

# Benthic Foraminifera and Environmental Changes in Long Island Sound

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## ABSTRACT

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Benthic foraminiferal faunas in Long Island Sound (LIS) in the 1940s and 1960s were of low diversity, and dominated by species of the genus *Elphidium*, mainly *Elphidium excavatum clavatum*, with common *Buccella frigida* and *Eggerella advena*. The distribution of these species was dominantly correlated with depth, but it was not clear which depth-related environmental variable was most important. Differences between faunas collected in 1996 and 1997, and in the 1940s and 1960s include a strong decrease in relative abundance of *Eggerella advena* over all LIS, an increase in relative abundance of *Ammonia beccarii* in western LIS, and a decrease in species diversity.

The decreased diversity suggests that environmental stress caused the faunal changes. Oxygen isotope data for *E. excavatum clavatum* indicate that a change in salinity is not a probable cause. Carbon isotope data suggest that the supply of organic matter to the benthos increased since the early 1960s, with a stronger increase in western LIS where algal blooms have occurred since the early 1970s, possibly as a result of nutrient input by waste water treatment plants. These blooms or the resulting episodes of anoxia/hypoxia may have played a role in the increased relative abundance of *A. beccarii*. There is no clear explanation for the decreased abundance of *E. advena*, but changes in the phytoplankton composition (thus food supply) are a possible cause. Benthic foraminiferal faunal and stable isotope data have excellent potential as indicators of physicochemical environmental changes and their effects on the biota in LIS.

**ADDITIONAL INDEX WORDS:** *Elphidium excavatum*, *Buccella frigida*, *Eggerella advena*, pollution, anoxia, hypoxia, oxygen isotopes, carbon isotopes.

## INTRODUCTION

Long Island Sound (LIS) is a large, urban estuary with a reduced salinity and a pronounced seasonal stratification in its western part (*e.g.*, RILEY, 1956, 1959; KOPPELMAN *et al.*, 1976; GORDON, 1980). Its tidal range increases from about 0.7 m in the east to about 2.2 m in the west, and its circulation is dominated by tidal currents (KOPPELMAN *et al.*, 1976). The temperature of LIS waters fluctuates between ~ 0 °C in the winter to more than 20 °C in the summer. Bottom-water salinity ranges from 32 ‰ in the east to 22 ‰ in the west. Surface-water salinity ranges from about 30 ‰ in the east to 20 ‰ in the west, with values down to 15 ‰ close to rivers (CONNECTICUT DEPARTMENT OF ENVIRONMENTAL PROTECTION, 1977). The Connecticut River contributes more than 70% of the fresh water influx, the Housatonic 12%, and the Thames 9%. Precipitation (110 cm/y.) is distributed evenly throughout the year, slightly exceeding the annual evaporation (93 cm/y.). The LIS surface water salinity is strongly linked to the river discharges, with a time lag of about 2 months (KOPPELMAN *et al.*, 1976).

The Sound traps sediment efficiently, and areas of deposition and erosion are distributed patchily throughout LIS

(GORDON, 1980; BOKUNIEWICZ and GORDON, 1980). Sidescan studies documented an area of sediment erosion and non-deposition east of the mouth of the Connecticut River, whereas environments of coarse-grained bedload transport (with sand-ribbons and sand waves) are present between the Connecticut River and Hammonasset. Deposition of fine-grained sediment occurs in the central and western basins (KNEBEL *et al.*, 1999; KNEBEL and POPPE, this volume).

The "quiet water" regions in LIS, especially in the western basins, experience periodic, seasonal bottom water hypoxia (dissolved O<sub>2</sub> < 3 ml/L) or anoxia (dissolved O<sub>2</sub> < 1 ml/L), with severe consequences to the biota (*e.g.*, EPA, 1994). Salinity differences between bottom and surface waters are usually less than 1 ‰, while temperature differences reach up to 8 °C. The density stratification is thus primarily thermally controlled (WELSH and ELLER, 1991), and low-oxygen conditions usually reach their peak in July–August, when thermal stratification is most pronounced (NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION AND CONNECTICUT DEPARTMENT OF ENVIRONMENTAL PROTECTION, 1999).

Historical data since the beginning of the 20<sup>th</sup> century show occasional anoxia close to New York City (East River) in the 1920s and mid 1950s, but pervasive anoxia in the western

basin of LIS was first observed in 1971 (PARKER and O'REILLY, 1991), and was more severe in the 1970s than in the following decades. There is no evidence for hypoxia in the eastern basin, but moderate hypoxia occurred in the 1980s in the central basin, where waters were well oxygenated in the 1950s (RILEY, 1956, 1959; PARKER and O'REILLY, 1991).

When nutrients are abundant, algal blooms occur during the periods of stratification. The algal blooms are more intense in western LIS (SUN *et al.*, 1994). The top 5–10 m of water is supersaturated in oxygen produced by photosynthesis (WELSH and ELLER, 1991). Lower in the water column, oxygen is consumed through the decay of the abundantly produced organic matter, and hypoxia occurs even though some dissolved oxygen is transported laterally into western LIS (TORGERSON *et al.*, 1997). Small density differences create a stable stratification and the pycnocline always coincides with the oxycline, at a depth of 10–11 m (*e.g.*, WELSH and ELLER, 1991). The complex interactive process of oxygen loss in the bottom waters, including the temporal and spatial variations in circulation, mixing, and biological processes, is not well understood.

The health of the LIS ecosystem is further affected by sediment pollution. Atmospheric deposition and river-borne fluxes of pollutants, both organic and metallic, led to the pollution of the top section of sediments (*e.g.*, ROBERTSON *et al.*, 1991; TURGEON and O'CONNOR, 1991; WOLFE *et al.*, 1991; BENOIT *et al.*, 1999; MECRAY and BUCHHOLTZ TEN BRINK, this volume; VAREKAMP *et al.*, this volume). In addition, some locations became contaminated by dredge-spoil dumping (*e.g.*, KOPPELMAN *et al.*, 1976; SCHUBEL *et al.*, 1979; TUREKIAN *et al.*, 1980) or outflow from sewage treatment plants (BUCHHOLTZ TEN BRINK *et al.*, this volume).

Records of abundant biota which easily fossilize may reflect the effects of anthropogenic and natural environmental changes in LIS. Benthic foraminifera are such biota and are abundant in LIS. Changes in foraminiferal faunas occurred over the last few decades, possibly in response to anthropogenic changes, in European coastal waters (*e.g.*, the Baltic region; ALVE and MURRAY, 1995; ALVE, 1996) and in Chesapeake Bay as a result of climatic variations (CRONIN *et al.*, 2000).

The earliest description of foraminifera from western LIS and New York Harbor dates from 1934 (SHUPACK, 1934). A more detailed study was conducted in the late 1940s (PARKER, 1952; faunas collected in 1948), followed by an exhaustive study in the 1960s (BUZAS, 1965; faunas collected in 1961–1962). BUZAS' (1965) data were further analyzed and discussed by MURRAY (1976). The morphology of the dominant *Elphidium* species in LIS was studied by BUZAS (1966), MILLER *et al.* (1982), and BUZAS *et al.* (1985).

LIS faunas are classified as 'marginally marine' (*e.g.*, MURRAY, 1991), and typically have a low species diversity. The most abundant species have high tolerances for fluctuations in temperature and salinity, as well as for low oxygen conditions and environmental pollution (*e.g.*, ALVE, 1995; CULVER and BUZAS, 1995). There is no correlation between substrate and species relative abundance, but foraminifera are absent in coarse sand, and thus rare or absent in eastern LIS.

BUZAS (1965) recognized three benthic foraminiferal as-

semblages in both the living and total (living plus dead) populations. In shallow waters (ranging from 3–19 m; average depth 11 m), he recognized the *Elphidium clavatum* assemblage (= *Elphidium excavatum clavatum* in MILLER *et al.*, 1982), dominated by the nominate species at >60%. At depths ranging from 15–33 m (average depth 26 m), *E. excavatum clavatum* was common to abundant, but *Buccella frigida* was present at >9% and *Eggerella advena* at <19%. At depths between 19–39 m (average depth 30 m) *Eggerella advena* was present at >19%. *Ammonia beccarii* was rare (<5%) in all samples. BUZAS' (1965) data agree well with PARKER's (1952) data, but the relative abundance of *E. advena* was somewhat higher in 1961, and the diversity was somewhat lower.

The LIS foraminiferal assemblages were thus depth-zoned, but the actual controlling, depth-linked parameter(s) were not known. BUZAS (1965) suggested that the foraminiferal populations might be largely controlled by the food influx from primary producers, with the *E. excavatum*-dominated faunas in the shallower waters feeding more on benthic algae and diatoms. MURRAY (1991) described *E. excavatum clavatum* as a herbivore and *E. advena* as a detritivore, using more degraded and refractory organic matter, as demonstrated by its high abundance close to sewage outfalls (ALVE, 1995).

*Elphidium excavatum* sequesters chloroplasts, mainly from diatoms (LOPEZ, 1979; BERNHARD and BOWSER, 1999), and can survive in polluted and low oxygen environments (CATO *et al.*, 1980; MOODLEY, 1990; MOODLEY and HESS, 1992; ALVE, 1995). The sequestered chloroplasts might help in survival during low oxygen conditions (CEDHAGEN, 1991), as well as in increasing feeding efficiency (*e.g.*, BERNHARD and BOWSER, 1999). *E. excavatum* dwells infaunally in marginal marine regions (LANGER *et al.*, 1989; MOODLEY, 1990), and it lives in the top 4 cm of sediment in LIS (BUZAS, 1965).

Shallow-water foraminifera have been used widely to monitor environmental pollution, specifically the influx of organic waste (*e.g.*, ALVE, 1995; SCOTT *et al.*, 1995). Benthic foraminiferal faunas are characterized by high specimen abundance and low species diversity close to sewage outfalls, and they react to different types of pollution (sewage, nutrient enrichment resulting from aquaculture, metals) by secreting deformed tests (*e.g.*, GESLIN *et al.*, 1998; YANKO *et al.*, 1998). The pollution levels necessary to cause deformation have not been quantified. It has been suggested that foraminiferal faunas could also be used to monitor heavy-metal pollution (*e.g.*, YANKO *et al.*, 1998; ALVE and OLSGARD, 1999). Extremely high levels of Cu pollution (>700 ppm in the sediment) have been reported to affect benthic foraminiferal faunas (ALVE and OLSGARD, 1999), but data on the specific levels of pollution required to influence the faunas are contradictory.

The oxygen isotopic composition of calcareous foraminiferal tests can be used to estimate the water temperature during the time of calcification of the organisms, as is commonly done on specimens from open marine environments (*e.g.*, ANDERSON and ARTHUR, 1983). In brackish environments, however, both salinity and temperature influence the  $\delta^{18}\text{O}$  composition of carbonate tests.

The carbon isotopic composition of foraminiferal tests in coastal waters also depends on salinity, because riverine bi-

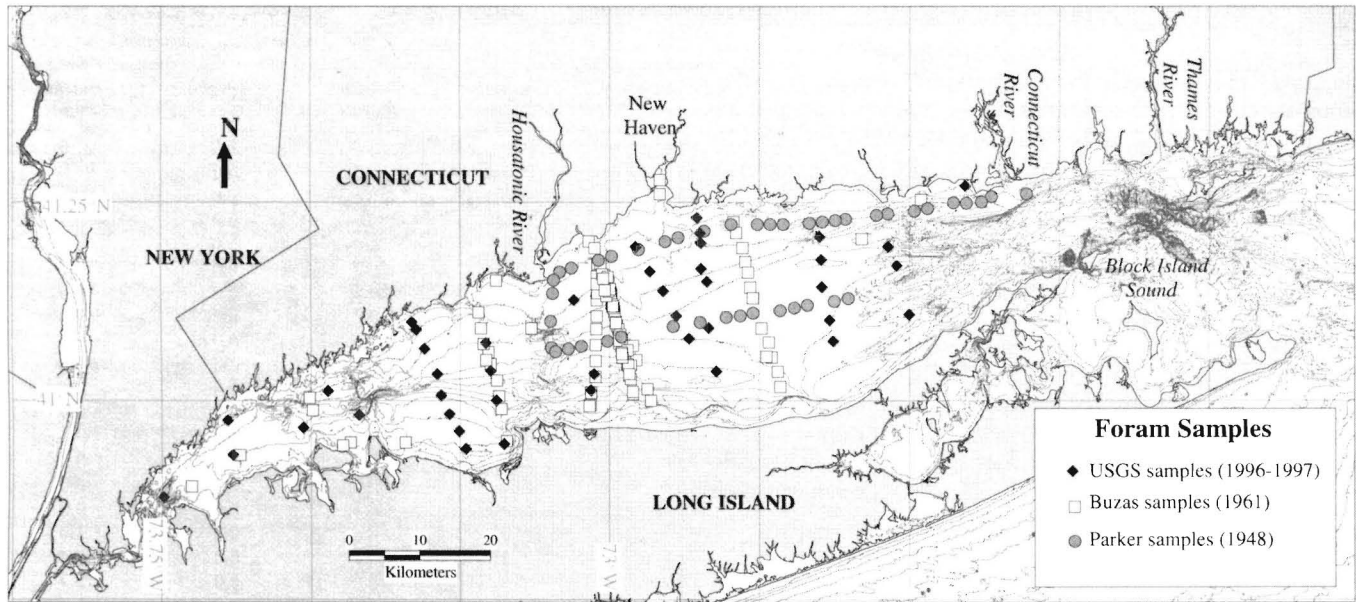


Figure 1. Location map of U. S. Geological Survey grab samples used in foraminiferal studies, with the locations of BUZAS' (1965) and PARKER's (1952) samples.

carbonate has lower  $\delta^{13}\text{C}$  values than open ocean bicarbonate (e.g., ANDERSON and ARTHUR 1983). In addition to the salinity effect, local primary productivity may cause more positive  $\delta^{13}\text{C}$  values in carbonates deposited at the location of productivity in surface waters, and oxidation of organic matter in bottom waters will create more negative  $\delta^{13}\text{C}$  values in carbonates. Oxidation of terrestrial organic carbon would create lighter  $\delta^{13}\text{C}$  values in bottom waters without the associated heavy values in surface waters. Oxidation of isotopically light organic carbon from local productivity and from terrigenous sources would result in oxygen consumption, and thus hypoxia or anoxia. According to the NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION and CONNECTICUT DEPARTMENT OF ENVIRONMENTAL PROTECTION (1999), during periods of anoxia/hypoxia up to about 25% of oxygen in western LIS may be consumed by oxidation of terrigenous organic material, the remainder by oxidation of locally produced organic matter. Negative carbon isotopic values in benthic foraminifera can indicate the occurrence of hypoxia or anoxia independent of the source of the organic carbon (e.g., McCORKLE and EMERSON, 1988).

We compare data on the composition of benthic foraminiferal assemblages in LIS in 1996/1997 with observations made before the first recognized episode of severe anoxia in 1971 (PARKER and O'REILLY, 1991), and present oxygen and carbon isotope data on benthic foraminiferal tests collected in 1961 and 1996/1997. The identification of changes in benthic foraminiferal distributions, linked to specific variations in environmental parameters, will be of great value for the reconstruction of past environments in LIS from core data.

#### MATERIALS AND METHODS

Surface sediments (0–2 cm below the sediment-water interface) were collected using a Van Veen grab sampler

equipped with a video and still camera system by the U. S. Geological Survey (POPPE and POLLONI, 1998). The R/V Seaward Explorer was used on two cruises in 1996 (MECRAY and BUCHHOLTZ TEN BRINK, this volume), and the R/V John Dempsey on a cruise in 1997 (POPPE and POLLONI, 1998).

We selected 42 samples for foraminiferal analysis (Figure 1, Table 1) to provide coverage along the east-west axis of LIS, as well as along north-south transects which cross its bathymetric features (e.g., BUCHHOLTZ TEN BRINK *et al.*, this volume). Our samples cover a depth range between 5 and 35 m, and a longitudinal range between 72.407 and 73.747 (decimal) degrees W (Figs. 2a, 2b). PARKER's (1952) data were collected in the eastern part of LIS, between 72.492 and 73.098 (decimal) degrees W, and between 6.5 and 29 m depth. BUZAS (1965) presents the largest data set and covers the largest depth range (3–43 m). His samples range in longitude between 72.852 and 73.700 (decimal) degrees W. There are few samples in westernmost LIS, and many samples close to longitude 73.0 °W (Figure 2).

In order to compare our benthic foraminiferal data with those in PARKER (1952) and BUZAS (1965) we needed a consistent taxonomy. The main taxonomic problems are with the species of the genus *Elphidium*. The taxonomy of this genus is complex because its species show great morphological variability (e.g., MILLER *et al.*, 1982; BUZAS *et al.*, 1985). We used the taxonomic concept of MILLER *et al.*, (1982), but BUZAS (1965) and PARKER (1952) used a different concept.

We compared our specimens with specimens in BUZAS' (1965) collection in the Peabody Museum of Yale University and concluded that *E. clavatum* in BUZAS (1965) is the same morphological group that we name *E. excavatum* forma *clavatum* (1965). We consider PARKER's (1952) informal taxonomic group '*Elphidium incertum* and variants' equal to our

Table 1. Percentages of common benthic foraminifera at Long Island Sound stations, with geographic position and water depth. Samples without information are either barren or contain a few, strongly corroded specimens of *Elphidium* spp.

1996/1997 sample name	Depth, m	Longitude Decimal	Latitude Decimal	<i>Elphidium</i> <i>excavatum</i> <i>clavatum</i>	<i>Elphidium</i> <i>incertum</i>	<i>Buccella</i> <i>frigida</i>	<i>Eggerella</i> <i>advena</i>	<i>Ammonia</i> <i>beccarii</i>
WLIS 97-95	24	73.747	40.878	22.4	17.2	31.9	0.0	27.6
WLIS 97-83	22	73.639	40.975	42.6	11.1	18.5	0.0	27.8
WLIS 97-81	26	73.630	40.931	43.4	8.5	20.8	0.0	27.4
43-01	22	73.513	40.965	37.5	21.2	30.8	0.0	10.6
42-01	24	73.472	41.012	52.0	21.0	18.0	0.0	7.0
40-02	30	73.419	40.982	46.6	19.4	29.1	0.0	4.8
A1G1	11	73.331	41.098	77.5	12.6	6.3	0.0	3.6
A2G2	17	73.324	41.089	67.4	18.8	9.0	0.0	4.9
A3G1	24	73.309	41.065	56.1	14.0	27.1	0.0	2.8
A4G1	26	73.288	41.032	57.1	7.1	33.7	0.0	0.0
A5G1	19	73.281	41.006	53.8	34.6	8.2	0.0	2.7
A6G2	16	73.251	40.961	63.5	21.8	14.7	0.0	0.0
A8G1	35	73.268	40.987	49.1	29.3	21.0	0.0	0.6
M2G1	15	73.206	41.073	19.0	50.5	27.6	0.0	0.0
M3G1	29	73.198	41.037	59.5	19.0	20.9	0.0	0.6
M5G2	15	73.175	40.945	49.1	29.3	28.7	0.0	0.0
M6G1	33	73.175	41.000	40.2	22.5	36.3	0.0	1.0
B3/29-01	16	73.059	41.126	71.2	6.3	16.2	0.0	5.4
B6G1	22	73.025	41.033	58.7	4.8	23.8	0.0	12.7
27-05	32	73.030	41.013	61.5	15.5	21.9	0.0	1.1
C2/26-01	12	72.956	41.193	89.0	3.9	7.2	0.0	0.0
C3/25-01	18	72.932	41.162	77.0	3.5	18.6	0.0	0.0
C3-C4/24-01	22	72.910	41.138	59.6	13.8	22.0	0.9	0.0
C4G1/23-02	29	72.888	41.107	63.6	2.5	28.3	0.6	3.1
C5G1	9	72.867	41.078	49.7	20.0	21.4	0.0	0.0
D1G2	14	72.584	41.230	92.3	2.1	5.6	0.0	0.0
D2G1	16	72.849	41.211	81.4	4.3	14.3	0.0	0.0
D3G1	22	72.847	41.198	34.8	31.3	29.6	0.0	2.6
D4/46B-01	20	72.847	41.166	67.0	8.7	22.3	0.0	1.9
D5G1	29	72.837	41.150	27.3	41.0	29.1	0.0	0.0
D6G1	29	72.834	41.091					
D7G1	14	72.821	41.037	28.0	41.0	20.0	1.0	0.0
E2G1	30	72.649	41.206	82.4	9.8	5.9	0.0	1.0
E3G1	27	72.646	41.177	89.4	6.2	0.9	0.9	1.8
E4G1	26	72.645	41.143	77.6	15.5	3.4	1.0	1.7
E5G1	24	72.632	41.101					
E6G1	13	72.626	41.074					
F3G1	23	72.536	41.193					
F4G1	32	72.521	41.169					
F5G1	5	72.499	41.108	71.3	16.7	4.6	0.9	2.8
G1G1	15	72.407	41.270	92.3	2.1	1.5	0.0	7.6

*E. excavatum clavatum*, conform MURRAY (1991). We consider her *E. subarcticum* equal to our *E. excavatum* forma *excavatum*.

The grab samples were processed as described in MECRAY and BUCHHOLTZ TEN BRINK (this volume); part of the freeze-dried samples was wet-sieved over a 63  $\mu\text{m}$  screen for foraminiferal analysis. The complete fraction larger than 63  $\mu\text{m}$  was used. BUZAS (1965) also used the >63  $\mu\text{m}$  size fraction, but no information was given on the size fraction used for foraminiferal study by PARKER (1952).

The grab samples were not stained to detect living specimens, so we could only study total faunas (living and dead specimens), and compare these with similar data in BUZAS (1965). At several locations a sub-sample of the grab samples was placed in formaldehyde. These samples were not buffered for long-term storage, and all carbonate material was dissolved at the time of analysis. We processed and studied several of these samples in order to determine whether agglu-

tinant specimens had been affected by freeze-drying. We found no differences between agglutinant taxa abundance in the formaldehyde and the freeze-dried samples.

We prepared splits of the samples to contain at least 100 specimens of foraminifera. Specimens were picked from all samples, identified to species level, and stored in foraminiferal slides. Relative abundances of the most common species of foraminifera are shown in Table 1. Locations of the sample stations of BUZAS (1965), who did not give latitude and longitude for his stations, were read from his original field map (Table 2), kept with BUZAS' (1965) collections of foraminifera at the Peabody Museum of Yale University. The locations of BUZAS' (1965) samples can not be determined with precision, because dead reckoning was used in navigation. PARKER (1952) listed latitude and longitude for her sample stations.

We analyzed specimens of *Elphidium excavatum clavatum* from our and BUZAS' (1965) samples for carbon and oxygen isotopic composition at the mass spectrometer facility, De-

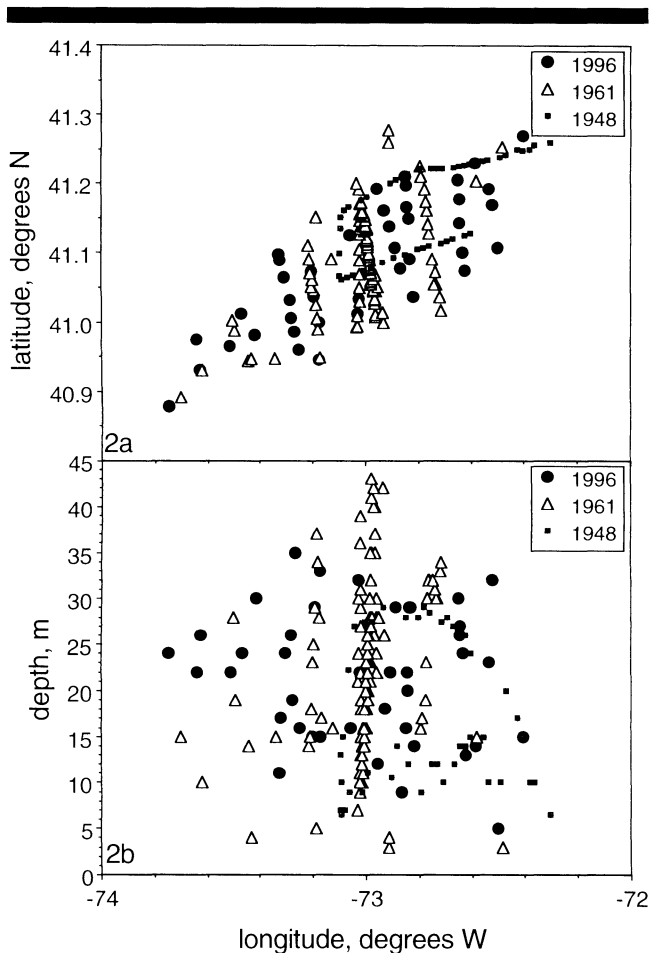


Figure 2. Comparison of the locations of the 1996–1997 USGS grab samples with those of BUZAS (1965) and PARKER (1952). (a) Longitude (decimal degrees W) plotted versus latitude (decimal degrees N) for our samples (1996), BUZAS' (1965) samples (1961), and PARKER'S (1952) samples (1948). (b) Longitude (decimal degrees W) plotted versus depth (m) for our samples (1996), BUZAS' (1965) samples (1961), and PARKER'S (1952) samples (1948).

partment of Geology and Geophysics, Yale University. The values are reported with respect to the general standard of isotope analyses of carbonates, PDB (the isotopic value of a belemnite from the PeeDee Formation); the analytical precision is  $\pm 0.1\%$  for both oxygen and carbon isotopic values.

## RESULTS

### Foraminiferal Data

Foraminifera were common in most samples (Table 1), with the exception of a few samples taken east of  $72.6^\circ\text{W}$  (Hammonasset), where the sediment is predominantly sandy, and sidescan data indicate sediment erosion, non deposition and transport (KNEBEL *et al.*, 1999; KNEBEL and POPPE, this volume). Samples in this region have only a few, badly corroded specimens of *Elphidium* spp. (no foraminifera listed in Table 1). These specimens can not be determined to the species level because they have been transported and eroded. *Elphidium*

*excavatum* preferentially survives extensive transport, as documented in the north-west European shallow-water environments of the Kattegat (NORDBERG *et al.*, 1999).

In addition to foraminifera, carbonate shells of bivalves and gastropods are common in the samples. This appears to be in contrast with previous work indicating that carbonate in LIS sediments is largely dissolved (ALLER, 1982; GREEN *et al.*, 1992, 1993; 1998; ALLER and ALLER, 1998). In samples in western LIS (west of  $73^\circ30'\text{W}$ ) some foraminifera show incipient dissolution (starting at the periphery), but in most samples even thin-walled specimens are well-preserved with no sign of dissolution. In BUZAS' (1965) samples, most specimens were also well-preserved, again with the exception of a few samples in western LIS (MURRAY, 1976). We do not understand this discrepancy between our observations and published chemical models. Possibly there is strong local variability in LIS in such factors as intensity of bioturbation and diagenesis (*e.g.*, KROM and BENNET, 1985; BUCHHOLTZ TEN BRINK *et al.*, this volume).

The LIS faunas are low-diversity as compared to open marine shelf faunas, and the most abundant species are those observed by PARKER (1952) and BUZAS (1965) (Figure 3a-d, Figure 4 a-d). By far the most abundant species belong to the genus *Elphidium* (Figures 3a, 4a). We identified most of the *Elphidium* species in LIS as *E. excavatum* s.l., following the species concepts of MILLER *et al.* (1982), with the forma *E. excavatum clavatum* most common. The second most common forma is *E. excavatum excavatum*; *E. incertum* (Williamson) is also common in many samples (BUZAS, 1966).

*E. excavatum clavatum* is most abundant in LIS at depths shallower than about 15 m, in agreement with BUZAS (1965). This trend is very broad, however, with numerous exceptions (Figure 3a). In our data, the relative abundance of *E. excavatum clavatum* is significantly correlated with longitude, with the species being less abundant in western LIS (Figure 4a). This correlation with longitude was more significant than the correlation with depth, whereas in BUZAS' (1965) the correlation with depth was significant, and the correlation with longitude was absent or non-significant (Table 3).

After *Elphidium* species, *Buccella frigida* is most common (Figures 3 b, 4b), in agreement with observations by PARKER (1952) and BUZAS (1965). This species tends to be more common at the deeper locations, particularly below about 15m, but this is a broad trend with numerous exceptions. The species is more common in the western and central basins of LIS than in the eastern basin, resulting in a weak positive correlation of its relative abundance with longitude (Table 3, Figure 4b).

The third most common species in the studies by PARKER (1952) and BUZAS (1965) was the agglutinant *Eggerella advena*, especially in the deeper parts of LIS (Figure 3c). This taxon occurred at less than a few percent in relative abundance in all our samples. The lack of abundant specimens of *E. advena* even in samples close to locations where it was common to abundant in BUZAS (1965) and PARKER (1952), was probably not caused by sampling artifacts (see section METHODS). PARKER'S (1952) study shows a lower maximum abundance of *E. advena* than BUZAS' (1965) study; east of  $73^\circ\text{W}$ , PARKER'S (1952) values are slightly higher than those of

Table 2. Geographic location and water depth of the sample stations of BUZAS (1965). Sta.: Station.

Sta.	Longitude Decimal	Latitude Decimal	Depth (m)	Sta.	Longitude Decimal	Latitude Decimal	Depth (m)	Sta.	Longitude Decimal	Latitude Decimal	Depth (m)
10	73.008	41.139	14	128	72.978	41.054	43	39	72.765	41.142	32
10'	73.008	41.139	14	129	72.983	41.076	32	40	72.761	41.129	32
100	73.015	41.172	13	129'	72.983	41.076	32	42	72.746	41.091	32
101	73.012	41.159	16	13-1	73.025	41.192	9	44	72.738	41.056	31
101a	73.012	41.159	16	13-2	73.025	41.192	10	45	72.734	41.073	30
101b	73.012	41.159	16	13-3	73.025	41.192	10	46	72.730	41.054	30
102	73.008	41.139	18	13-4	73.025	41.192	9	47	72.719	41.037	33
102'	73.008	41.139	18	13-5	73.025	41.192	11	48	72.715	41.017	34
103	73.003	41.156	21	13-6	73.025	41.192	11	5	72.983	41.072	35
103a	73.003	41.156	21	13-7	73.025	41.192	10	50	72.580	41.203	15
103b	73.003	41.156	21	13-8	73.025	41.192	10	59	72.481	41.253	3
103c	73.003	41.156	21	130	72.989	41.098	30	59'	72.481	41.253	3
104	72.998	41.136	24	131	72.994	41.119	26	6	72.987	41.094	30
104'	72.998	41.136	24	131'	72.994	41.119	26	60	73.015	41.172	13
105	72.992	41.117	27	132	72.999	41.141	23	63	72.996	41.122	20
107	72.984	41.078	35	133	73.005	41.132	20	64	72.991	41.108	23
107a	72.984	41.078	35	133'	73.005	41.132	20	65	72.985	41.090	27
107b	72.984	41.078	35	134	73.011	41.153	16	66	72.979	41.072	28
107c	72.984	41.078	35	135	73.015	41.172	14	68	72.961	41.069	30
108	72.979	41.059	41	14	73.619	40.931	10	69	72.955	41.051	28
108'	72.979	41.059	41	14'	73.619	40.931	10	7	72.992	41.112	26
109	72.968	41.044	42	15'	73.700	40.892	15	71	72.936	41.014	42
109a	72.968	41.044	42	17	73.189	41.151	5	73	73.015	41.172	13
109b	72.968	41.044	42	18	73.035	41.200	7	74	73.008	41.158	15
109c	72.968	41.044	42	19	72.916	41.278	3	74a	73.008	41.158	15
11	73.012	41.159	11	19'	72.916	41.278	3	75	73.002	41.138	18
110	73.502	41.003	28	20	72.916	41.260	4	76	72.995	41.118	19
111	73.497	40.988	19	22	73.020	41.172	13	77	72.989	41.098	21
112	73.446	40.943	14	23	73.021	41.156	15	78	72.982	41.083	23
113	73.341	40.947	15	24	73.020	41.136	18	79	72.970	41.063	26
114	73.171	40.949	17	24'	73.020	41.136	18	8	72.997	41.133	22
116	73.180	40.989	28	25	73.021	41.147	19	80	72.964	41.044	24
117	73.184	41.006	34	26	73.021	41.127	22	84	72.930	41.000	26
118	73.188	41.026	37	27	73.021	41.106	27	86	73.012	41.159	16
119	73.198	41.046	29	28	73.022	41.090	29	88	73.003	41.156	20
12	73.015	41.172	10	29	73.023	41.070	31	89	72.998	41.137	22
12	73.015	41.172	12	3	72.967	41.032	40	9	73.002	41.148	16
120	73.202	41.061	25	30	73.023	41.050	36	90	72.994	41.118	25
121	73.206	41.051	23	31	73.023	41.030	39	91	72.989	41.099	28
122	73.211	41.071	18	32	73.030	41.010	30	92	72.984	41.080	32
123	73.215	41.091	15	33	73.031	40.994	24	93	72.980	41.061	35
124	73.219	41.111	14	34	72.793	41.225	16	94	72.970	41.046	40
125	73.130	41.091	16	35	72.789	41.211	17	95	72.964	41.027	37
125'	73.130	41.091	16	36	72.778	41.192	19	96	72.961	41.008	22
126	72.961	41.011	28	37	72.773	41.174	23	97	73.033	40.993	21
127	72.967	41.033	35	38	72.769	41.161	30	98a	73.433	40.947	4

BUZAS (1965), but her values for stations at about 73 °W are lower. The calcareous taxon *Ammonia beccarii* (Figures 3d, 4d) was more common in our samples than in the older data sets. This species was rare (<5%) in all samples described by PARKER (1952) and BUZAS (1965), but it reaches peak abundances of about 27% in our samples from the westernmost region of LIS.

Evaluation of the number of species (normalized to the number of specimens counted) shows that the diversity of benthic foraminifera decreased somewhat since the 1960s, and that the diversity may also have been somewhat lower in the 1960s than in the 1940s (Figure 5). Alpha-diversity was below 1 for almost all our samples, and varied between 1 and 3 in the 1960s (BUZAS, 1965). The drop in diversity is caused by a decrease in abundance of the uncommon to rare

species, which occur in a few samples only, as single or a few specimens. They include *Rheophax dentaliniformis*, *Rheophax nana*, *Quinqueloculina seminula*, *Trochammina squammata*, and *Cornuspira planorbis*. In a few samples towards the eastern end of LIS (E- and F transect, fig. 1) specimens of *Cibicides lobatulus*, *Nonion commune* and *Dentalina* spp. occurred as rare individuals. In samples from close to the Connecticut shoreline, a few specimens of the marsh foraminiferal species *Trochammina macrescens*, *Haplophragmoides manilaensis* and *Trochammina inflata* occur, which are probably transported into LIS from the coastal marshes. Neither we, nor PARKER (1952), nor BUZAS (1965) did find planktonic foraminifera, which do not occur in such marginally marine environments as LIS and are apparently not transported into LIS from the Atlantic Ocean.

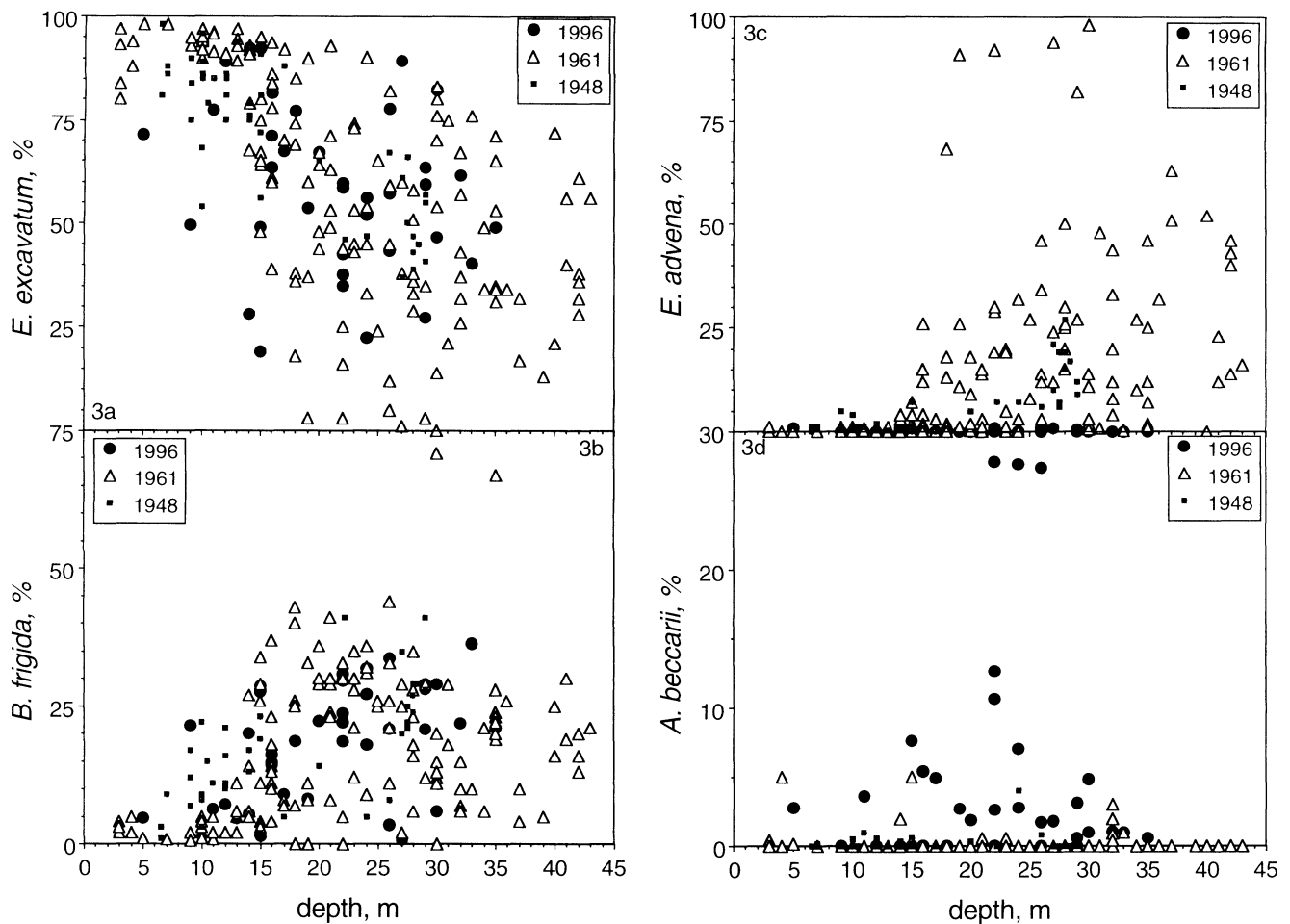


Figure 3. Relative abundances of the most common species in Long Island Sound by depth. (a) Relative abundance of *Elphidium excavatum clavatum* in our samples and in samples in BUZAS (1965; samples collected in 1961 and 1962) and PARKER (1952; samples collected in 1948). (b) Relative abundance of *Buccella frigida* in our samples and in samples in BUZAS (1965; samples collected in 1961 and 1962) and PARKER (1952; samples collected in 1948). (c) Relative abundance of *Eggerella advena* in our samples and in samples in BUZAS (1965; samples collected in 1961 and 1962) and PARKER (1952; samples collected in 1948). (d) Relative abundance of *Ammonia beccarii* in our samples and in samples in BUZAS (1965; samples collected in 1961 and 1962) and PARKER (1952; samples collected in 1948).

### Stable Isotope Data

We determined carbon and oxygen isotope compositions of *Elphidium excavatum clavatum* in twelve LIS surface sediment samples from the 1996/1997 cruises and four samples from the 1961 collection of Buzas (1965) (Table 4, Fig. 6). Most of the  $\delta^{18}\text{O}$  values are lighter than those in the open ocean, reflecting the mixing of sea water with isotopically light river water in LIS. The  $\delta^{18}\text{O}$  values are significantly lighter in western LIS (Figure 6), as expected from the overall lower salinities in western LIS (e.g., KOPPELMAN *et al.*, 1976). If the few studied samples may be considered representative for LIS, there are no significant differences in  $\delta^{18}\text{O}$  values of samples from 1961 and from 1996.

We made a preliminary mixing model of river water and sea water for LIS, and calculated the  $\delta^{18}\text{O}$  values in water and the  $\delta^{13}\text{C}$  values in dissolved bicarbonate as a function of salinity (Figure 7; Table 5). According to this model, the  $\delta^{18}\text{O}$

values in LIS waters should vary between  $-1$  and  $-4$ ‰. We compiled average bottom water salinities for each LIS sampling site (after KOPPELMAN *et al.*, 1976) and calculated  $\delta^{18}\text{O}$  values for water with the mixing model. From the calculated water and measured carbonate  $\delta^{18}\text{O}$  values, we obtained water-calcite equilibration temperatures (ANDERSON and ARTHUR, 1983), which range from  $7.0$  to  $10.6$  °C, with one anomalously low value of  $5.4$  °C (Figure 6). Such bottom water temperatures occur from late spring through summer (KOPPELMAN *et al.*, 1976), at which time the foraminifera show a major population increase (BUZAS, 1965). The life span of *E. excavatum clavatum* probably ranges from a few months to a year (MURRAY, 1991). The calculated temperatures provide an average water temperature over the life span of the organisms, because foraminifera calcify their tests incrementally by chamber addition.

The oxygen isotope values change with longitude, so we

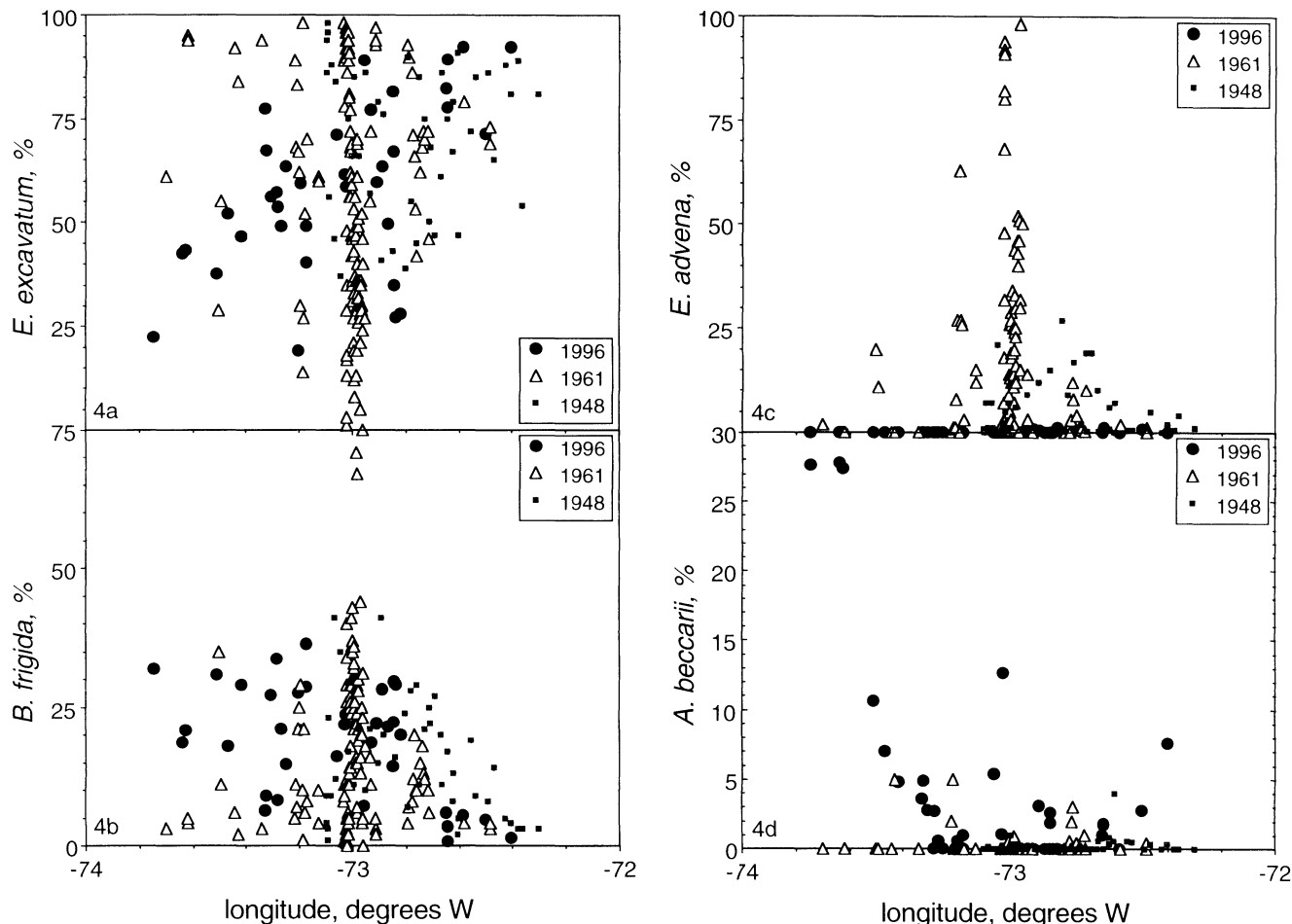


Figure 4. Relative abundances of the most common species in Long Island Sound by longitude. (a) Relative abundance of *Elphidium excavatum clavatum* in our samples and in samples in BUZAS (1965; samples collected in 1961 and 1962) and PARKER (1952; samples collected in 1948). (b) Relative abundance of *Buccella frigida* in our samples and in samples in BUZAS (1965; samples collected in 1961 and 1962) and PARKER (1952; samples collected in 1948). (c) Relative abundance of *Eggerella advena* in our samples and in samples in BUZAS (1965; samples collected in 1961 and 1962) and PARKER (1952; samples collected in 1948). (d) Relative abundance of *Ammonia beccarii* in our samples and in samples in BUZAS (1965; samples collected in 1961 and 1962) and PARKER (1952; samples collected in 1948).

need to look at data from a fixed longitude to see whether a depth effect exists (Figure 6). Four data points on the approximately north-south trending A-transect in west LIS (Figure 1) show no relationship between depth and  $\delta^{18}\text{O}$ . In

Table 3. Correlation coefficients between relative abundance of species in 1996 (our data) and 1961–1962 (BUZAS, 1965) and longitude and depth. No values are given for the data in PARKER (1952) because of the smaller spatial and depth ranges of her samples.

Species	1996	1961	1996	1961
	Longitude $r^2$	Longitude $r^2$	Depth $r^2$	Depth $r^2$
<i>E. excavatum clava-</i> <i>tum</i>	-0.317	0.006	0.056	-0.375
<i>B. frigida</i>	0.248	0.005	0.164	0.120
<i>E. advena</i>	0.211	0.001	0.006	0.202
<i>A. beccarii</i>	0.332	0.009	0.012	0.009

these preliminary data we therefore do not find evidence for thermal or salinity-related stratification (e.g., RILEY, 1956, 1959; KOPPELMAN *et al.*, 1976; GORDON, 1980), probably because all samples are from below 10–11 m, the average depth of the pycnocline (e.g., WELSH and ELLER, 1991).

The  $\delta^{13}\text{C}$  values also show an east-west trend, with lighter values in western LIS. There is no correlation between  $\delta^{13}\text{C}$  values and depth (Figure 6); we do not see an effect of photosynthesis in shallow waters, nor an effect of symbiotic algae. This may result from the fact that we do not have samples from shallower depths than about 10 m, which is about the depth of light penetration (e.g., BUZAS, 1965).

The range in observed  $\delta^{13}\text{C}$  values (Table 4; between -4.21 and -1.89‰) is considerably larger than would be expected from the mixing of fresh and salt water alone (Figure 7). Most likely, the oxidation of isotopically light organic matter is reflected in the carbon isotopic data. Because oxidation of or-



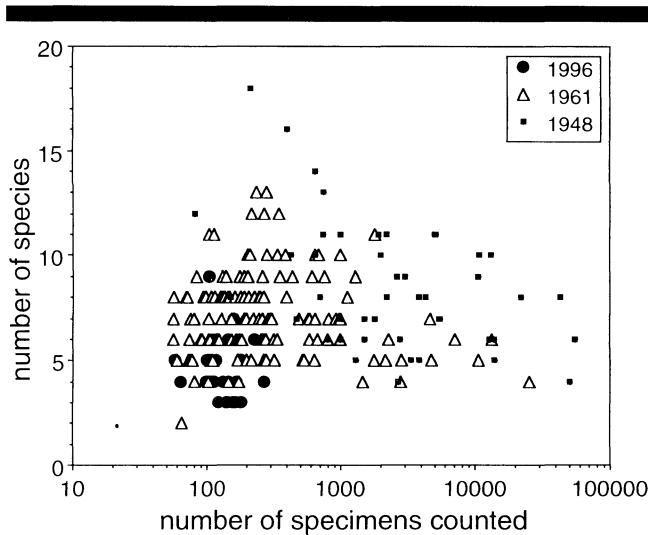


Figure 5. Comparison in number of species for number of specimens counted in our samples and in samples in BUZAS (1965; samples collected in 1961 and 1962) and PARKER (1952; samples collected in 1948).

ganic matter consumes oxygen, the carbon isotope data thus provide an indirect estimate of the level of oxygenation. In order to evaluate this oxidation effect, we removed the salinity effect from the  $\delta^{13}\text{C}$  data by calculating water salinities at an assumed water temperature from the measured  $\delta^{18}\text{O}$  data, using 10 °C as a time-averaged LIS-wide bottom water temperature.

Our calculations involved the following steps: from the measured  $\delta^{18}\text{O}$  values in carbonate, we calculated the  $\delta^{18}\text{O}$  of the water, and then used the LIS mixing model to estimate the salinity. From the calculated salinity we estimated the  $\delta^{13}\text{C}$  value of dissolved inorganic carbon in LIS water, again using the mixing model. We subtracted the calculated values from the observed  $\delta^{13}\text{C}$  values, which we label the  $\delta^{13}\text{C}$ -excess data ( $\delta^{13}\text{C}^*$ ) or

$$\delta^{13}\text{C}^* = \text{measured } \delta^{13}\text{C}_{\text{carbonate}} - \text{calculated } \delta^{13}\text{C}_{\text{water}}$$

Table 4. Carbon and oxygen isotope data from *Elphidium excavatum clavatum*.

Station	$\delta^{13}\text{C}$ ‰ PDB	$\delta^{18}\text{O}$ ‰ PDB	Depth, m	Latitude	Longitude
WLIS 97-81	-3.56	-1.18	26	40.931	73.630
WLIS 97-75	-4.21	-1.11	24	40.878	73.747
W 40-02	-2.68	-0.80	30	40.982	73.419
W 42-01	-3.06	-0.76	24	41.012	73.472
A1G1	-2.89	-0.36	11	41.098	73.331
A2G1	-3.57	-1.06	17	41.089	73.324
A3G1	-3.36	-0.47	24	41.065	73.309
A6G2	-3.07	-0.67	16	40.961	73.251
B6G1	-1.56	0.10	22	41.033	73.025
C3G1	-2.32	-0.31	18	41.162	72.932
D4G1	-1.50	-0.73	20	41.166	72.847
E3G1	-1.27	-0.01	27	41.177	72.646
Buzas 116	-1.52	-0.28	28	41.020	73.248
Buzas 120	-3.08	-1.89	25	41.117	73.213
Buzas 14	-2.66	-0.74	10	40.897	73.630
Buzas 34	-1.60	-0.44	16	41.267	72.842

under the assumption that little or no carbon isotope fractionation takes place during calcification. We do not know the ‘vital effect’ of the calcification of *E. excavatum clavatum*, but this is not important for the present discussion because we are looking at differences in  $\delta^{13}\text{C}$  between individuals of the same species. The use of higher temperatures results in more negative calculated excess  $\delta^{13}\text{C}$  values.

The  $\delta^{13}\text{C}^*$  values show a strong east-west trend, with lighter  $\delta^{13}\text{C}^*$  data at the west end of LIS (Figure 8). The “salinity-corrected” light carbon isotope values in western LIS are thus probably caused by the oxidation of organic matter, which adds isotopically light carbon to the dissolved inorganic carbon pool (e.g., ANDERSON and ARTHUR, 1983; MCCORKLE and EMERSON, 1988; MCCORKLE *et al.*, 1990; CHANDLER *et al.*, 1996). *Elphidium excavatum clavatum* lives in the upper 1–4 cm of sediment (Buzas, 1965). The carbon isotopic composition of its test can thus be expected to reflect the isotopic value of dissolved carbonate in the pore waters of the upper part of the sediment column or in the overlying bottom waters.

In western LIS, the planktonic primary productivity is highest (SUN *et al.*, 1994), and the oxidized organic carbon could thus have been derived from local productivity. In that case, we would expect the dissolved bicarbonate in the surface waters (where the primary productivity occurs) to be enriched in  $\delta^{13}\text{C}$ . We have no evidence for this, because we have no data on samples shallower than 10 m, where we would expect the surface  $\delta^{13}\text{C}$  enrichment to occur (WELSH and ELLER, 1991). Alternatively, the oxidized organic carbon in western LIS could have been terrigenous material, natural or anthropogenic in origin. Additional data on the carbon isotopic composition of foraminifera from shallow water (5–10 m depth) are needed before we can decide whether the oxidized organic carbon was mainly derived from local productivity or from terrigenous sources.

The foraminifera in the 1961 samples time had slightly heavier  $\delta^{13}\text{C}$  values than in 1996/1997 (Figure 8), indicating that a smaller amount of organic matter was oxidized in LIS in the early 1960s than in the late 1990s. Our data suggest

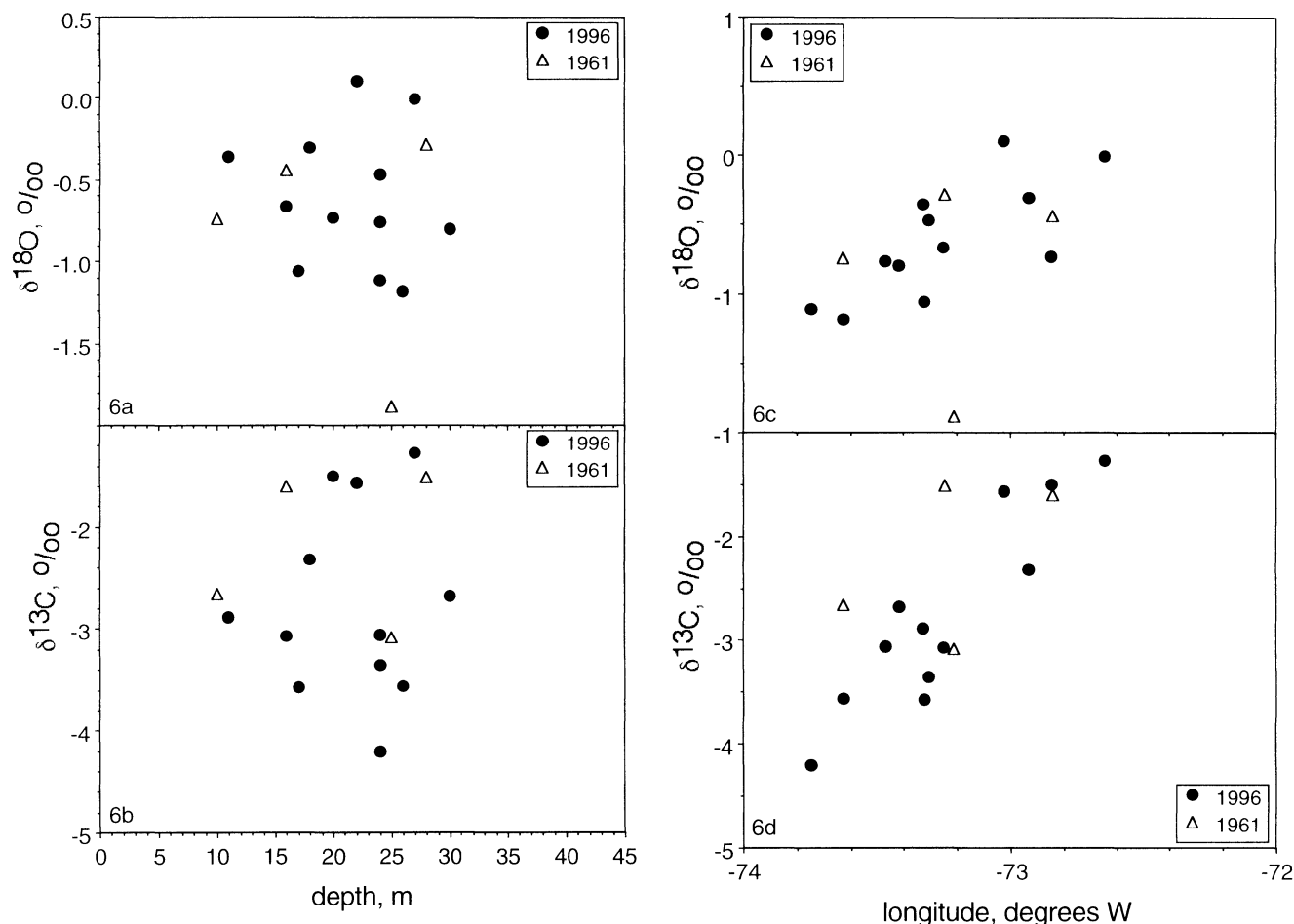


Figure 6. Carbon and oxygen isotope data for *Elphidium excavatum clavatum* from Long Island Sound.

not only that the amount of organic carbon that could be oxidized in LIS increased since the early 1960s, but also that the difference in the amount of organic matter from east to west in LIS increased, as indicated by the steeper slope of the correlation line between  $\delta^{13}\text{C}^*$  and longitude (Figure 8). Although based on few data points, these preliminary results are in agreement with the hypothesis that anoxic/hypoxic conditions in LIS did not occur in the early 1960s, in agreement with e.g., PARKER and O'REILLY (1991). If further research confirms our observations on the carbon isotopic composition of *E. excavatum clavatum*, the magnitude of  $\delta^{13}\text{C}^*$  in foraminiferal tests in LIS cores can be used to detect the occurrence and severity of anoxic periods of the past.

## DISCUSSION

The relative abundances of common benthic foraminifera in LIS have changed since the early 1960s. The changes include: (1) an increase in relative abundance of *Ammonia beccarii* in west LIS; (2) a decrease in relative abundance of *Eggerella advena* in the deeper parts of the whole Sound; (3) an increase in correlation between longitude and the relative

abundance of species, and a decrease in correlation with depth; and (4) a decrease in the already low species diversity. Our preliminary isotope data suggest that organic productivity in LIS has increased since the early 1960s, with a stronger increase in western LIS. Both faunal and isotope data thus indicate increased differences between eastern and western LIS since the early 1960s. The decrease in species diversity coeval with changes in relative species abundances strongly suggests that there has been an increase in environmental stress, from pollution, seasonal anoxia, or other causes (e.g., MURRAY, 1991).

These conclusions are preliminary. In order to interpret the isotopic data fully we must establish the isotope systematics of living *E. excavatum clavatum* and the magnitude of its possible deviation from isotopic equilibrium. In order to demonstrate unequivocally that the present benthic foraminiferal fauna in LIS differs from that in 1961, we need to establish which foraminifera were alive at the time of sampling (WALTON, 1952), and what the effects are of seasonal changes in foraminiferal distribution.

To understand the causes of benthic foraminiferal faunal

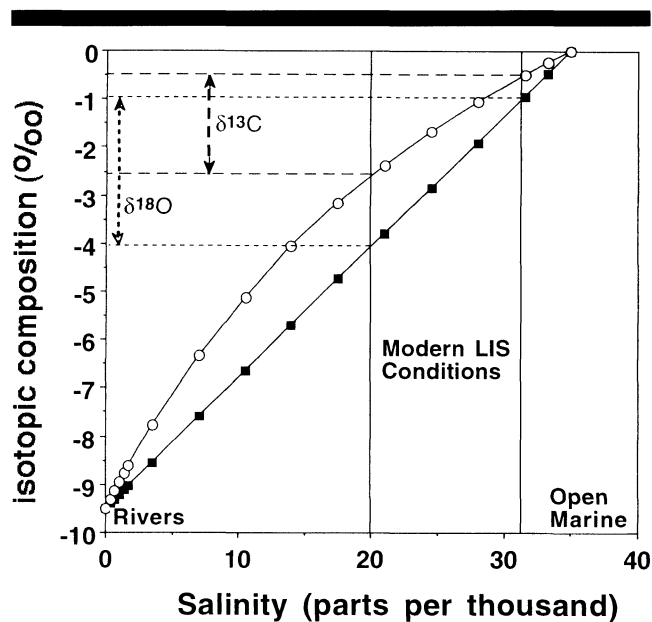


Figure 7. Estimated values of  $\delta^{18}\text{O}$  (filled squares) in LIS water and  $\delta^{13}\text{C}$  (open circles) in dissolved bicarbonate as a function of mixing between sea water and river water. The  $\delta^{18}\text{O}$  composition of biogenic carbonate reflects the water temperature during growth of the test, the isotopic composition of the water, and species-specific fractionation effects. Variations in the  $\delta^{18}\text{O}$  composition of a specific species of foraminifera in LIS depend on the global sea water isotopic composition (which varies as a function of global ice volume), the local mixing-ratio between seawater and continental run off, and bottom water temperature. Also shown are the  $\delta^{13}\text{C}$  values as they would be expected from mixing between sea water and river water only, without any effects of the oxidation of organic matter.

change over the last few decades in LIS, we must understand which environmental variables affect the abundance of the most common species. BUZAS (1965) suggested that the overall zonation with depth (with *Elphidium excavatum clavatum* most dominant at shallower levels) might be explained by the fact that foraminifera are selective feeders, and that their depth zonation is related to the distribution of the material upon which they feed. There appears to be no physicochemical factor in the water column to cause a foraminiferal depth zonation; LIS waters are thoroughly mixed every fall through spring, with stratification only present during the summer, and all the common species have been reported to survive low oxygen conditions (e.g., ALVE, 1995). Oxygen isotope values measured on *E. excavatum clavatum* show no correlation with depth (Figure 6).

*Elphidium excavatum* sequesters chloroplasts, mainly from diatoms, and these chloroplasts might actively photosynthesize within the foraminiferal protoplasm (LOPEZ, 1979; BERNHARD, 1996; BERNHARD and BOWSER, 1999). The lower limit of benthic microflora in LIS is about 11 m (BUZAS 1965); the highest abundance of this species might occur in the photic zone where the sequestered chloroplasts can perform photosynthesis.

The weak correlation between the relative abundance of *Buccella frigida* and longitude (Table 3) is probably caused by the occurrence of this species in the deeper parts of the

Table 5. Mixing end-members for modern LIS waters. The  $\delta^{18}\text{O}$  values are after ROZANSKI *et al.* (1993) and the  $\delta^{13}\text{C}$  data are after ANDERSON and ARTHUR (1983). *S* is the salinity in parts per mille; oxygen isotope values as compared to Standard Mean Ocean Water (SMOW).

	<i>S</i> , ‰	$\delta^{18}\text{O}$ , ‰	$\delta^{13}\text{C}$ , ‰	$\text{HCO}_3^-$
Ocean	35	0	0	140
River	0	-9.5	-9.5	70

depositional basins of LIS (KNEBEL *et al.*, 1999; KNEBEL and POPPE, this volume), where sediment is dominantly fine-grained and total organic carbon levels in the sediment are high (Figure 9). The species is less common in the eastern basins, where sediment erosion, non deposition, and bedload transport occur (KNEBEL *et al.*, 1999; KNEBEL and POPPE, this volume). This difference between eastern and western basins fully explains the weak correlation with longitude in the relative abundance of *Buccella frigida*. This species is probably a detritivore, which becomes dominant below depths where *E. excavatum* can dominate by using the sequestered chloroplasts, but only in regions where there is abundant fine sediment with organic carbon.

The decrease in relative abundance of *Elphidium excavatum clavatum* towards western LIS in the 1996/1997 data is linked to the strong increase in relative abundance of *A. beccarii*. Both *E. excavatum clavatum* and *A. beccarii* are able to survive extreme variability in oxygenation (MOODLEY and HESS 1992), in salinity, and in temperature (MURRAY, 1991), as well as high levels of pollution (e.g., ALVE, 1995). *E. excavatum* has a slightly smaller range in optimal temperature and salinity than *A. beccarii*, but our preliminary oxygen isotope data suggest that there were no significant changes in these parameters since 1961.

The east-west gradient in the abundance of *A. beccarii* in

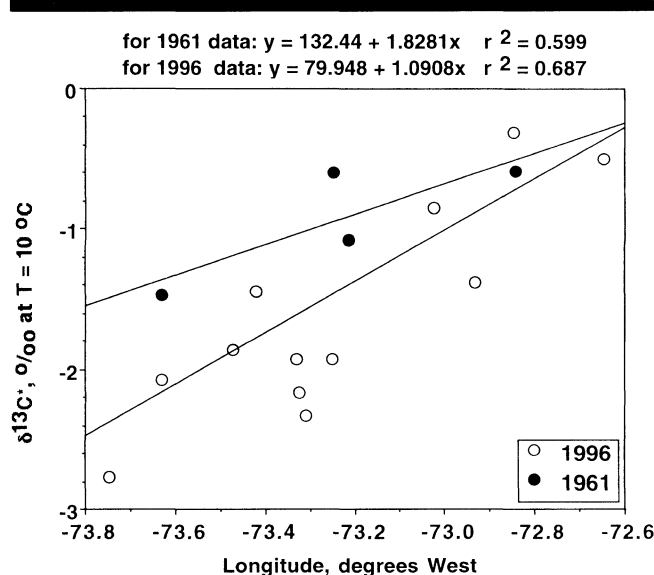


Figure 8. 'Excess'  $\delta^{13}\text{C}$  values for LIS grab samples at various longitudes.

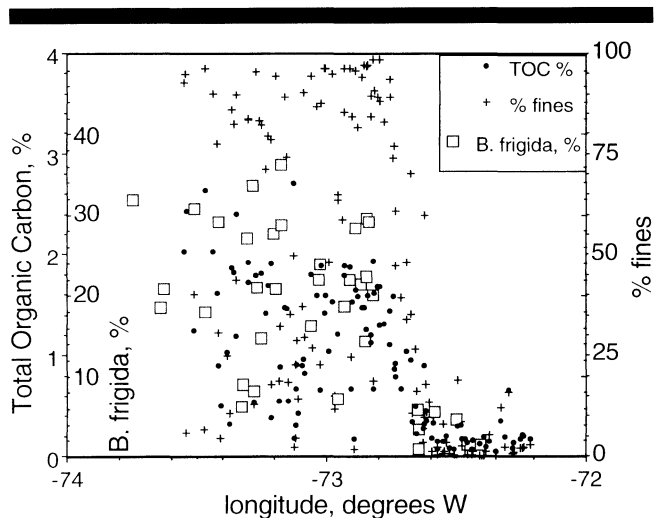


Figure 9. Comparison of the relative abundance of *Buccella frigida* (open squares) with the percentage of fine grained material ( $<63 \mu\text{m}$ ) in bulk sediment samples (crosses; POPPE and POLLONI, 1998) and the organic carbon content of the bulk sediment (filled circles; POPPE *et al.*, this volume).

1996/1997 suggests that its increase in relative abundance since 1961 is linked to an environmental variable which shows an east-west gradient. Metal pollution increases from the east to the west (*e.g.*, TURGEON and O'CONNOR, 1991; WOLFE *et al.*, 1991; WILLIAMS *et al.*, 1997; MECRAY and BUCHHOLTZ TEN BRINK, this volume; VAREKAMP *et al.*, this volume), and foraminiferal populations may be affected by metal pollution (YANKO *et al.*, 1998; ALVE and OLSGARD, 1999). Copper levels in LIS sediments (MECRAY and BUCHHOLTZ TEN BRINK, this volume) do not reach the high levels reported to affect foraminifera (ALVE and OLSGARD, 1999). Neither we, nor BUZAS (1965), nor PARKER (1952), observed high percentages of deformed tests, and metal pollution is therefore probably not implicated.

The seasonal episodes of anoxia in western LIS which have occurred since 1971 (PARKER and O'REILLY, 1991) might be implicated, although both *E. excavatum* and *A. beccarii* can survive very low oxygen concentrations (MOODLEY and HESS, 1992). A comparison of our relative abundance data with the data on abundance of the bacterial spore *Clostridium perfringens*, an indicator of sewage pollution (BUCHHOLTZ TEN BRINK *et al.*, this volume), shows that the highest abundance of *A. beccarii* occurs in samples with the highest sewage input (Figure 10). *Clostridium perfringens* has become more abundant over the last few decades (BUCHHOLTZ TEN BRINK *et al.*, this volume), and the increased abundance of *A. beccarii* thus might result from increased sewage inputs into western LIS.

The linkage between sewage input and abundance of *A. beccarii* could very well be indirect. In Chesapeake Bay, planktonic centric diatoms increased in relative abundance over the last few hundreds of years, while benthic diatoms decreased, reflecting increased turbidity and eutrophication (COOPER and BRUSH, 1991, 1993; COOPER, 1999a, b). In Nar-

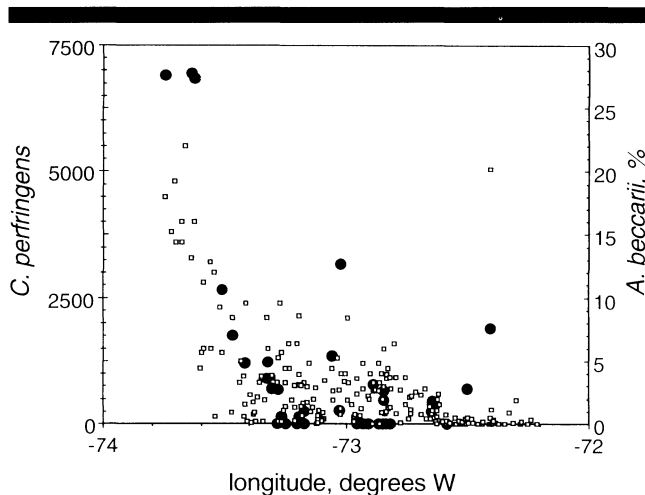


Figure 10. Comparison of the relative abundance of *Ammonia beccarii* (closed circles) with the absolute abundance of *Clostridium perfringens* spores (small open squares). *C. perfringens* data in numbers of spores per gram of dry sediment from BUCHHOLTZ TEN BRINK *et al.* (this volume).

ragansett Bay, just to the east of LIS, such eutrophication has also occurred (NIXON, 1997). Similar processes probably also occurred in LIS, but no record is available. Centric diatoms are very abundant in our samples, especially in western LIS, where algal blooms are most intense (SUN *et al.*, 1994). In addition, our carbon isotope data (Figure 8) indicate that the amount of organic matter that was oxidized in LIS increased, and that the difference in the amount of organic matter available from east to west LIS increased. Possibly, *A. beccarii* became more successful than *E. excavatum clavatum* under increasingly eutrophic conditions resulting from increased sewage input. Additional data on  $\delta^{13}\text{C}$  values of *E. excavatum clavatum* in BUZAS' (1965) material, and in  $\delta^{13}\text{C}$  values of *E. excavatum clavatum* and *A. beccarii* in our samples, might help to decide whether *A. beccarii* uses sewage directly or feeds upon algal production fueled by the nutrients in sewage influx.

It is more difficult to find an explanation for the strong decrease in relative abundance of *E. advena* since the 1960s. *Eggerella advena* appears to have varied in relative abundance in LIS over short time scales. BUZAS (1965) documented a variable relative abundance of this species between the years 1961 and 1962. The species was more abundant in 1961 and 1962 than it was in PARKER'S (1952) data. *Eggerella advena* has less tolerance for low salinity than the other LIS species (MURRAY, 1991). The year 1948, as well as the years 1961–1962, were drought years, and the diminished freshwater discharge could have resulted in higher-than-average salinities (KOPPELMAN *et al.*, 1976). Our preliminary oxygen isotopic data, however, suggest no apparent salinity differences between 1961 and 1996 (Figure 5).

*Eggerella advena* decreased in abundance over the full east-west extent of LIS, suggesting that this decrease can not be linked to an environmental variable with an east-west gradient, such as anoxia, pollution, or eutrophication. This species survives in even highly polluted and oxygen depleted

waters, such as close to sewage outfalls, where it is said to out-compete *E. excavatum* and to use refractory organic matter efficiently (e.g., ALVE, 1995; CULVER and BUZAS, 1995). We speculate that the relative abundance of *E. advena* might have been influenced by changes in the phytoplankton community of LIS. As suggested above, centric diatoms could have increased in abundance in LIS as a result of increased eutrophication. The carbon isotope data (Figure 8) indicate that local productivity might have increased over the full length of LIS since the early 1960s. If that was the case, the decrease in abundance of the detritivorous *E. advena* may have been caused by a change in the composition of the food supply, with a larger part of the total made up by fresh phytoplankton, less by more refractory (possibly terrigenous) organic carbon. More research is needed to establish what caused the abundance fluctuations of this species, which may turn out to be a sensitive environmental indicator species on short time scales.

### CONCLUSIONS

Benthic foraminifera (dead plus live) in LIS in 1996/1997 were low-diversity, and dominated by *Elphidium excavatum clavatum*, as they were in 1948 (PARKER, 1952) and 1961 (BUZAS, 1965). The second most common species in 1996 was *Buccella frigida*, also as in 1948 and 1961. The third most common species in 1948 and 1961, *Eggerella advena*, was rare in all samples in 1996. *Ammonia beccarii* was rare in 1948 and 1961, but formed up to 27% of the assemblage in western LIS in 1996/1997. Species diversity decreased since the 1960s, suggesting that environmental stress from hypoxia, pollution or other causes increased and caused the changes in species' relative abundance.

We can not explain the decrease in relative abundance of *E. advena* that occurred since the early 1960s over the full east-west length of LIS. Our preliminary data on oxygen isotopes in *E. excavatum clavatum* suggest that there were no significant changes in salinity over this time period, but our carbon isotope data suggest that the rate of oxidation of organic matter in LIS increased between the early 1960s and the late 1990s. Therefore, we speculate that possible changes in composition of the phytoplankton and/or in the total primary productivity may have caused the decline in abundance of *E. advena*. The increase in relative abundance of *A. beccarii* in western LIS since the early 1960s might have been caused by increased sewage input, either directly, or indirectly by algal blooms fueled by the nutrients in the sewage. Our carbon isotopic data indicate that more organic matter was oxidized in western LIS than further to the east, and that this gradient in oxidation of organic matter increased between the early 1960s and the late 1990s.

More research is needed to fully understand the isotope systematics of the LIS benthic foraminifera and the changes in benthic foraminiferal faunas over the last 35 years, but the observation that their assemblages changed over this time period suggests that they can be valuable environmental indicator species. The information obtained from stable isotope data is important in understanding which environmental changes could have caused these faunal changes.

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