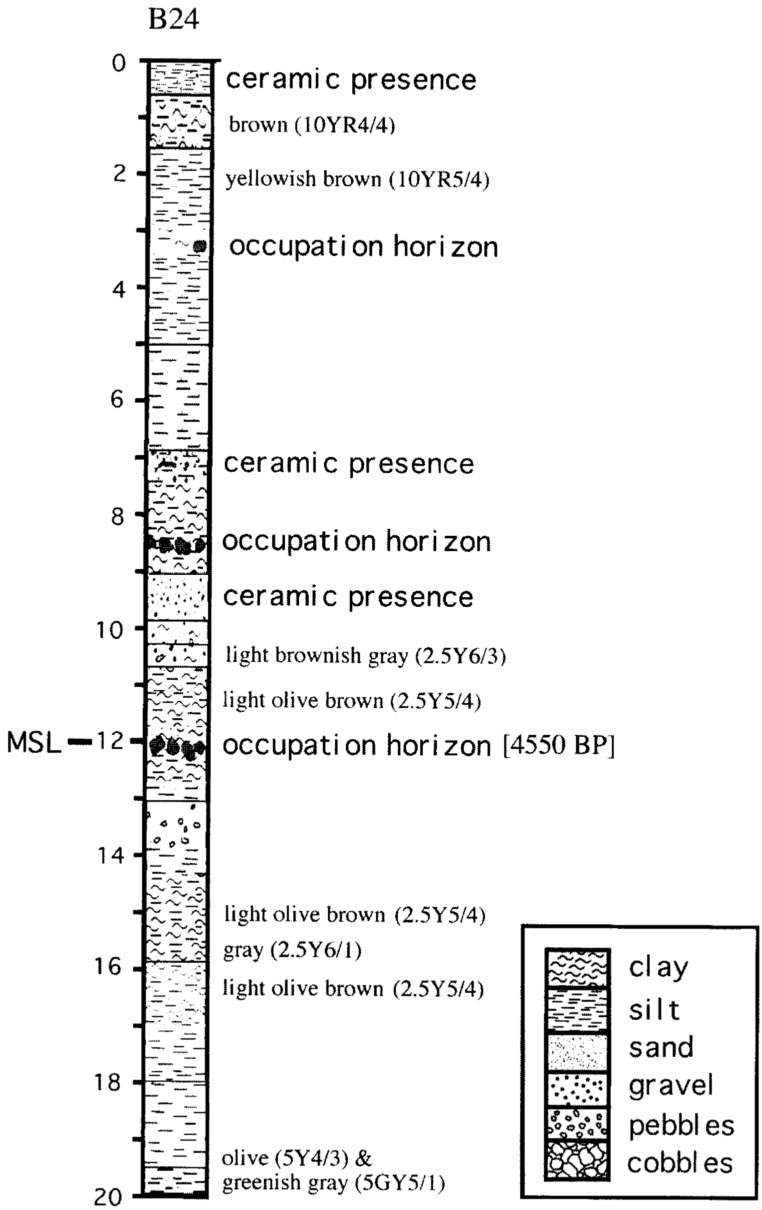

Figure 10. Profile of bore hole B24 in Nikolaiika, showing six levels containing ceramics. The lowest, at 12 m depth, included burnt ceramics which gave an OSL date of 4550 ± 700 B.P.

(B24, 51, 54, 56, 57, 58), we also found ceramic fragments or stones with burnt surfaces, mostly in the deeper occupation horizons (Figure 9).

Environmental Indicators

Analysis of the environment of deposition of selected core samples was based mainly on the identification of microfauna. The data are given in Soter et al. (1999), and Figure 11 summarizes the results. The upper parts of the cores show predominantly fresh water facies, while most of the samples deeper than about 8 m below present sea level represent marine facies. The transition from marine to fresh water

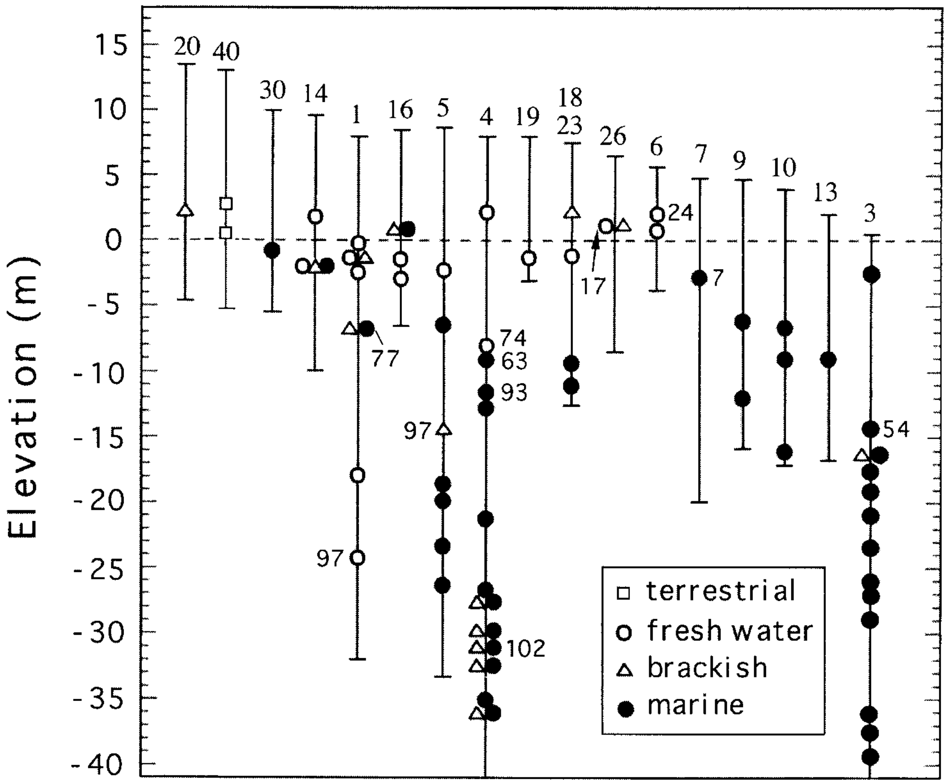

Figure 11. Vertical profiles, in rank order of local surface elevation, showing core samples analyzed for environmental indications based on microfauna (Soter et al., 1999). Each profile is labeled at the top by its bore hole number. Dated samples are labeled alongside some profiles in hundreds of years before present. "Terrestrial" refers to alluvial flood deposits, "fresh water" to lakes or ponds, "brackish" to lagoonal or near-shore environments, 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, have been combined.

or brackish deposits dates from about 7 kyr B.P., and probably reflects the global deceleration in the rise of sea level at the end of the last Ice Age, as discussed below. Bore hole B1 appears to be exceptional for the midplain area, since it shows fresh water facies at almost all depths. Most of the ceramic occupation horizons were found above present sea level. In only one case so far (B18) have we found evidence for a brackish or marine environment above an occupation horizon.

Core samples containing indicators of a brackish environment were presumably deposited close to sea level. In five bore holes drilled in the mid-plain (B1,14,16,18,20), we found evidence of brackish environments within about 2 m of the present sea level, as shown in Figure 11. Some of these brackish segments contained olive-green or gleyed clay and silt (Soter et al., 1999). In bore hole B18 we found brackish ostracods in a layer of sandy green silt and clay at 6.5 m depth, between two ceramic-bearing horizons (Figure 12).

In examining the five deep bore holes, we note that B2, drilled near the Helike Fault, yielded only terrestrial indicators, while B3, drilled near the present shore, yielded only marine indicators. However, B1, 5, and 4, drilled in the midplain, all yielded samples characteristic of fresh water, brackish, and marine environments (Figure 8). It thus appears that the Holocene shoreline has oscillated across the location of the mid-plain of the present delta.

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 potsherds, luminescence dating of nondiagnostic ceramic fragments, and radiocarbon dating of organic fragments and sediment. The data are plotted in Figure 13 as a function of depth in meters and age in thousands of years before present (1950 A.D.).

Archaeological Dating

Only a few of the many ceramic fragments found in the bore holes could be dated by archaeological criteria. These included a Roman glass fragment found at 2.3 m in B56, Hellenistic sherds found at 3 m in B37 and at 2 and 5 m in B55, and black-glazed vase fragments of the 5th century B.C., found at 10.3 m in B40 and at 1–2 m in B52. These bore hole samples are listed in Table I, together with dated artifacts found in auger holes (described below).

Luminescence Dating

Several nondiagnostic ceramic fragments were dated by optically stimulated luminescence (Liritzis et al., 1997). The OSL technique can be applied to ceramic fragments as small as 2 cm^2. This allows one to date some of the fragments from the bore holes, most of which are too small for conventional thermoluminescence dating. Table II gives the ceramic luminescence dates from the bore holes. These data are shown as solid triangles in the age-depth plot of Figure 13. The fragments

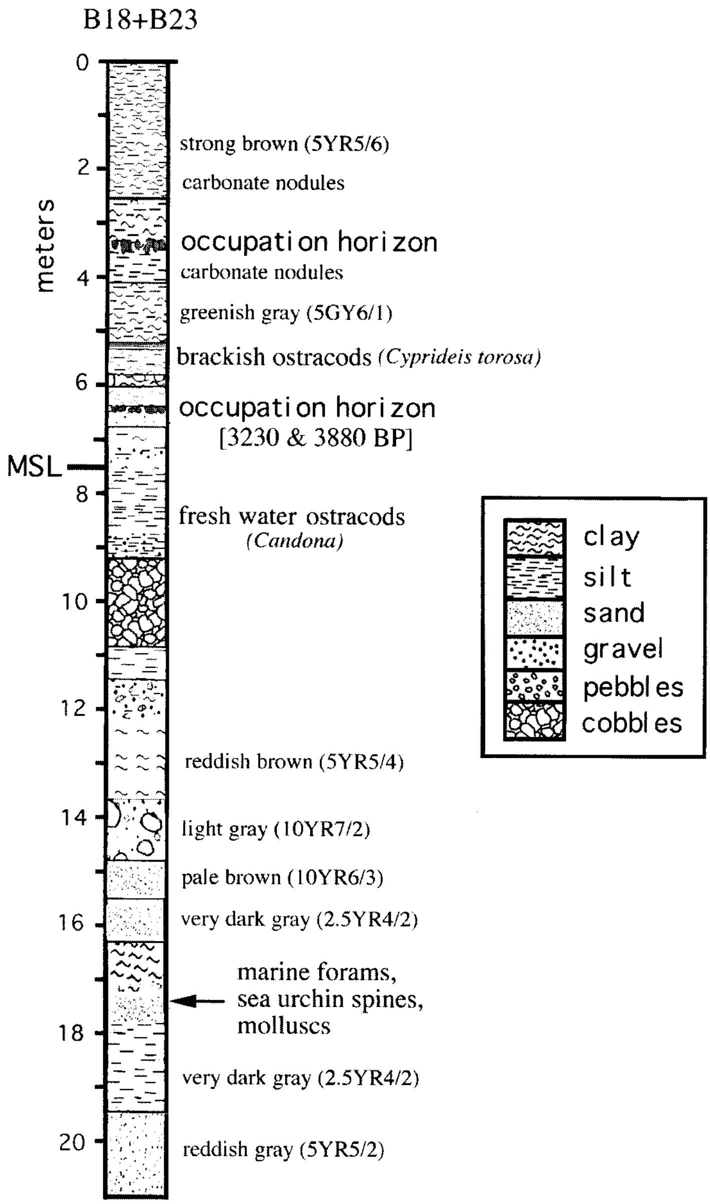

Figure 12. Composite profile of bore holes B18 and B23, which were drilled a few meters apart, showing a brackish green clay layer between ceramic occupation horizons at 3.3 and 6.5 m below ground in B18. Ceramic OSL dates from Table II are given in brackets.

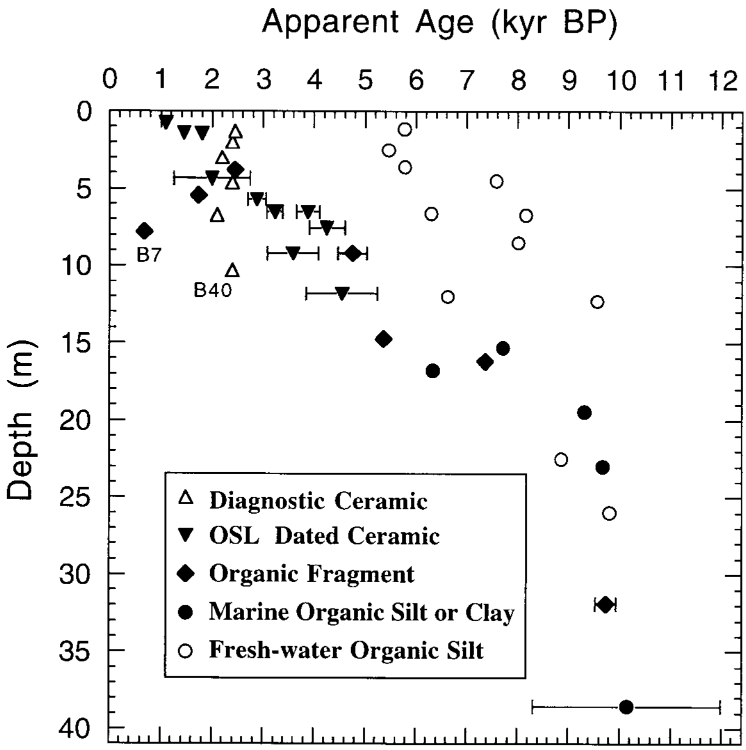

Figure 13. Plot of apparent age of dated samples in thousands of years before present (1950 A.D.), versus depth below the surface in meters (data in Tables I, II, and III). Open triangles represent archaeologically diagnostic ceramic fragments; solid triangles represent the nondiagnostic ceramic samples dated by optical (OSL) or thermoluminescence (TL), from Liritzis et al. (1997); solid diamonds represent radiocarbon dates of organic fragments (wood, sea grass, charcoal, etc.); solid and open circles represent, respectively, radiocarbon dates of marine and fresh-water amorphous organic carbon, mostly from Maniatis et al. (1996). The fresh-water samples (not listed in Table III) apparently contain unknown amounts of radioactively "dead" carbon and cannot be calibrated.

K:1 and K:2, recovered from the Klonis site prior to its excavation, yielded OSL dates that agree with the archaeological evidence for late Roman occupation (3rd to early 5th centuries A.D.).

Radiocarbon Dating

Maniatis et al. (1996) obtained radiocarbon dates for Helike bore hole samples of organic fragments (wood, peat, sea grass, etc.) and amorphous organic carbon (AOC) consisting of black silt or clay. We examined the microfauna (mainly ostracods) in the dated AOC samples to determine whether the material was deposited in marine or fresh-water conditions (Soter et al., 1999). The calibrated dates for the organic fragments and the marine AOC samples are listed in Table III and

Table I. Diagnostic sample dates.

No.	d(m)	h(m)	Description	Date
A10	0.3	12.7	Massive tile floor	Roman
A11	1.0	12.5	Terracotta statue fragment	Archaic
A9	1.4	10.6	Massive tile floor	Roman
B52	1.3	34.7	Black-glazed vase fragment	Classical
B52	2.0	34.0	Black-glazed vase fragment	Classical
B55	2.1	7.6	Black-glazed vase fragment	Hellenistic
B56	2.3	8.7	Glass fragment	Roman
B37	3.0	19.0	Ceramic fragment	Hellenistic
B55	4.6	5.1	Black-glazed vase fragment	Hellenistic
B40	10.3	2.7	Black-glazed vase fragment	Classical

Notes: No. = auger (A) or bore hole (B) number, d(m) = sample depth in meters below surface, h(m) = sample elevation in meters above sea level.

plotted in Figure 13 as solid diamonds and solid circles, respectively. Those data points (except B7, discussed later) are generally consistent with the broad age-depth trend obtained for the ceramic fragments.

However, most of the *fresh-water* AOC samples from the upper 15 m of the cores yielded unacceptably old radiocarbon ages. This is most obvious in the case of samples from near the surface which yielded apparent ages of 5-6 kyr B.P. The fresh-water AOC ages determined by Maniatis et al. (1996) are plotted as open circles in Figure 13, but not listed in Table III. We consider them to be unreliable as a class. It is possible that some of the anomalous data are due to reworking of older sediments. However, Soter (1998) suggested that the excessive ages for most of these samples are due to an extreme "hard water effect," reflecting the uptake of radioactively "dead" carbon derived from the prevailing limestone of the region.

MacDonald et al. (1991) showed that up to half the CO_2 dissolved in the ground

Table II. Ceramic luminescence dates.

No.	d(m)	h(m)	Date
B36	0.8	14.3	900 ± 230 A.D.
K:1	1.4	11.1	550 ± 300 A.D.
K:2	1.5	11.0	200 ± 250 A.D.
B25:2	4.4	6.7	50 ± 750 B.C.
B42	5.7	37.3	930 ± 180 B.C.
B18:1	6.5	1.0	1280 ± 160 B.C.
B18:2	6.5	1.0	1930 ± 230 B.C.
B25:3	7.2	3.8	2300 ± 350 B.C.
B45	9.2	17.8	1800 ± 500 B.C.
B24:1	11.8	0.2	2600 ± 700 B.C.

Notes: No. = bore hole (B) or Klonis site (K) number:sample number, d(m) = sample depth below surface, h(m) = sample elevation above sea level. All samples were dated by OSL, except B36, which was dated by thermoluminescence (Liritzis et al., 1997).

Table III. Radiocarbon dates.

No.	d(m)	h(m)	Description	Calibrated Date	Lab No.
B6	3.8	1.9	Peat	440 ± 60 B.C.	DEM-375
B26	5.5	1.0	Carbonized stem*	210 ± 130 A.D.	AA-15022
B7	7.8	−3.0	Sea grass	1270 ± 25 A.D.	Beta-72211
B45	9.2	17.8	Charcoal*	2755 ± 285 B.C.	AA-18115
B3:2	14.8	−14.3	Sea grass	3415 ± 105 B.C.	DEM-188
B1:1	15.3	−7.3	Marine silt	5765 ± 35 B.C.	DEM-191
B4:1	16.2	−8.2	Wood	5415 ± 150 B.C.	DEM-187
B4:2	16.8	−8.8	Sea grass	4330 ± 90 B.C.	DEM-283
B4:3	16.8	−8.8	Marine silt	4390 ± 50 B.C.	HD-16126
B4:4	19.5	−11.5	Marine silt	7365 ± 65 B.C.	DEM-192
B5	23.0	−14.3	Marine silt	7725 ± 135 B.C.	DEM-198
B1:2	31.9	−23.9	Wood	7780 ± 200 B.C.	DEM-185
B4:5	38.6	−30.6	Marine clay	8200 ± 1840 B.C.	DEM-186

Notes: No. = bore hole:sample number, d(m) = depth in meters below surface, h(m) = sample elevation in meters relative to sea level, * = organic fragments from a ceramic site; DEM = Demokritos (Maniatis et al., 1996), AA = University of Arizona, Beta = Beta Analytic, HD = Heidelberg. For marine sediments, we used a reservoir correction factor of ΔR = 380 yr.

water in limestone terrain may come from such sources, the rest being derived from the atmosphere. Fresh water aquatic plankton then metabolizes the dissolved CO_2 and the dead carbon ends up in the AOC of lake and pond sediments. This could account for spurious age increments of up to the half-life of carbon-14. Similar results have been reported in other limestone-rich deltaic environments. For example, radiocarbon-dated sediment samples from a bore hole in the Nile Delta were found to be several thousand years older than archaeologically diagnostic pottery fragments at various depths in the same core (Stanley et al., 1992; Warne and Stanley, 1993).

The AOC from *marine* sediment deposits, however, yielded acceptable radiocarbon ages, requiring only a correction for the marine reservoir effect. Heezen et al. (1966) sampled surface water from the Gulf of Corinth in 1956 (before significant bomb contamination) 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 therefore used a reservoir correction factor ΔR = 380 years in calibrating all the radiocarbon ages for marine organics (Soter, 1998).

Discussion of Age-Depth Results

The radiocarbon dates at first presented a confusing picture, but once we separated out the fresh-water AOC data (open circles in Figure 13), the remaining points defined a broad linear trend of increasing age with depth. The scatter is not severe, considering that the samples came from bore holes drilled in various parts of the delta with different surface elevations and sedimentation histories.

However, two of the samples, labeled in Figure 13, had ages significantly younger than the main trend. Sample B7 is from a bore hole near the present shore, in a part of the delta where we found no evidence of ancient occupation. This sample may represent a sloping marine foreset bed, its anomalous depth reflecting perhaps a recent progradation of the shoreline across the drill site.

The Classical black-glazed ceramic vase fragment found at 10.3 m in B40 is more difficult to explain. It is younger by about 2 kyr than the average age-depth trend for that depth. We cannot exclude the possibility that this fragment fell during the drilling of this bore hole from an undated ceramic-bearing layer encountered at 4 m depth. However, the Classical fragment was recovered from a layer containing other sherds, which suggests that it was *in situ*. The local depth of the Classical horizon may thus be far from uniform in parts of the delta.

We have not yet dated the remains of walls found in the bore holes. However, the wall stones with clay mortar in B57, in the depth interval from 10.7 to 14.7 m, may well date from Mycenaean times, based on dated samples from these depths in other bore holes. In all bore holes except B40, all the dated samples found below 8 m were older than 1200 B.C. Dörpfeld (1885) found clay mortar and plaster used in the construction of house walls at Mycenaean Tiryns.

The burnt ceramic fragments and stones were all found more than 4 m deep (Figure 9). The average depth of nine such occurrences was 8.4 m, which suggests that many of them date from the Bronze Age.

The age-depth data in Figure 13 suggest that sediment deposits from about the last thousand years are missing. This could reflect a hiatus due to a recent decline in the rate of sediment supply, for which however we have no independent evidence.

Figure 13 shows that the main age-depth trend was nearly linear for the last 8 kyr, with a slope of about 2.5 m/kyr, but that in earlier times the slope was about ten times steeper. This transition occurs in the bore holes at a depth corresponding to about 8 m below the present sea level, where the sediments change (moving upward) from marine to fresh water deposits (Figure 11). It reflects a change in the rate of aggradation on the delta. If the long-term rates of local sediment supply and tectonic displacement were nearly constant, then the rate of delta aggradation would be controlled largely by global sea level. A decrease in aggradation would then be accompanied by an increase in progradation of the delta front, in order to accommodate the steady input of sediment (Hardy et al., 1994). In reality, the sediment supply rates for rivers in the Peloponnesus are likely to vary over time.

The change in the evolution of the Helike Delta was apparently part of a global pattern. Stanley and Warne (1994) showed that marine deltas throughout the world began prograding between about 9500 and 7400 cal yr B.P., due to the deceleration in the rate of global sea level rise with the end of the last Ice Age. Prior to that period, aggradation of the Helike Delta would have kept pace with the rapid rise of sea level and the subaerial delta would have been smaller than today. However, with a decline in the rate of sea level rise, a comparable sediment supply would have produced a rapid progradation of the delta front.

GEOPHYSICAL OBSERVATIONS, AUGER HOLES AND EXCAVATION

The Helike Project carried out several geophysical surveys in the general search area, using magnetometry and ground penetrating radar (GPR). To verify some of the targets detected by these surveys, we dug 11 hand auger holes, with depths ranging from 0.3 to 2.0 m. Our magnetic survey led to the discovery and initial excavation of the Klonis site.

Ground Penetrating Radar

In 1996 the Helike Project carried out small scale GPR surveys at several locations in the plain. We used a SIR-2 radar system operating at 80 and 480 MHz. At sites R1, R2, and R3 in Figure 7, the radar indicated possible buried structures (Kutrubes et al., 1997).

In the survey at the site R1 in Nikolaiika, the alignment of many discrete targets (hyperbolic reflectors) suggested the presence of a wall at least 45 m long, within 1 m of the surface. The radar also showed a complex structure near the wall at greater depth. At the Romanos site (R3 in Figure 7), where antiquities had been reported over many years (apparently Roman), we observed many hyperbolic radar reflectors at depths of 1.3 to 3.5 m.

The GPR site R2 in Nikolaiika was investigated because we found ancient cut stones near the surface in the area, and our adjacent bore holes B24 and B25 penetrated a shallow ceramic horizon. The radar showed strong hyperbolic reflectors, mostly within about 1.5 m depth. We dug several auger holes to verify these targets and to probe the surrounding area. Two of them (A9, A10) were terminated by massive tile floors of Roman age, at 0.3 m and 1.4 m, respectively.

Another auger hole (A11) was located east of R2 in Nikolaiika. At a depth of 1.1 m, we found a 10-cm terracotta fragment of an architectural statue (Figure 14) from an Archaic building, ca. 600 B.C.. The fragment, which preserves traces of red color, may represent braided hair.

Magnetometry

In June 1994, the Laboratory of Geophysics of the University of Patras carried out a geophysical survey for the Helike Project at what is now known as the Klonis site in Eliki (shown at K in Figure 7). The clay content of the soil severely limited the use of GPR, but magnetometry gave excellent results. Figure 15(a) shows the magnetic intensity contours of a small grid (14 × 24 m), which revealed the rectilinear outlines of a building. We dug three auger holes where the magnetic contours suggested walls, and in each case we found a carpet of Roman potsherds overlying the tops of walls at a depth of about 1.4 m.

Figure 14. Terracotta fragment of an architectural statue from an Archaic building, ca. 600 B.C., found about 1 m below ground in Nikolaiika. The fragment, 13 cm high, preserves traces of red color.

Excavation

In 1995, we began an excavation of the Klonis site, in collaboration with the Ephoreia of Patras (Katsonopoulou, 1998b). The excavation reached a depth of 3.9 m and brought to light a large rectangular building from the Roman period (Figure 16). The main perimetric wall, including foundations, stands about 2 m high. The wall is constructed in a typical Roman style, with alternating courses of unworked stone and brick. The excellent correlation between the magnetic contours and the wall (Figure 15) is due to the brick. The thickness of the perimetric wall, the careful type of construction, and the size of the structure, all indicate the importance of the building. This is the first ancient structure brought to light in the Helike Delta, and it may belong to a Roman settlement, still called Helike, which Pausanias (7.24.5) visited at the site of the Classical city. Ptolemy's *Geography*, written in the 2nd century A.D., also listed Helike among the inhabited cities of Achaea.

The stratigraphic analysis showed that the erection of the main building was followed by a long phase of habitation, to the northwest of the building, represented by five successive floors (Figure 16[b]). The excavation yielded eight bronze coins, dating from the time of Aurelian (270 to 275 A.D.) to the 4th and perhaps early 5th century A.D. In addition to much Roman pottery, we found fragments of glass vases, objects of bone and bronze, fragments of marble floor decorations, and remains of food. An extensive destruction layer of stones, bricks, roof tiles, and plaster, found

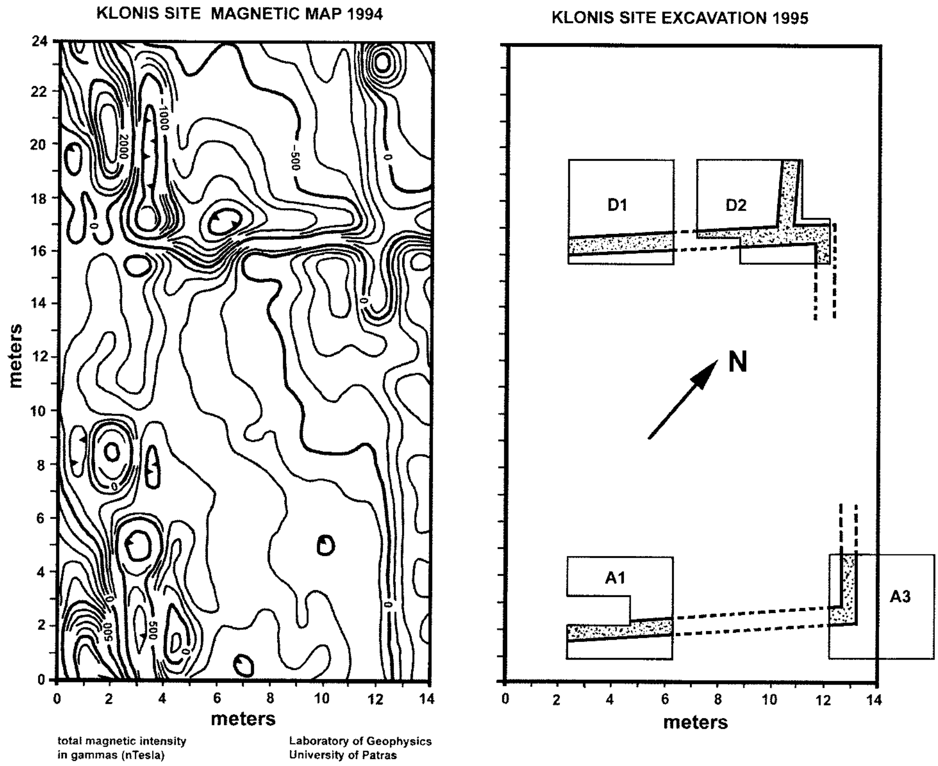

Figure 15. The Klonis site: (a) contours of magnetic intensity, surveyed by the Laboratory of Geophysics, University of Patras, in 1994; (b) the four squares excavated in 1995, showing locations of walls corresponding to the magnetic contours. The Helike Project excavated squares D1 and D2; the Ephoreia of Patras excavated squares A1 and A3.

both within and outside the building, shows that it was destroyed by an earthquake, probably in the late 4th or early 5th century A.D. In the deeper strata of the excavation we found several fine black-glazed ceramic fragments of the 5th century B.C. and other potsherds from the Protogeometric and Mycenaean periods. We interpret the presence of these pre-Roman potsherds by supposing that they were originally uncovered during the Roman period, either in a well dug near the building or in the excavation for its foundations.

DISCUSSION AND CONCLUSIONS

Although Helike was reportedly submerged during the earthquake of 373 B.C., most of the occupation horizons in the bore holes, including the oldest dated ones, were found at or above the present sea level. This may be due to tectonic uplift since antiquity. The evidence from raised relic shorelines on the foot wall of the a

b

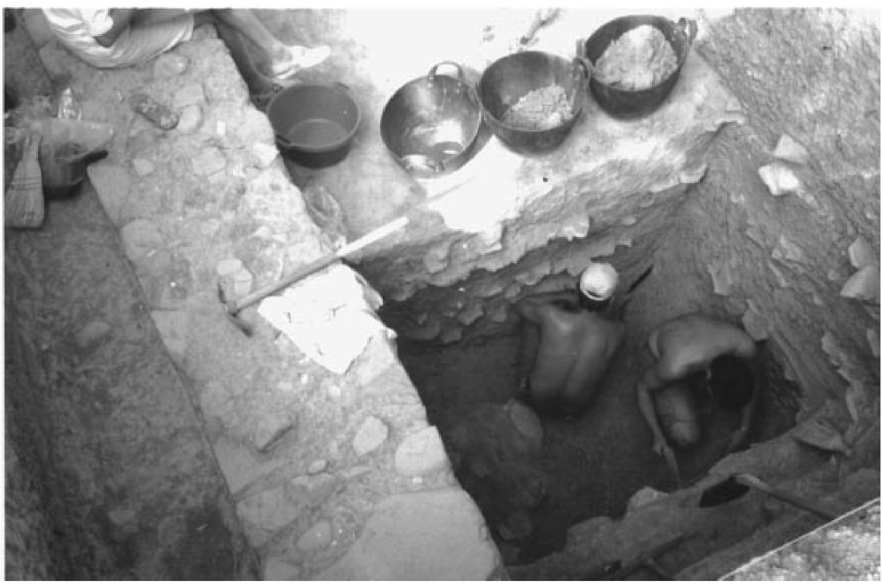

Figure 16. Klonis excavation site: (a) square D2 in Figure 15b at the midpoint of the excavation, revealing the tops of Roman walls and, at left, a destruction layer half excavated; (b) square D1 at the end of the excavation, at a depth of 3.9 m. Multiple occupation horizons are visible, postdating construction of the original walls.

Helike Fault southeast of the delta suggests that the Helike Delta may in fact have registered several meters of uplift in the last 24 centuries (Soter, 1998; Stewart and Vita-Finzi, 1996). This uplift may be partly aseismic, and partly due to earthquakes on faults in the Gulf of Corinth. During such earthquakes the Helike Delta would find itself on the uplifted (foot wall) side of the fault.

Marine or brackish sediments should have been deposited over the submerged site of Helike, 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 OSL date of the ceramics appeared to be from the Bronze Age. The area around B18 was evidently an occupied site in the 2nd millennium B.C., and was later covered by a lagoon. We note that B18 lies on the seaward fringe of the region defined by occupation horizons (Figure 7). This is the only case we have found so far of marine or brackish sediments overlying an occupation horizon.

Perhaps only the parts of Helike lying at lower elevations were actually submerged, while most of our ceramic horizons come from the upper parts of the city. According to this hypothesis, the subsidence of the delta would have drowned only the harbor town and other low-lying areas, including presumably the sanctuary of Poseidon. The upper parts of the city, situated on and around the Katourla Fan at the foot of the "acropolis" hill, would never have subsided below sea level.

The Katourla Fan, a topographic rise of over 20 m, existed in antiquity. It lies above the level vulnerable to periodic flooding from the Selinous and Kerynites Rivers, and would thus have been a natural place for a city to emerge. The Katourla Fan would not have been submerged by the earthquake of 373 B.C., although it could have been devastated by the seismic sea wave and perhaps by landslides. If this explanation is correct, then those 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 largely removed by erosion after the subsequent uplift.

Figure 17 summarizes the bore hole analysis in a schematic profile of the Helike Delta, which combines ceramic, environmental, and age results. The ceramic horizons are mostly above MSL. The olive green and gleyed clay strata, which mostly occur below the occupation horizons, generally reflect a brackish environment.

The sample ages suggest that the delta was repeatedly occupied from Early Helladic through Byzantine times. This occupational history is not surprising, given the natural advantages of the site. The Archaic and Classical horizons appear to lie within about 6 m of the surface, with the Bronze Age horizons extending down to 15 m. However, there may be large deviations in the isochron depths in various parts of the plain.

The presence of Hellenistic and Roman artifacts in bore holes and auger holes over an extensive part of the Helike Delta, together with the discovery of a large Roman building with Classical and Bronze Age potsherds in its foundations, sug-

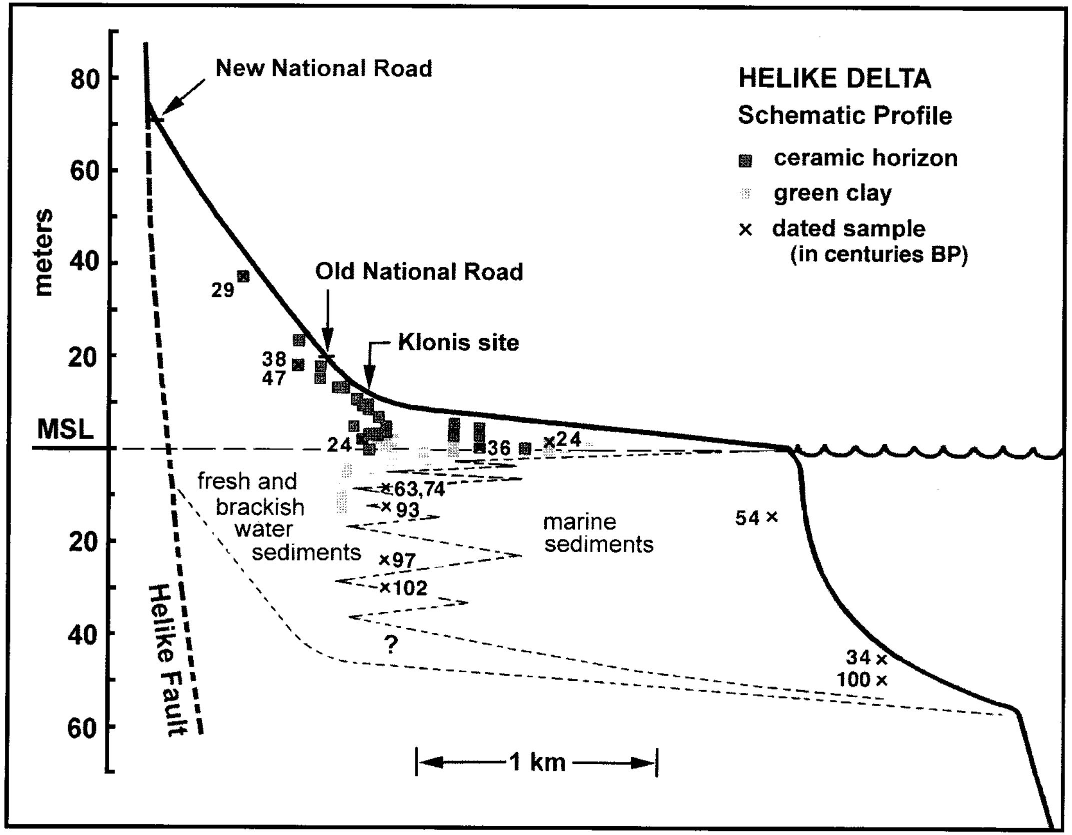

Figure 17. Schematic profile of the Helike Delta. The ceramic horizons occur mostly above the present mean sea level (MSL). The green clay strata often occur below the ceramic horizons, and generally reflect a brackish environment (based on microfaunal analysis). Dated samples are calibrated and labeled in hundreds of years before present. The ages of the two seafloor samples are based on data from Schwartz and Tziavos (1979).

gests that the seismic destruction of Classical Helike was followed by a hiatus of only a few centuries, after which the area was reoccupied.

The upper part of the coastal plain between the Selinous and Kerynites Rivers has evidently supported a substantial population since the Early Bronze Age. While we have yet to determine by excavation whether the occupation horizons include the center of a city, this area appears to be a strong candidate for the site of ancient Helike.

The Helike Project is conducted under the auspices of the American School of Classical Studies at Athens. We thank the Tria Epsilon Group of Companies (Hellenic Bottling Company) for partial financial support. We wish to thank our colleagues for technical contributions: for the sonar survey, Paul Kronfield; for bore hole drilling, Kostas Markantonis; for stratigraphic logging of the first five bore holes, Panos Karanikolas; for environmental analysis of core samples, Patricia Blackwelder, Carlos Alvarez-Zarikian, Terri Hood and Christos Tziavos; for ground penetrating radar, Doria Kutrubes; for magnetometry, Stavros Papamarinopoulos and Panagiotis Stephanopoulos; for radiocarbon dating, Yannis Maniatis and Yorgos Facorellis; for ceramic luminescence dating, Yannis Liritzis and Robert Galloway; for excavation, Eric Brulotte. We thank our assistants Maria Argyropoulou, Katerina Bichta, Stefano Garbin, Alexandra Georgiou, Alexis Liogas, Eirini Maganioti, Demitris Palaiologos, Dimitra Papantoni, Maria Stephanopoulou, and Annie Trikka. For special contributions to the Helike Project in other important ways, we wish to thank Demetrius Schilardi, Elias Sotiropoulos, Elias Papaioannou, Susan George, John Kraft, Vincent Murphy, and Daniel Jean Stanley. We also thank the Presidents of Eliki, Keryneia, Nikolaiika, Rizomylos, and Zachloritika for their hospitality and assistance.

REFERENCES

Ambraseys, N.N., & Jackson, J.A. (1997). Seismicity and strain in the Gulf of Corinth (Greece) since 1694. Journal of Earthquake Engineering, 1, 433–474.

Armijo, R., Meyer, B., King, G.C.P., Rigo, A., & Papanastassiou, D. (1996). Quaternary evolution of the Corinth Rift and its implications for the Late Cenozoic evolution of the Aegean. Geophysical Journal International, 126, 11–53.

Bernard, P., Briole, P., Meyer, B., et al. (1998). The $M_S = 6.2$, June 15, 1995 Aigion earthquake (Greece): Evidence for low angle normal faulting in the Corinth rift. Journal of Seismology, 1, 131–150.

Bintliff, J.L., & Snodgrass, A.M. (1991). Off-site pottery distributions: a regional and interregional perspective. Current Anthropology, 29, 506–513.

Dart, C.J., Collier, R.E.L., Gawthorpe, R.L., Keller, J.V.A., & Nichols, G. (1994). Sequence stratigraphy of (?)Pliocene-Quaternary synrift, Gilbert-type fan deltas, northern Peloponnesus, Greece. Marine & Petroleum Geology, 11, 545–560.

Davies, H.L. (1999). The Sissano Tsunami 1998. Port Moresby: University of Papua New Guinea.

Demangel, R. (1951a). Une ville Grecque engloutie: Helike. Bulletin van de Vereniging tot Bevordering der Kennis van de Antieke Beschaving te 's-Grevenhage, 24–26, 29–31.

Demangel, R. (1951b). Recherches sous-marines in Grèce. Bulletin Correspondance Hellénique, 75, 198.

Dontas, A. (1952). Hydrographic detection in the Gulf of Corinth of the submerged ancient city of Helike. Praktika tis Akademias Athinon, 27, 90–101 (in Greek).

Dörpfeld, W. (1885). The buildings of Tiryns. In H. Schliemann (Ed.), Tiryns: The prehistoric palace of the kings of Tiryns (Chapter V, pp. 254–255). New York: Scribner's.

Doutsos, T., & Poulimenos, G. (1992). Geometry and kinematics of active faults and their seismotectonic significance in the western Corinth-Patras rift (Greece). Journal of Structural Geology, 14, 689–699.

Edgerton, H.E. (1973). Search for Helice with sonar. National Geographic Society Research Reports, 1966, 75–77.

Edgerton, H.E. (1981). Search for the lost city of Helice with sonar. Athens: Hellenic Club of Aigion. In First International Scientific Meeting on Ancient Elike, Aigion, December 1979 (pp. 161–163).

Edgerton, H.E., & Throckmorton, P. (1979). Exploration by sonar and coring of the Helice site, Greece. National Geographic Society Research Reports, 1970, 135–141.

Hardy, S., Dart, C.J., & Waltham, D. (1994). Computer modelling of the influence of tectonics on sequence architecture of coarse-grained fan deltas. Marine & Petroleum Geology, 11, 561–574.

Heezen, B.C., Ewing, M., & Johnson, G.L. (1966). The Gulf of Corinth floor. Deep-Sea Research, 13, 381–411.

Katsonopoulou, D. (1998a). On the topography of Aigialeia (in Greek). In D. Katsonopoulou, S. Soter, & D. Schilardi (Eds.), Ancient Helike and Aigialeia: Proceedings of the Second International Conference, Aigion, December 1995 (pp. 31–66). Athens: The Helike Society.

Katsonopoulou, D. (1998b). The first excavation at Helike: Klonis Field. A preliminary report (in Greek). In D. Katsonopoulou, S. Soter, & D. Schilardi (Eds.), Ancient Helike and Aigialeia: Proceedings of the Second International Conference, Aigion, December 1995 (pp. 125–145). Athens: The Helike Society.

Kawata, Y., Benson, B.C., Borrero, J.C., Borrero, J.L., Davies, H.L., deLange, W.P., Imamura, F., Letz, H., Nott, J., & Synolakis, C.E. (1999). Tsunami in Papua New Guinea was as intense as first thought. Eos, 80, 101–105.

Keraudren, B., Falgueres, C., Bahain, J., Sorel, D., & Yokoyama, Y. (1995). Nouvelles datations radiométriques des terrasses marines de Corinthie (Péloponnèse septentrional, Grèce). Comptes Rendus de l'Académie des Sciences, Paris, 320, 483–489.

Koukouvelas, I.K., & 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.

Kutrubes, D.L., Soter, S., & Katsonopoulou, D. (1997). The search for ancient Helike: A GPR case study. In R.S. Bell (Ed.), Symposium on Application of Geophysics to Engineering & Environmental Problems, Proceedings Wheat Ridge, CO: Environmental and Engineering Geophysics Society (pp. 973–981).

Lekkas, E., Lozios, S., Skourtsos, E., & Kranis, H. (1996). Liquefaction, ground fissures and coastline change during the Egio earthquake (15 June 1995: Central-Western Greece). Terra Nova, 8, 648–654.

Leonards, G.A., Sotiropoulos, E.S., & Kavvadas, M.J. (1988). Helice: The lost town of ancient Greece. In P.G. Marinos & G.C. Koukis (Eds.), Engineering geology of ancient works, monuments and historical sites (pp. 1307–1313). Rotterdam: Balkema.

Liritzis, I., Galloway, R.B., & Hong, D.G. (1997). Single aliquot dating of ceramics by green light stimulation of quartz. Nuclear Instruments & Methods B, 132, 457–467.

MacDonald, G.M., Beukens, R.P., & 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., & 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.

Mouyaris, N., Papastamatiou, D., & Vita-Finzi, C. (1992). The Helice Fault? Terra Nova, 4, 124–129.

Ori, G.G. (1989). Geologic history of the extensional basin of the Gulf of Corinth (?Miocene-Pleistocene), Greece. Geology, 17, 918–921.

Papatheodorou, G., & Ferentinos, G. (1996). Submarine and coastal sediment failure triggered by the 1995, $M_S = 6.1$ R Aegion earthquake, Gulf of Corinth, Greece. Marine Geology, 137, 287–304.

Poulimenos, G. (1993). Tectonics and sedimentation in the western Corinth graben, Greece. Geologie und Palaeotologie, 10, 607–630.

Schmidt, J. (1862). Sur le grand tremblement de terre qui a eu lieu en Grèce le 26 décembre 1861. Comptes Rendus de l'Académie des Sciences, Paris, 54, 669–671.

Schmidt, J.F.J. (1875). Studien über Erdbeben. Leipzig: Carl Schottze.

Schwartz, M.L., & Tziavos, C. (1979). Geology in the search for ancient Helike. Journal of Field Archaeology, 6, 243–252.

Seger, M., & Alexander, J. (1993). Distribution of Plio-Pleistocene and Modern coarse-grained deltas south of the Gulf of Corinth, Greece. In L.E. Frostick & R.J. Steel (Eds.), Tectonic controls and signatures in sedimentary successions. Oxford: Blackwell. Special Publications, International Association of Sedimentologists. 20, pp. 37–48.

Soter, S. (1998). Holocene uplift and subsidence of the Helike Delta, Gulf of Corinth, Greece. In I. Stewart & C. Vita-Finzi (Eds.), Coastal Tectonics (Special Publications 146, pp. 41–56), London: Geological Society.

Soter, S. (1999). Macroscopic seismic precursors and submarine pockmarks in the Corinth-Patras Rift, Greece. Tectonophysics, in press.

Soter, S., & Katsonopoulou, D. (1998a). The search for ancient Helike, 1988–1995: Geological, sonar and bore hole studies. In D. Katsonopoulou, S. Soter, & D. Schilardi (Eds.), Ancient Helike and Aigialeia: Proceedings of the Second International Conference, Aigion, December 1995 (pp. 67–116). Athens: The Helike Society.

Soter, S., & Katsonopoulou, D. (1998b). Geophysical surveys on the hill of Agios Georgios, the possible acropolis of ancient Helike. In D. Katsonopoulou, S. Soter, & D. Schilardi (Eds.),Ancient Helike and Aigialeia: Proceedings of the Second International Conference, Aigion, December 1995 (pp. 153–162), Athens: The Helike Society.

Soter, S., Blackwelder, P., Tziavos, C., Katsonopoulou, D., Hood, T., & Alvarez-Zarikian, C. (1999). Environmental analysis of bore hole cores from the Helike Delta, Gulf of Corinth, Greece. In preparation.

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

Stanley, D.J., Arnold,D., & Warne, A.G. (1992). Oldest pharaonic site. National Geographic Research & Exploration, 8, 264–275.

Stewart, I. (1996). Holocene uplift and palaeoseismicity on the Eliki Fault, Western Gulf of Corinth, Greece. Annali di Geofisica, 39, 575–588.

Stewart, I., & Vita-Finzi, C. (1996). Coastal uplift on active normal faults: The Eliki Fault, Greece. Geophysical Research Letters, 23, 1853–1856.

Warne, A.G., & Stanley, D.J. (1993). Archaeology to refine Holocene subsidence rates along the Nile delta margin, Egypt. Geology, 21, 715–718.

Received October 10, 1998
Accepted for publication March 23, 1999