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MORPHOLOGICAL DEFORMITIES OF BENTHIC FORAMINIFERAL TESTS IN RESPONSE TO POLLUTION BY HEAVY METALS: IMPLICATIONS FOR POLLUTION MONITORING

VALENTINA YANKO[1], MUNA AHMAD[2] AND MICHAEL KAMINSKI[2]

ABSTRACT

Live foraminiferal assemblages were studied along the Mediterranean coast of northern Israel. Two hundred seventeen benthic foraminiferal species were identified, 30% of which (65 species from 20 calcareous families and one agglutinated family) exhibited 11 distinct types of morphological deformities of their tests. These include: wrong coiling, aberrant chamber shape and size, poor development of the last whorl, twisted chamber arrangement, additional chambers, protuberances, multiple apertures, irregular keel, twinning, lateral asymmetry, and lack of sculpture. Morphological deformities are independent of latitude, taxonomic position, mode of life and feeding strategy of foraminifera. In small numbers (up to 1% of total live population) they can occur within the range of natural variability of a given species in given environmental conditions. However, several species display an increase in the proportion of deformed foraminifera in live assemblages that can be caused by low salinity (e.g., for *Adelosina cliarensis*) or by an increase in concentrations of heavy metals within the sediment. For example, an increase in deformed *Amphistegina lobifera* indicates an increase in Cd, *Cibicides advenum* - Cr, *Pseudotriloculina subgranulata* - Ti concentrations in sediments. The highest concentrations of Cd are attributed to coarse carbonate substrates adjacent to hard grounds, while Cr and Ti have a strong affinity to muddy-clay substrates enriched with organic matter. Test deformities of benthic foraminifera appear to be sensitive *in situ* monitors of marine pollution by heavy metals. However, the biochemical and crystallographic mechanisms controlling the development of test deformities remain to be studied by culture experiments under controlled conditions.

INTRODUCTION

Morphological deformities in fossil foraminiferal tests have been noted by researchers since the last century (e.g., Carpenter, 1856; Rhumbler, 1911). In recent years, reports of deformities have become increasingly more common. Many investigators have reported deformed foraminiferal tests in fossil assemblages (e.g., Bogdanowich, 1952, 1960; Pflum and Frerichs, 1976). Abundant references to deformities in larger foraminifera (e.g., Numulitidae and Fusulinidae can be found in the monograph of Tasnadi-Kubaska (1962). Documentation of deformities among smaller foraminifera is exemplified by description of deformed Miocene Miliolidae by Bogdanowich (1971). Most of the available data on deformities were summarized by Boltovskoy and Wright (1976), Haynes (1981), and Boltovskoy and others (1991), who noted that deformities may be attributed to mechanical damage or environmental stress, but concluded that there is no consensus as to the underlying causes of most deformities.

Deformities have been linked to a number of environmental factors, such as: (1) changes in temperature, reduced or elevated salinity, which also affects the size of foraminifera; (2) the lack or overabundance of food, which causes aberrant growth and affects the size of foraminifera; (3) the type of substrate, which affects the outline and shape of foraminiferal tests; (4) low dissolved oxygen content, which may create dwarfed, thin-walled, less ornamented and aberrant forms; (5) insufficient light, which may affect size of foraminifera; (6) and pollution in marine environments. Deformed tests of foraminifera have been reported from areas contaminated by heavy metals, domestic sewage, various chemicals and liquid hydrocarbons. See Boltovskoy and others (1991) and Alve (1995) for a detailed review of deformities and their probable reasons.

The percentage of deformed foraminifera has been reported to increase dramatically in polluted areas (e.g., Lidz, 1965) where foraminifera display a wide variety of deformities, including extreme compression, double apertures, twisted coiling, aberrant chamber shape, and protuberances. Yanko and others (1995), using sulfaflavine fluorescence and chlortetracycline fluorescence, distinguished morphological deformities caused by mechanical damage from those caused by pathological morphogenesis.

In 1991, the senior author set up a multidisciplinary field and experimental study of benthic foraminifera as proxy indicators of various pollution sources along the Israeli coast. The pilot project revealed that heavy metals have a deleterious effect upon benthic foraminifera, denoted by reduced population diversity and density, stunting of tests, the presence of deformed tests, and elevated concentrations of magnesium in deformed tests (Yanko and Kronfeld, 1992, 1993). Since 1991, subsidiary projects have provided new data on benthic foraminifera as indicators of pollution along the eastern Mediterranean margin. The purpose of this article is to present our data using qualitative and quantitative parameters of deformed foraminifera as proxy indicators of marine heavy metal pollution along the northern Mediterranean coast of Israel. As a working hypothesis, we proposed that selected biologically active heavy metals might damage the foraminiferal cytoskeleton and cause morphological deformities independent of taxonomy and mode of life. An increase in abundance of deformed tests among the species examined would then delineate areas with elevated concentrations of heavy metals in the sediments. Accordingly, the following objectives were set: 1) to examine the taxonomic

[1] Institute for Nature Conservation Research, Faculty of Life Sciences, Tel Aviv University, Ramat Aviv 69978, Tel Aviv, Israel.
[2] Department of Geological Science, University College London, Gower Street, London, UK WC1E 6BT

TABLE 1. Location and oceanographic parameters of bottom water at sampled stations (Israeli coast, Cruise AVI-1, May 11–13, 1993).

Station	Lat. N	Long. E	Depth, m	Salinity, ‰	T° C	pH	DO, mg/l^{-1}	Chl-α, μg/l^{-1}
1 HB	32°49.10′	35°01.35′	7.0	39.03	19.99	8.3	10.1	26.77
2 HB	32°49.71′	35°02.38′	7.0	38.92	20.41	8.3	10.1	29.01
3 HB	32°50.87′	35°03.25′	7.0	38.92	20.25	8.3	10.3	27.94
4 HB	32°51.8′	35°03.70′	7.0	38.94	19.99	8.3	10.2	13.53
5 HB	32°52.6′	35°04.00′	7.0	38.97	19.98	8.1	10.0	8.82
6 HB	32°53.83′	35°04.32′	7.0	38.94	20.27	8.2	7.6	4.12
7 HB	32°54.6′	35°04.5′	6.5	39.03	19.93	8.2	8.2	11.76
8 HB*	32°55.3′	35°03.25′	13.0	39.13	19.44	8.2	8.4	0.92
9 HB*	32°54.3′	35°03.2′	13.3	39.10	19.59	8.3	9.0	0.60
10 HB*	32°53′	35°02.81′	13.5	39.09	19.77	8.1	9.7	1.06
11 HB	32°52.15′	35°02.6′	12.5	39.09	19.71	8.1	9.5	1.24
12 HB	32°51.27′	35°02.16′	13.5	39.08	19.51	8.1	8.7	1.38
13 HB	32°50.02′	35°02.16′	12.0	16.62	19.49	8.2	9.2	35.00
14 HB	32°50.5′	35°00.2′	15.5	17.42	19.05	8.1	8.8	3.09
15 HB*	32°51.6′	35°03.25′	21.0	39.16	19.03	8.1	8.6	1.82
16 HB	32°52.5′	35°01.5′	19.0	39.14	19.16	8.2	9.0	1.18
17 HB	32°53.36′	35°07.76′	21.0	39.13	19.08	8.0	8.7	0.56
18 HB	32°54.6′	35°02.16′	19.0	39.15	19.00	8.1	8.5	0.37
19 HB*	32°55.3′	35°02.12′	18.0	39.15	19.03	8.0	9.0	0.36
20 HB	32°55.7′	35°01.05′	32.0	21.97	18.09	8.2	9.6	0.18
21 HB	32°55′	35°01.1′	30.0	39.15	17.94	8.1	9.9	
22 HB	32°52.75′	35°00.6′	29.0	39.18	17.96	8.2	9.9	
23 HB	32°52.85′	35°00.3′	27.0	39.15	18.29	8.2	9.7	
24 HB	32°51.93′	34°59.93′	25.0	39.13	19.08	8.0	9.7	
25 HB	32°50.9′	34°59.05′	16.0	17.45	19.07	8.1	8.8	
26 HB	32°51.3′	34°57.95′	19.0	39.14	19.16	8.2	9.0	
27 HB	32°52.3′	34°58.75′	26.0	39.15	18.29	8.2	9.7	
28 HB	32°53.25′	34°58.75′	29.0	39.18	17.96	8.2	9.9	
29 HB	32°54.1′	34°59.5′	30.0	39.15	17.94	8.1	9.9	
30 HB	32°55.4′	34°59.9′	32.0	39.21	17.92	8.1	9.9	
31 HB	32°56.03′	34°58.85′	32.0	39.21	17.93	8.1	9.8	
32 HB	32°56.5′	34°58.85′	34.0	39.15	17.84	8.2	9.9	
33 HB	32°55.75′	34°58.8′	32.0	39.20	18.22	8.1	9.9	
34 HB	32°54.5′	34°58.4′	30.0	39.16	17.96	8.1	9.9	
35 HB	32°53.7′	34°58.1′	28.0	39.15	18.26	8.1	9.8	
36 HB	32°52.7′	34°57.8′	28.0	39.15	18.26	8.1	9.9	
37 HB	32°51.7′	34°56.83′	27.0	39.15	18.29	8.2	9.7	
38 HB	32°52.13′	34°55.74′	31.5	39.16	17.96	8.1	9.9	
39 HB	32°52.24′	34°56.64′	34.0	39.15	17.84	8.2	9.9	
40 HB	32°54′	34°57′	33.5	39.13	17.77	8.2	10.0	
41 HB	32°54.9′	34°57.3′	33.0	24.09	17.74	8.1	10.0	0.24
42 HB	32°56.14′	34°57.61′	36.0	39.11	17.51	8.1	10.0	0.25
43 HB	32°56.8′	34°57.6′	32.0	39.12	17.62	8.2	10.0	0.22
44 HB	32°57.3′	34°56.8′	48.0	36.54	17.24	8.1	10.0	0.24
45 HB	32°56.5′	34°56.5′	47.0	39.11	17.34	8.2	10.0	0.20
46 HB	32°55.2′	34°56.1′	45.0	27.70	17.03	8.3	9.9	0.19
47 HB	32°54.35′	34°56.1′	43.0	39.12	17.29	8.3	10.2	0.59
48 HB	32°53.5′	34°55.3′	48.0	39.15	17.63	8.2	10.1	1.35
49 HB	32°52.4′	34°54.7′	44.0	39.13	17.56	8.3	9.4	0.14
50 HB	32°52.8′	34°53.6′	47.0	39.10	16.88	8.3	9.0	0.96
51 HB	32°54′	34°54.5′	67.0	39.08	16.84	8.27	9.1	0.61
52 HB	32°54.7′	34°54.7′	67.0	39.09	16.44	8.25	9.0	0.29
53 HB	32°55.6′	34°54.95′	66.0	39.09	16.43	8.2	9.1	0.16
54 HB	32°56.85′	34°55.4′	74.0	38.38	16.33	8.2	9.1	0.15
55 HB	32°57.5′	34°55.6′	72.0	39.10	16.29	8.28	9.2	0.16
56 HB	32°58′	34°54.6′	210.0	39.07	15.12	8.3	9.0	2.06
57 HB	32°57.3′	34°54.36′	200.0	36.40	15.4	8.2	9.3	0.16
58 HB	32°56′	34°54′	184.0	39.13	15.31	8.15	9.1	0.15
59 HB	32°54.28′	34°53.29′	82.0	39.13	16.08	8.3	10.2	0.14
60 HB	32°53.24′	32°52.65′	75.0	39.11	16.1	8.4	9.0	0.06
84 HB	32°54.34′	35°04.48′	6.0	38.75	20.70	8.3	9.0	
85 HB	32°53.09′	35°03.09′	6.5	38.72	21.31	8.4	15.3	65.88
86 HB	32°52.19′	34°03.83′	6.5	38.98	20.80	8.3	12.4	43.53
87 HB	32°48.52′	35°01.63′	3.0	39.30	20.90	8.2	12.3	55.29
61 AB	32°48.4′	34°52′	66.0	39.10	16.39	8.35	10.3	0.73
62 AB	32°48.3′	34°53.2′	54.0	39.20	16.52	8.3	10.3	
63 AB	32°48.25′	34°54.1′	47.0	39.10	16.88	8.3	10.2	
64 AB*	32°48.2′	34°55.25′	31.0	39.16	17.96	8.1	10.1	
65 AB*	32°48.1′	34°56.3′	14.0	39.09	19.77	8.1	9.9	
66 AB	32°43.7′	34°55.6′	20.0	39.13	19.08	8.0	9.9	

TABLE 1. Continued.

Station	Lat. N	Long. E	Depth, m	Salinity, ‰	T° C	pH	DO, mg/l^{-1}	Chl-α, μg/l^{-1}
67 AB	32°43.8′	34°54.6′	35.0	39.15	17.84	8.2	10.0	
68 AB	32°43.9′	34°53.3′	51.0	39.06	16.82	8.2	10.1	
69 AB	32°43.9′	34°52.5′	56.0	39.20	16.52	8.3	10.1	
70 AB	32°44′	34°51.3′	68.0	39.10	16.39	8.4	10.1	
71 AB	32°40.6′	34°50.7′	63.0	39.06	16.82	8.2	10.0	
72 AB	32°40.4′	34°52′	53.0	39.06	16.82	8.2	9.9	
73 AB*	32°40.35′	34°53.4′	37.0	39.11	17.51	8.1	10.1	
74 AB	32°40.25′	34°54.55′	24.0	39.13	19.08	8.0	9.9	
75 AB	32°40.35′	34°55.24′	7.0	39.11	19.99	8.1	9.9	0.24
76 AB	32°43.7′	34°56.4′	7.0	39.12	19.63	8.3	10.0	0.52
77 AB	32°47.1′	34°36.9′	6.0	39.14	20.09	8.2	10.0	0.58
78 AB	32°48.1′	34°56.9′	7.0	39.10	20.00	8.2	10.0	0.46
79 AB*	32°47.1′	34°55.7′	30.0	39.14	18.70	8.1	9.9	0.10
80 AB*	32°47.2′	34°54.4′	36.0	39.08	17.78	8.3	10.1	0.12
81 AB	32°47.3′	34°53.1′	57.0	39.06	16.66	8.2	10.3	0.06
82 AB	32°47.4′	34°51.8′	71.0	39.09	16.32	8.3	10.1	0.04
83 AB	32°47.8′	34°50.8′	102.0	39.13	16.19	8.3	10.1	0.04

HB = Haifa Bay Region; AB = Atlit Bay Region; * = hard ground.

affinities, mode of life, and morphotypes of living deformed foraminifera; 2) to examine the quantitative distributions of living deformed foraminifera; 3) to examine sizes of living deformed foraminifera and differentiate the different types of morphological deformities; 4) to examine responses of living deformed foraminifera to oceanographic (salinity, temperature, pH, dissolved oxygen and chlorophyll) and sedimentological (grain-size, $C_{org.}$, $CaCO_3$) parameters; 5) to examine a possible response of living deformed foraminifera to particular biologically important heavy metals and to determine indicator species of marine pollution.

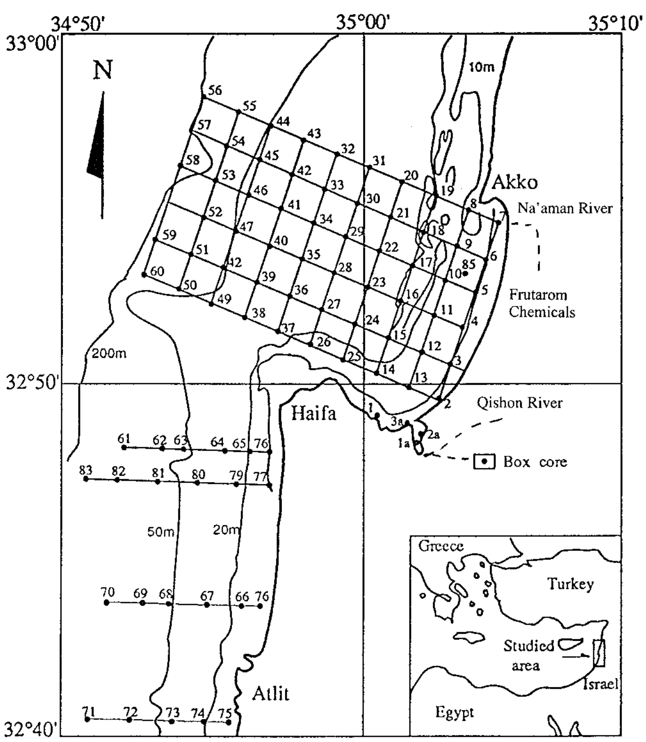

FIGURE 1. Location map of study area, Mediterranean northern Israeli coast.

DESCRIPTION OF STUDY AREA

The studied area includes the Mediterranean shelf of northern Israel (3–210 m water depth) from Akko to Atlit (Fig. 1). This area was subdivided into two regions: the Haifa Bay Region (HB) and the Atlit Bay Region (AB).

Haifa Bay is surrounded by the industrial center of Israel. There are several sources that may introduce industrial waste to the sea. Two small rivers, the Qishon and the Na'aman, are used as non-treated sewage canals. The Qishon River is located in the southern part of the bay, brings industrial wastes to Qishon Harbor and subsequently into the bay. Hornung and others (1989) noted that ratios among the trace metals in a sample station in the bay close to the harbor were similar to those in the Qishon River. Kronfeld and Navrot (1974) concluded that the trace metals were derived from the river. In the lower reaches of the Qishon River, there is a major oil refinery that also contaminates the river with an organic sludge.

The Na'aman River empties into the northern part of the bay, bringing mainly agricultural and domestic waste. Just south of the river mouth is a large fertilizer industry, ''Frutarom Chemicals'', that had been disposing its waste directly into the bay. At the same time, commercial fishing is carried out in the bay, and its vicinity and the beaches are important recreational and tourist sites.

There are no industrial activities on the coast adjacent to the AB, which is located on south of the HB. Natural environmental conditions of the AB are similar to those of the HB, and the same species of foraminifera are expected to be found. We therefore selected the AB as a control area because it is comparatively free of industrial pollution.

MATERIALS AND METHODS

Sampling was completed during May 1993 using the research vessel ''Shikmona'' (Israeli Oceanographic and Limnological Research Ltd.). Eighty-seven stations were sampled on a one mile grid: 64 stations in HB and 23 stations in AB. Sampling was most dense along the coast (0.5 mile grid) (Fig. 1).

TABLE 2. Heavy metals, C_{org} and $CaCO_3$ in sediments (Cruise AVI-1, May 1993, Israeli coast).

Station	$CaCO_3$, %	Cd, ppm	Pb, ppm	As, ppm	Cr, ppm	Cu, ppm	Zn, ppm	Co, ppm	Ni, ppm	Ti, ppm	V, ppm	C_{org}, %
1 HB	40.6	2.1	28.0		15.9	12.8	50.0					4.2
2 HB	11.3	0.6	6.3	2.0	7.3	2.0	16.5	4.7	2.5	30.1	2.8	1.6
3 HB	10.9	0.8	8.8		7.6	3.1	16.8					2.6
4 HB	15.6	0.8	4.9		7.1	2.6	14.8					1.5
5 HB	13.4	1.0	10.6		8.5	3.6	18.4					2.4
6 HB	25.8	1.9	23.0		9.6	5.6	24.9					5.2
7 HB	41.0	1.4	17.4		11.8	5.8	28.6					3.3
8 HB*	65.6											
9 HB*	55.0											
10 HB*	78.1											
11 HB	61.5	2.6	36.0		10.4	9.0	28.2					5.2
12 HB	93.8	4.0	64.0		10.6	12.2	32.0					6.0
13 HB	14.0	0.8	8.8	2.4	9.0	3.7	24.7	2.3	3.9	41.9	4.5	2.4
14 HB	14.0	1.2	12.0		6.5	4.5	12.0					2.1
15 HB*	0.5											
16 HB	84.5	2.7	39.6		10.4	8.4	14.2					6.4
17 HB	68.0	3.2	45.3	9.9	7.6	8.1	12.9	1.6	1.5	24.9	6.9	6.9
18 HB	77.3	3.0	40.0	14.9	8.1	8.0	10.6	1.9	1.9	27.6	9.3	7.8
19 HB*	71.1											
20 HB	61.5	0.9	10.3		15.1	10.0	31.7					4.4
21 HB	8.8	1.3	20.0	4.5	11.3	8.0	25.2	8.6	15.7	91.4	29.0	4.5
22 HB	9.4	1.3	20.0	4.8	12.0	9.7	27.5	8.2	15.3	465.0	29.1	4.2
23 HB	14.6	0.8	10.2		14.2	9.7	30.5					4.7
24 HB	18.5	2.2	13.8	3.1	15.9	10.2	25.6	1.8	5.5	100.0	8.4	2.9
25 HB	13.5	0.5	4.3	2.0	4.2	1.7	7.5	1.2	2.1	28.4	3.0	1.9
26 HB	88.5	3.2	47.8	8.7	6.8	7.0	8.4	0.8	1	11.1	3.2	6.6
27 HB	24.7	0.7	26.7	3.9	12.3	9.2	27.6	6.7	12.1	205.0	17.1	3.9
28 HB	13.4	1.1	11.0	3.2	12.9	7.4	23.1	6.6	11.8	257.0	19.3	4.4
29 HB	9.4	1.2	16.0	4.0	11.4	8.0	24.5	9.7	16.6	382.0	28.6	4.0
30 HB	8.3	0.8	7.7	3.6	13.2	8.6	27.6	9.8	16.1	354.0	27.5	3.8
31 HB	3.1	0.4	9.8		14.2	8.0	27.6					3.3
32 HB	8.3	1.1	13.0		8.3	5.6	18.6					3.2
33 HB	9.3	0.4	9.8		11.6	5.9	24.0					3.3
34 HB	14.6	2.2	19.0		20.8	18.0	53.0					4.6
35 HB	35.0	1.2	12.0		6.9	4.4	13.2					3.0
36 HB	14.6	0.9	16.0		7.2	6.4	13.0					2.4
37 HB	84.5	3.4	45.1	9.4	6.5	8.2	12.0	0.9	1.3	16.0	4.5	1.6
38 HB	89.6	3.1	45.7	7.6	7.0	7.8	11.0	1.6	2.2	26.5	6.4	6.2
39 HB	13.4	1.0	9.0		9.3	4.6	15.4					2.5
40 HB	99.0	2.0	96.0	17.1	9.6	12.2	17.0	5.0	4.7	63.1	17.6	6.9
41 HB	16.7	0.5	11.2	3.4	9.5	5.0	17.1	5.8	7.3	114.0	10.8	2.9
42 HB	5.2	1.3	9.0		13.6	7.8	23.8					3.5
43 HB	4.0	1.2	9.0		14.4	8.2	26.0					3.6
44 HB	0.5	1.1	13.0		20.8	16.6	35.1					6.0
45 HB	7.3	1.3	14.0		19.4	15.5	35.2					5.0
46 HB	34.0	1.3	12.0		15.1	9.3	24.1					4.6
47 HB	21.6	0.6	10.3		11.6	7.5	23.7					4.0
48 HB	33.0	1.4	13.0		15.2	9.8	23.8					4.6
49 HB	75.3	2.3	37.7	8.5	10.6	11.6	20.4	3.8	6.1	62.6	15.4	7.9
50 HB	71.1	1.6	73.0		56.6	35.6	75.0					7.9
51 HB	26.8	1.6	17.0		23.2	17.8	33.4					7.3
52 HB	12.5	0.8	19.1	4.4	19.2	17.7	32.9	8.7	15.5	141.0	31.4	8.1
53 HB	5.2	0.6	14.9		24.4	24.4	40.1					8.9
54 HB	3.5	0.5	11.1		18.1	16.9	38.8					7.1
55 HB	0.5	0.4	27.4		27.5	11.8	39.9					6.6
56 HB	0.5	0.3	24.2	4.4	32.2	29.2	52.9	13.4	25.9	230.0	49.3	9.0
57 HB	68.8	0.5	24.3	7.4	30.4	26.7	54.0	13.2	24.6	214.0	48.0	9.8
58 HB	4.2	0.5	19.1	6.0	22.8	20.5	44.8	11.6	20.6	230.0	38.6	8.5
59 HB	5.2	0.3	22.9	5.0	22.0	23.4	41.1	12.7	21.7	127.0	35.4	9.1
60 HB	27.0	1.0	18.8	3.6	17.9	17.3	37.7	7.4	12.9	112.0	24.2	7.9
84 HB	2.1	0.8	17.7		24.5	22.4	50.2					8.1
85 HB	18.6	0.9	10.2		8.2	4.2	17.8					1.7
86 HB	21.9	0.9	10.3		8.5	4.6	22.6					1.7
87 HB	13.4	0.7	7.4		6.0	2.5	12.8					1.4
61 AB	54	0.5	22.8	4.2	18.5	15.1	34.6	9.1	15.2	133.0	28.0	7.2
62 AB	60.4	0.5	21.4		19.2	15.4	35.8					6.3
63 AB	27.6	0.7	10.6	3.1	11.7	7.2	22.8	7.1	9.5	126.0	15.8	3.5
64 AB*	65.6											
65 AB*												
66 AB	4.2	0.3	3.9	1.9	3.2	0.7	3.8	0.8	1.1	20.7	2.2	0.9

TABLE 2. Continued.

Station	$CaCO_3$, %	Cd, ppm	Pb, ppm	As, ppm	Cr, ppm	Cu, ppm	Zn, ppm	Co, ppm	Ni, ppm	Ti, ppm	V, ppm	C_{org}, %
67 AB	17.7	0.7	6.7	4.1	4.6	1.2	6.4	2.1	1.9	28.5	3.6	1.5
68 AB	50.5	0.9	28.0	2.8	16.6	14.0	33.4	6.6	11.1	77.6	17.8	7.2
69 AB	41.7	0.7	12.8	5.6	13.2	12.9	30.7	6.1	9.7	76.4	17.6	5.7
70 AB	22.0	0.5	18.3	4.1	12.4	11.8	27.3	7.1	10.4	90.3	17.4	5.8
71 AB	6.3	0.2	13.0	3.9	14.2	14.7	27.5	9.7	13.3	144	24.9	7.0
72 AB	3.1	0.1	20.1	3.6	10.2	13.0	21.9	6.7	8.5	56.0	16.3	7.4
73 AB*												
74 AB	1.0	0.2	2.5		4.0	1.7	4.5					1.5
75 AB	17.7	0.3	2.3		2.9	0.7	2.7					0.6
76 AB	5.0	0.2	4.0	1.6	2.2	0.3	8.2	0.4	0.8	15.8	1.8	0.7
77 AB	5.2	0.2	7.9	0.9	2.9	0.9	8.3	0.1	0.4	8.2	1.1	0.9
78 AB	8.5	0.1	7.8	1.5	2.9	0.7	3.8	0.02	0.4	0.1	1.2	0.8
79 AB*	57.3											
80 AB*	84.4											
81 AB	66.7	0.6	25.0	4.2	19.5	20.4	43.8	10.2	17.3	99.8	34.3	7.6
82 AB	25.8	0.3	20.1	2.8	16.9	16.2	34.5	9.6	16.0	121.0	29.7	6.1
83 AB	15.6	0.6	28.6		27.9	27.2	53.7					9.1

HB = Haifa Bay; AB = Atlit Bay; * = hard ground.

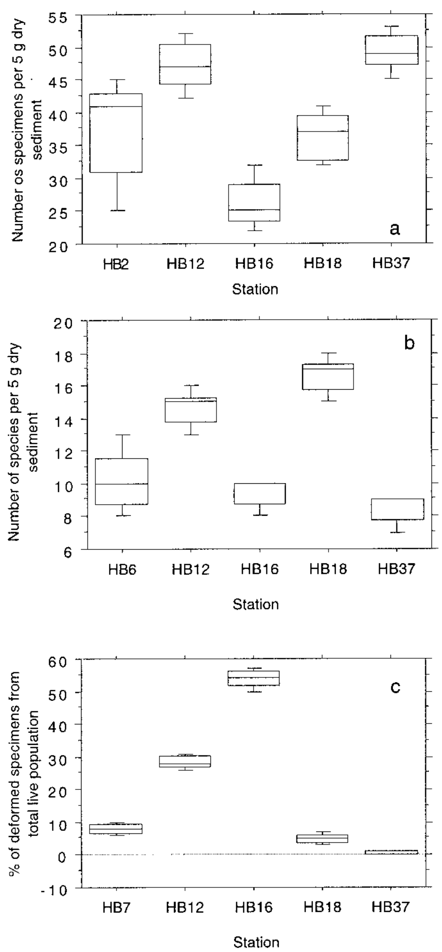

FIGURE 2. Box-plots of five replicate calculations of: (a) number of live specimens per 5 g of dry sediment, (b) number of species per 5 g of dry sediment, (c) percentage of deformed foraminifera from total live population.

At the majority of sampling stations, salinity and temperature of bottom water were measured using a Neil Brown Instruments Systems (STD) with a General Oceanic rosette and Niskin bottles. Dissolved oxygen (DO) and pH were measured in bottom water samples on board. Water samples from the euphotic zone were taken for chlorophyll-a analyses. A volume of 0.6–1.5 liters was filtered through GF/F filters. The seston was covered with aluminum foil, immediately frozen and subsequently processed in the laboratory within two weeks from the end of the cruise (Yanko, ed., 1995).

Sediment samples were taken from 85 stations. We could not obtain a sediment sample from station 73. Sampling was performed by box corer (BX 700 AI Compact Box Corer). Sediment samples were collected from the uppermost 2 cm of the sediment column with the aid of a wooden spatula. Each sample was subdivided for grain-size, organic carbon, calcium carbonate, heavy metals, and foraminiferal analyses. Samples for foraminiferal analysis were treated in 4% formalin solution with sea water buffered with 20 g of $Na_2B_4O_7$ per liter. Samples for organic carbon and heavy metals were frozen immediately after sampling.

Grain-size analysis of the sediment was performed according to methods described by Folk (1974). For each sediment sample the wetness was determined by using the formula:

$$w = (P_1 - P_2)/P_2 * 100\% \qquad (1)$$

w = wetness; P_1 = weight of wet sample; P_2 = weight of the sample after drying.

Organic matter was measured using the Loss on Ignition (LI) method (550°C, 1 hour). Organic carbon was calculated to be half of the organic matter (Vollenweider, 1969). The total carbonate content (expressed as percent $CaCO_3$) of the sediment was measured by titration.

Five heavy metals (Cd, Cr, Cu, Pb, Zn) were analyzed by Atomic Absorption Spectrophotometry (AAS) and another five (As, Co, Ni, Ti, V) by Induced Coupled Plasma (ICP) (Yanko, ed., 1995). The maximum, minimum, and median concentrations of each heavy metal were determined for HB

TABLE 3. Some statistical parameters for the Haifa Bay and Atlit Bay Regions (Cruise AVI-1, May 1993).

Parameter	Minimum		Maximum		Coefficient of variance		Median	
	HB	AB	HB	AB	HB	AB	HB	AB
Depth, m	3.00	6.00	210.00	102.00	1.10	0.61	29.00	37.00
Salinity, ‰	16.60	39.06	39.30	39.20	0.15	0.00	39.10	39.11
Temperature, °C	15.12	16.19	21.30	20.09	0.08	0.08	18.10	17.51
pH	8.00	8.00	8.40	8.40	0.01	0.01	8.20	8.20
DO, mg/l	8.00	10.00	15.00	10.00	0.10	0.00	10.00	10.00
Chl, $\mu g/l^{-1}$	0.10	0.04	66.00	0.70	1.98	0.95	0.60	0.15
$CaCO_3$, %	0.50	1.00	99.00	84.40	0.97	0.85	15.10	22.00
Cd, ppm	0.30	0.10	4.00	0.90	0.67	0.57	1.10	0.40
Pb, ppm	4.30	2.30	96.00	28.60	0.82	0.63	14.90	12.90
As, ppm	2.00	0.90	17.10	5.60	0.65	0.42	4.45	3.35
$C_{org.}$, %	1.00	1.00	10.00	9.00	0.48	0.63	4.00	6.00
Cr, ppm	4.20	2.20	56.60	27.90	0.61	0.68	11.60	12.05
Cu, ppm	1.70	0.30	35.60	27.20	0.68	0.85	8.20	12.35
Zn, ppm	7.50	2.70	75.00	53.70	0.50	0.70	24.70	25.05
Co, ppm	0.80	0.02	13.40	10.20	0.68	0.72	6.20	6.65
Ni, ppm	1.00	0.40	25.90	17.30	0.77	0.75	9.55	9.60
Ti, ppm	11.10	0.10	456.00	144.00	0.91	0.70	106.00	77.00
V, ppm	2.80	1.10	49.30	34.30	0.73	0.76	17.35	16.85
Number of specimens	25.00	31.00	339.00	569.00	0.57	0.55	130.00	315.00
Number of species	9.00	6.00	51.00	45.00	0.42	0.39	28.00	32.00
Shannon-Wiener Index	1.00	1.20	3.50	3.10	0.25	0.24	2.80	2.70
Number of deformed specimens	0.00	0.00	21.00	19.00	1.00	2.10	3.00	0.00
Deformed specimens, %	0.00	0.00	52.00	3.60	1.69	1.22	2.90	0.50
XL	0.00	0.00	190.00	225.00	1.46	1.53	12.00	20.00
L	0.00	14.00	205.00	311.00	0.84	1.19	45.00	40.00
M	0.00	0.00	204.00	412.00	0.73	0.73	49.00	213.00
S	0.00	0.00	36.00	97.00	1.25	0.90	4.00	25.00

XL, L, M, S = number of specimens in each size group of foraminifera: >05, 0.5–0.25, 0.25–0.125, 0.125–0.063 mm, respectively.

and AB separately, and enrichment factors were calculated using the formulas:

$$\epsilon_1 = C_{i\,max}/C_{median\text{-}Atlit} \quad (2)$$

$$\epsilon_2 = C_{i\,max}/C_{clark} \quad (3)$$

$$\epsilon_3 = C_{imax}/C_{carbonates} \quad (4)$$

ϵ_1 = local enrichment factor of a given heavy metal; ϵ_2 = global enrichment factor of a given heavy metal; ϵ_3 = regional (Mediterranean) enrichment factor of a given heavy metal; C_{imax} = the maximum concentration of a given metal found in a given study area; $C_{median\text{-}Atlit}$ = median concentration of a given metal in our control area, AB; C_{clark} = crustal average concentration (Clark value) of a given metal; $C_{carbonate}$ = average concentration of a given metal in Mediterranean carbonates.

For foraminiferal analysis in the laboratory, wet sediment samples equal to 5 g of dry sediment mass were subsampled. The amount of wet sediment needed was calculated by means of the wetness (water content) at each station using formula #1:

$$P_5 = (w/100+1)^{*}\ 5 \quad (5)$$

P_5 = wet sediment samples equal to 5 g of dry sediment mass.

The wet sample was stained with buffered rose Bengal for 48 hours, and sieved using 0.5, 0.250, 0.125, 0.063 mm mesh sizes. Foraminifera were picked by hand from each of these fractions and divided into four size-groups: XL (extra large ≥ 500 μm), L (large = 250–500 μm), M (medium = 125–250 μm), S (small = 63–125 μm). Live and dead foraminifera were studied separately, but only the live (stained) foraminifera are discussed here. Whenever possible, 300 specimens of live foraminifera from all fractions together were counted from the 5 g dry sediment sample. If the number of live specimens was small at a given station (<50 specimens per 5 g sediment) we repeated the foraminiferal analysis five times, using the same amount of sediment, and the mean of five replicates was used (Fig. 2).

All deformed tests, where present, were picked from each sample and morphologically examined using both the SEM (Tel Aviv University and University College London) and a standard binocular microscope.

Taxonomic identifications of foraminifera were carried out by the senior author by direct comparison with the original collections of d'Orbigny, Schlumberger, and Le Calvez in the Museum of Natural History, Paris. Other published data (Cimerman and Langer, 1991; Hottinger and others, 1993; Sgarella and Monsharmont Zei, 1993, among others) were used as well. The generic classification of Loeblich and Tappan (1987) has been used in this report. Representative collections of foraminifera from the eastern Mediterranean are now stored in the Museum of Natural History, Paris and at Tel Aviv University. A duplicate collection is stored at University College London. At present, 350 species are on file.

Statistical treatment

All measured parameters at the sampled stations were treated using the StatView statistical package. Regression analysis and the z-test were performed between the percentage of deformed tests (from the total number of live specimens in each sample), and other parameters such as: salinity, temperature, pH, DO, Chl-α (in sea-water), $CaCO_3$, C_{org}, heavy metals (in sediments), the number of foraminiferal species, the number of specimens, and the Shannon-Wiener Index. Correlation in this study was considered strong and meaningful if $R \geq 0.4$ ($P < 0.0001$), at greater than the 95% confidence level. If $R \geq 0.3$ ($P < 0.0006$) we consider such correlation as a trend.

In statistical analyses we used the percentage of deformed live specimens from the total number of live specimens at each station (P_d), and percentage of deformed live specimens of a given species from the total number of live deformed specimens at each station (P_{ds})

$$P_d = N_d/N_t*100 \quad (6)$$

$$P_{ds} = N_{ds}/N_d*100 \quad (7)$$

N_d = number of deformed live specimens per 5 g sediment sample; N_{ds} = number of deformed live specimens of a given species per 5 g sediment sample; N_t = total number (deformed + non-deformed) of live specimens per 5 g dry sediment sample.

RESULTS

1. Oceanographic, Sedimentological and Geochemical Parameters

Most of the measured oceanographic, sedimentological and geochemical parameters and their main statistical characteristics are listed in Tables 1–3. The water depth varies from 3 to 210 m in HB and from 6 to 102 m in AB; the median depth is 29 and 37 m, respectively. The temperature varies between 15.1° C and 21.3° C in HB, and between 16.2° C and 20.1° C in AB; the median temperature is 18.1° C and 17.5° C, respectively. There is a strong negative correlation between the bottom water temperature and depth (Table 4). The salinity ranged between 16.6 to 39.3‰ in HB, and from 39.06 to 39.2‰ in AB; the median salinity is 39.3 and 39.11, respectively. There is no difference in minimum (8.0), maximum (8.4) and median (8.2) pH value in both regions. Dissolved oxygen, DO, varies between 8 mg/l and 15 mg/l (median 10.0 mg/l) in HB. This parameter is almost constant (10 mg/l) in AB.

There is a huge difference in the maximum concentration of Chlorophyll-α (Chl-α) in sea water. It ranged from 0.1 to 66 mg/l^{-1} (median 0.6 mg/l^{-1}) in HB, and from 0.0 to 0.7 mg/l^{-1} (median 0.15 mg/l^{-1}) in AB. The concentration of $CaCO_3$ in sediments of HB varied from 0.5 to 99%, and in AB from 1 to 84.8%. The median concentration is 15.1 and 22%, respectively. There is a strong positive correlation between $CaCO_3$ and coarse sediments (Table 4). The concentration of C_{org} in sediments ranged between 1 and 10% in HB, and between 1 and 9% in AB. The median concentration is 4 and 6%, respectively. The amount of C_{org} in sediments has strong inverse correlation with temperature of bottom water but a positive correlation with depth and amount of silt-clay fraction (Table 4) (Yanko, ed., 1995; Yanko and Kravchuk, 1996).

In HB the heavy metal concentrations (ppm) varied as follows: Cd—between 0.3 and 4 (median 1.1), Pb—between 4.3 and 96 (median 14.9), As—between 2 and 17.1 (median 4.45), Cr—between 4.2 and 56.6 (median 11.6), Cu 1.7–35.6 (median 8.2), Zn—between 7.5 and 75 (median 24.7), Co—between 0.8 and 13.4 (median 6.2), Ni—between 1 and 25.9 (median 9.55), V—2.8 and 49.3 (median 17.35), Ti—11.1 and 456.0 (median 106.0). In AB the heavy metal concentrations (ppm) displayed the following ranges: Cd—between 0.1 and 0.9 (median 0.4), Pb—between 2.3–28.6 (me-

Table 4. Coefficient of linear correlation (R) between measured oceanographic, sedimentological and geochemical parameters in the Haifa Bay and Atlit Bay Regions. Only figures $r \geq 0.4$ ($P < 0.0001$), greater than at 95% confidence level are presented.

	Parameter	R	P-Value
	Depth, Temperature	−.812	<.0001
	Depth, Silt-clay	.525	<.0001
	Depth, Corg.	.675	<.0001
	DO, Corg.	−.489	<.0001
	Temperature, Silt-clay	−.427	<.0001
	Temperature, Corg.	−.687	<.0001
First geochemical association	Cd, As	.711	<.0001
	Cd, Pb	.655	<.0001
	Pb, As	.886	<.0001
	$CaCO_3$, As	.778	<.0001
	$CaCO_3$, Cd	.712	<.0001
	$CaCO_3$, Pb	.777	<.0001
	$CaCO_3$, Coarse sediment	.675	<.0001
	Cd, Coarse sediment	.693	<.0001
	Pb, Coarse sediment	.667	<.0001
	As, Coarse sediment	.732	<.0001
Second geochemical association	Co, Ni	.975	<.0001
	Co, Ti	.677	<.0001
	Co, V	.956	<.0001
	Cr, Co	.868	<.0001
	Cr, Cu	.914	<.0001
	Cr, Ni	.906	<.0001
	Cr, V	.914	<.0001
	Cr, Zn	.921	<.0001
	Cu, Co	.821	<.0001
	Cu, Ni	.843	<.0001
	Cu, V	.887	<.0001
	Cu, Zn	.900	<.0001
	Ni, Ti	.708	<.0001
	Ni, V	.979	<.0001
	Ti, V	.669	<.0001
	Zn, Co	.901	<.0001
	Zn, Ni	.928	<.0001
	Zn, V	.917	<.0001
	Corg., Co	.645	<.0001
	Corg., Cr	.696	<.0001
	Corg., Cu	.856	<.0001
	Corg., Ni	.630	<.0001
	Corg., Pb	−.503	<.0001
	Corg., V	.715	<.0001
	Corg., Zn	.683	<.0001
	Cr, Silt-clay	.480	<.0001
	Cu, Silt-clay	.478	<.0001
	Co, Coarse sediment	−.603	.0001
	Depth, Co	.733	<.0001
	Depth, Cr	.611	<.0001
	Depth, Cu	.705	<.0001
	Depth, Ni	.770	<.0001
	Depth, V	805	<.0001
	Depth, Zn	.575	<.0001
	Temperature, Co	−.829	<.0001
	Temperature, Cr	−.600	<.0001
	Temperature, Cu	−.682	<.0001
	Temperature, Ni	−.819	<.0001
	Temperature, V	−.838	<.0001
	Temperature, Zn	−.539	<.0001

TABLE 5. Enrichment factors of heavy metals of the first and the second geochemical association.

Geochemical association	Heavy metal	$C_{clarke,}$ ppm (Beus, 1975)	$C_{carbonates}$, ppm (Drever, 1982)	ϵ_1		ϵ_2		ϵ_3	
				HB	AB	HB	AB	HB	AB
First	Cd	0.19	0.03	10.00	2.20	21.00	4.70	133.30	30.00
	As	1.90	1.00	7.40	2.20	17.20	1.80	17.1	5.60
	Pb	9.00	9.00	5.10	1.10	10.70	3.00	10.7	3.20
Second	Cr	120.00		4.70	2.30	0.50	0.20		
	Cu	65.00		3.00	2.20	0.50	0.40		
	Zn	87.00		3.00	2.10	0.90	0.60		
	Co	34.00		2.00	1.50	0.40	0.30		
	Ni	95.00		2.70	1.80	0.30	0.20		
	V	190.00		3.00	2.00	0.30	0.20		
	Ti	3300.00		5.90	1.90	0.14	0.04		

dian 12.9), As—between 0.9 and 5.6 (median 3.35), Cr—between 2.2 and 27.9 (median 12.05), Cu—0.3–27.2 (median 12.35), Zn—between 2.7 and 53.7 (median 25.02), Co—between 0.02 and 10.2 (median 6.65), Ni—between 0.4 and 17.3 (median 9.6), V—1.1 and 34.3 (median 16.85), Ti—0.1 and 144.0 (median 77.0).

We recognized two geochemical associations of heavy metals (Yanko, ed., 1996; Yanko and Kravchuk, 1996). The first geochemical association (Cd, Pb, As) is strongly related to the $CaCO_3$ content and coarse sediment fraction. The second geochemical association (Zn, Cu, Cr, Co, Ni, Ti, V) is strongly related to C_{org} and the silt-clay sediment fraction (Table 4).

The local, regional and global enrichment factors (ϵ_1, ϵ_2, ϵ_3), are given in Table 5. HB is characterized by strongly elevated concentrations of all heavy metals from the first geochemical association compared with their local background values, regional values in Mediterranean carbonates and crustal averages.

2. FAUNAL PARAMETERS AND THE OCCURRENCE OF DEFORMED FORAMINIFERA

Selected foraminiferal parameters are listed in Table 6. Two hundred nineteen live foraminiferal species were identified in the study area (Yanko, ed., 1995). In spite of the fact that the number of sampled stations in HB (63 stations) is almost three times higher than in AB (22 stations), the total number of live foraminifera at all sampled stations is only slightly higher in HB (8,712 specimens) than in AB (6,338 specimens) (Fig. 3a).

The median number of live specimens in HB is 130 specimens. This is two and half times less than that of AB (315 specimens). There is no significant difference in the median value of the number of species as well as the Shannon-Wiener Index. The former ranged between 28 species in HB and 32 species in AB. The latter varied between 2.8 and 2.7, respectively (Table 3).

Deformed specimens were observed among 65 species, and occurred at 80% of the stations in HB and at 45% of stations in AB (Table 7). The percentage of live, deformed foraminifera, calculated from the total live population (P_d) recovered from all stations, is 3.5% in HB and 0.7% in AB (Fig. 3b). The median P_d is 2.9% in HB and 0.5% in AB (Table 3). The total range of observed P_d values varies from 0 to 52% in HB (Table 3, Fig. 4a), and 0–4% in AB (Table 3, Fig. 4b). The highest P_d (26–52%) occurred at Stations #12 and 16 (coastal zone of HB) where the Cd concentration in sediments was 4.0 and 2.7 ppm, respectively. The lowest concentrations of deformed tests (0.0%) were recorded at twenty stations, mostly located in AB (Table 2).

A strong positive correlation (R = 0.5) was discovered between P_d and Cd content in sediments of the HB region (Fig. 5a, b). There is a negative trend (R = −0.3) between P_d and the number of live specimens in HB (Fig. 5c). This

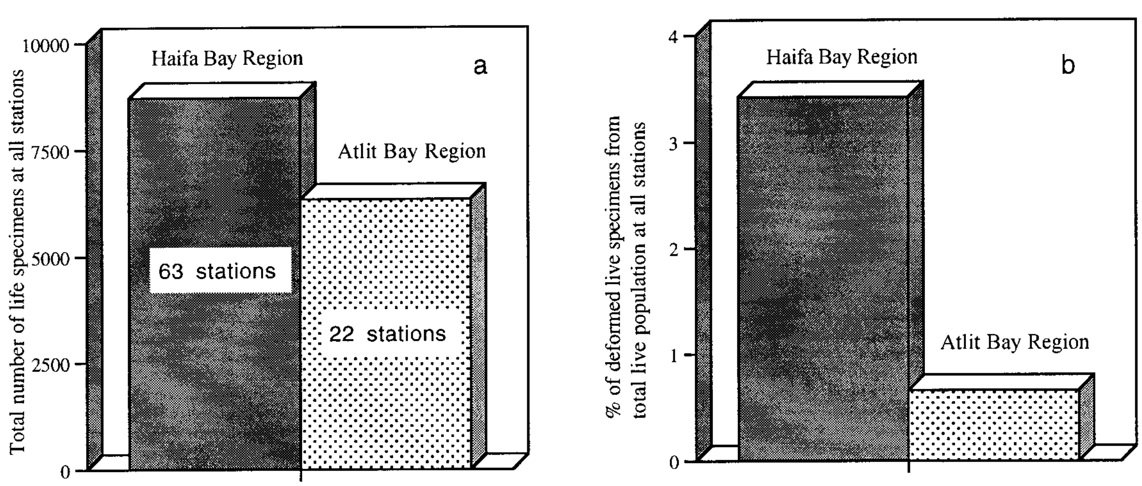

FIGURE 3. Total number of live foraminifera in Haifa Bay and Atlit Bay Regions: (a) non-deformed + deformed, (b) deformed.

TABLE 6. Selected foraminiferal parameters at sampled stations (Cruise AVI-1, May 1993, Israeli coast).

Station	Number of species	Number of specimens per 5 g dry sediment	Shannon-Wiener Index	Deformed tests, % from total number of specimens
1 HB	19	103	2.1	1.9
2 HB	10	41	1.8	0.0
3 HB	12	85	1.5	4.7
4 HB	13	55	1.5	1.8
5 HB	10	99	1.0	3.0
6 HB	16	120	1.8	10.0
7 HB	15	41	2.2	7.3
8 HB*	29	110	2.9	5.5
9 HB*	27	151	2.8	1.3
10 HB*	19	135	2.0	2.2
11 HB	24	183	2.3	11.2
12 HB	15	45	2.0	26.7
13 HB	25	80	2.7	23.8
14 HB	27	89	2.7	12.4
15 HB*	29	79	2.9	10.2
16 HB	10	25	1.5	52.0
17 HB	10	70	1.0	21.4
18 HB	17	33	2.5	3.0
19 HB*	26	266	1.8	3.8
20 HB	31	153	3.1	2.0
21 HB	26	277	2.8	3.2
22 HB	44	179	3.3	4.5
23 HB	24	78	2.8	3.8
24 HB	27	139	2.9	9.4
25 HB	22	89	2.6	3.4
26 HB	33	68	3.3	2.9
27 HB	40	219	3.3	1.8
28 HB	30	106	3.2	4.7
29 HB	39	161	3.3	3.7
30 HB	41	208	3.1	4.3
31 HB	38	264	3.0	3.8
32 HB	36	169	3.1	2.4
33 HB	31	159	3.0	3.1
34 HB	12	103	1.6	4.8
35 HB	32	89	3.0	3.4
36 HB	36	105	3.3	1.9
37 HB	9	49	1.4	0.0
38 HB	43	339	2.9	2.1
39 HB	29	136	2.8	0.7
40 HB	22	54	2.8	1.9
41 HB	40	183	3.4	4.4
42 HB	33	195	2.1	3.2
43 HB	37	233	3.0	4.3
44 HB	14	45	2.4	0.0
45 HB	46	172	3.4	1.2
46 HB	34	229	2.8	1.7
47 HB	28	137	2.9	0.0
48 HB	30	129	3.1	0.0
49 HB	44	308	3.0	4.5
50 HB	38	152	3.3	2.0
51 HB	38	201	3.1	0.0
52 HB	31	147	2.8	1.4
53 HB	30	136	2.6	0.7
54 HB	29	102	3.0	1.0
55 HB	26	131	2.9	0.0
56 HB	21	53	2.7	0.0
57 HB	29	102	3.0	0.0
58 HB	48	158	3.5	0.0
59 HB	20	93	2.1	0.0
60 HB	51	331	3.2	4.2
84 HB		no foraminifera		
85 HB	15	107	1.7	0.9
86 HB	18	180	1.7	1.1
87 HB	18	277	1.6	0.0
61 AB	37	574	2.8	3.3
62 AB	36	291	2.7	2.4
63 AB	42	388	3.1	1.0
64 AB*	28	92	2.7	1.1
65 AB*	17	373	1.2	0.5
66 AB	32	255	2.5	0.0
67 AB	32	207	2.8	1.5
68 AB	33	404	3.0	0.0
69 AB	37	354	3.1	1.1
70 AB	39	377	3.0	0.0
71 AB	32	343	2.9	0.0
72 AB	40	362	3.1	0.0
73 AB*		no sample		
74 AB	29	305	2.7	0.0
75 AB	6	31	1.3	0.0
76 AB	36	465	2.7	0.0
77 AB	33	392	2.1	0.0
78 AB	26	315	2.6	0.6
79 AB*	26	169	2.2	1.2
80 AB*	15	38	2.3	0.0
81 AB	21	115	2.3	0.0
82 AB	24	117	2.4	1.7
83 AB	45	376	1.2	0.0

TABLE 6. Continued.

trend becomes a strong negative correlation ($R = -0.6$), if the data from Qishon Harbour and its entrance, where the Cd content in sediments was 40.0 ppm (Yanko, 1994), are included in the regression analysis (Fig. 5d). No correlation was found between P_d and the other measured environmental and foraminiferal parameters.

We combined all species that exhibit morphological deformities into four groups based on their distributional patterns (Table 8). The first group consists of 3 species that display deformities at more than 10 stations. The larger foraminifer *Amphistegina lobifera* displays the highest number of deformed specimens (15 specimens per 5 g dry sediment). The second group includes 17 species that display deformities at 4–8 stations. The highest numbers of deformed specimens (6 specimens per 5 g dry sediment) in this group are displayed by *Pararotalia spinigera* and *Ammonia tepida*. The third group includes 15 species that display deformities at 3 stations. The highest number of deformed specimens (6 specimens per 5 g dry sediment) is observed in *Adelosina inticata*. The fourth group contains 30 species. Most of these exhibit morphological deformities at only one station. This group was excluded from the further analysis.

Several species from the first and the second groups exhibit strong positive correlation ($R = 0.5$–0.7) with Cd (*Amphistegina lobifera*), Cr (*Cibicides advenum*), and Ti (*Pseudotriloculina subgranulata*) content in sediments (Fig. 6a–c). There is also strong negative correlation ($R = -0.6$) between P_d of *Adelosina cliarensis* and salinity (Fig. 6d).

3. SIZE-DISTRIBUTION OF DEFORMED FORAMINIFERA AND TYPES OF MORPHOLOGICAL DEFORMITIES

In the HB region most of the live foraminifera belong to the L and M size groups, while in the AB region they are dominated by the M size group (Fig. 7a). Among deformed

TABLE 7. Taxonomic content and some data on their distribution along northern Israeli shelf.

No	Species	Count	Min	Max	CV	Group
1	*Amphistegina lobifera* Larsen	10	1	15	0.8	
2	*Adelosina cliarensis* (Heron-Allen et Earland)	15	1	5	0.7	I
3	*Triloculina marioni* Schlumberger	16	1	3	0.5	
4	*Pararotalia spinigera* (Le Calvez)	7	1	6	0.9	
5	*Cibicides advenum* (d'Orbigny)	4	1	4	0.9	
6	*Ammonia tepida* (Cushman)	6	1	6	0.8	
7	*Pseudotriloculina subgranulata* (Cushman)	8	1	4	0.7	
8	*Heterostegina depressa* d'Orbigny	4	1	3	0.7	
9	*Adelosina pulchella* d'Orbigny	5	1	3	0.6	
10	*Triloculina schreiberiana* d'Orbigny	8	1	2	0.4	
11	*Adelosina mediterranensis* (Le Calvez, J. et Y.)	8	1	2	0.4	
12	*Elphidium crispum* (Linne)	7	1	2	0.4	II
13	*Miliolinella subrotunda* Montagu	5	1	2	0.4	
14	*Peneroplis planatus* (Fichtel and Moll)	4	1	2	0.4	
15	*Quinqueloculina disparalis* d'Orbigny	4	1	2	0.4	
16	*Triloculina earlandi* Cushman	7	1	1	0.0	
17	*Challengerella bradyi* Billman, Hottinger and Oesterle	5	1	1	0.0	
18	*Asterigerinata mamilla* (Williamson)	4	1	1	0.0	
19	*Spiroloculina antillarum* d'Orbigny	4	1	1	0.0	
20	*Eggerelloides advenus* (Cushman)	4	1	1	0.0	
21	*Adelosina intricata* (Terquem)	3	1	6	1.1	
22	*Eponides concameratus* (Williamson)	3	1	5	1.0	
23	*Quinqueloculina phoenicia* Colom	2	1	5	0.9	
24	*Cycloforina colomi* (Le Calvez, J. and Y.)	2	1	2	0.5	
25	*Hauerina diversa* Cushman	3	1	2	0.4	
26	*Haynesina depressula* (Walker et Jacob)	3	1	2	0.4	
27	*Rosalina macropora* (Hofker)	3	1	2	0.4	
28	*Lobatula lobatula* (Walker et Jacob)	3	1	2	0.4	III
29	*Elphidium* sp. 3	3	1	2	0.4	
30	*Vertebralina striata* d'Orbigny	3	1	2	0.4	
31	*Pseudotriloculina oblonga* (Montagu)	3	2	3	0.3	
32	*Cycloforina* sp. 2	3	1	1	0.0	
33	*Edentostomina cultrata* (Brady)	3	1	1	0.0	
34	*Elphidium macellum* (Fichtel et Moll)	3	1	1	0.0	
35	*Spiroloculina rostrata* Reuss	3	1	1	0.0	
36	*Nodophthalmidium antillarum* (Cushman)	2	1	1	0.0	
37	*Ammonia compacta* Hofker	2	1	1	0.0	
38	*Nummoloculina* sp.	2	1	1	0.0	
39	*Quinqueloculina lamarckiana* d'Orbigny	2	1	1	0.0	
40	*Quinqueloculina stelligera* Schlumberger	2	1	1	0.0	
41	*Lenticulina cultrata* (Montfort)	2	1	1	0.0	
42	*Quinqueloculina undosa* Karrer	2	1	1	0.0	
43	*Sorites variabilis* Lacroix	1	7	7	0.0	
44	*Quinqueloculina elegans* (d'Orbigny)	1	4	4	0.0	
45	*Quinqueloculina williamsoni* Le Calvez	1	3	3	0.0	
46	*Spiroloculina corrugata* Cushman and Todd	1	3	3	0.0	
47	*Triloculina plicata* Terquem	1	2	2	0.0	
48	*Lachlanella undulata* (d'Orbigny)	1	1	1	0.0	
49	*Polymorphina* sp. 4	1	1	1	0.0	
50	*Quinqueloculina* sp. 4	1	1	1	0.0	IV
51	*Spiroloculina excavata* d'Orbigny	1	1	1	0.0	
52	*Miliolinella elongata* Kruit	1	1	1	0.0	
53	*Loxostomina limbata* (Brady) *robusta* (Said)	1	1	1	0.0	
54	*Nonionella atlantica* Cushman	1	1	1	0.0	
55	*Quinqueloculina viennensis* Le Calvez	1	1	1	0.0	
56	*Spiroloculina communis* Cushman and Todd	1	1	1	0.0	
57	*Peneroplis pertusus* (Forskal)	1	1	1	0.0	
58	*Sigmoilinita costata* (Schlumberger)	1	1	1	0.0	
59	*Ammonia parkinsoniana* (d'Orbigny)	1	1	1	0.0	
60	*Quinqueloculina seminula* (Linne)	1	1	1	0.0	
61	*Monalysidium acicularis* (Batsch)	1	1	1	0.0	
62	*Siphonina reticulata* (Czjzek)	1	1	1	0.0	
63	*Sorites orbiculus* Ehrenberg	1	1	1	0.0	
64	*Elphidium ponticum* (Dolgopolskaja and Pauli)	1	1	1	0.0	
65	*Pseudoeponides falsobeccarii* Rouvillois	1	1	1	0.0	

Count = number of stations with deformed specimens of a given species; Min = smallest number of deformed specimens at stations where deformed tests are present; Max = largest number of deformed specimens at stations where deformed tests are present; CV = Coefficient of Variation.

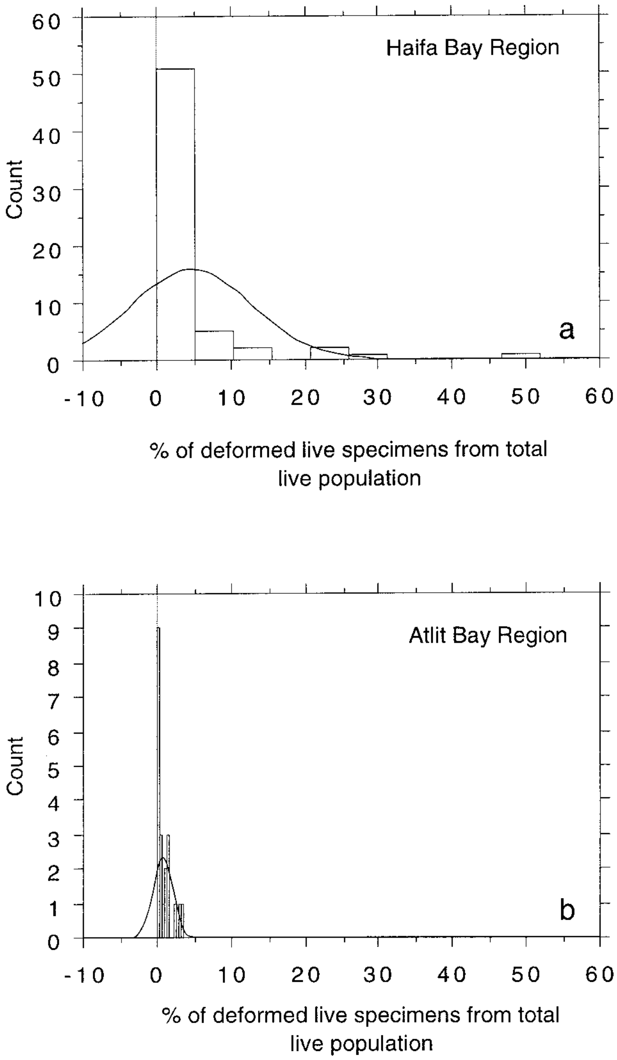

FIGURE 4. Histograms of distribution of live deformed foraminifera in Haifa Bay and Atlit Bay Regions.

foraminifera the XL and L size groups are dominant in both regions (Fig. 7b).

The main types of test deformities are listed in Table 8 and shown in Plates 1–7. They vary from mildly deformed (e.g., Pl. 1, figs. 7, 8, 11, 12) to severely deformed (e.g., Pl. 1, figs. 1–5. Mild deformities were found in different ontogenetic stages, from the earliest juvenile (Pl. 7, fig. 8) to the adult (Pl. 4, fig. 14).

Based on the number of whorls and chambers, deformed tests can be categorized as early (e.g., Pl. 7, figs. 8, 9, 15), intermediate (Pl. 6, fig. 8) and adult stages (e.g., Pl. 7, figs. 2, 3, 5). Mildly deformed foraminifera can usually be identified to the species level. Severely deformed foraminifera can only be identified to the suprageneric level, and sometimes their identification is impossible. About 70% of deformed foraminifera were megalospheric and had an enormously large proloculus, similar to that reported by Yanko and others (1994b).

Irregular keel development and lateral asymmetry are typical for deformed tests of *Amphistegina lobifera* (Pl. 3, fig. 15, 16). Twinning by the dorsal or ventral side is characteristic for rotaliids (e.g., *Ammonia tepida* [Pl. 2, fig. 3], *Challengerella bradyi* [Pl. 2, fig. 8], *Pararotalia spinigera* [Pl. 1, fig. 9]), but rare in the miliolids (e.g. *Peneroplis planatus* [Pl. 2, fig. 12]). The most widely distributed types are the aberrant chamber shapes and abnormal coiling (Table 8).

DISCUSSION

1. Taxonomic Position, Feeding Patterns and Morphotypes of Live Deformed Foraminifera

Sixty-five species belonging to 21 families exhibit morphological deformities. Sixty-four species are calcareous benthics (60% of them are miliolids) and one species is agglutinated. Among them are representatives of the porcellaneous, hyaline and agglutinated forms. They have various modes of life: epifaunal, infaunal, attached, epiphytic, symbiotic, mud-dwelling, sand-dwelling, etc. They belong to different morphotypes: milioline, trochospiral, planospiral, flattened, etc. Thus, morphological deformities are a general feature occurring among all benthic foraminifera. Neither their taxonomic affinity, feeding strategy, nor test morphology has any influence on the occurrence of deformities.

A certain percentage of deformities can be regarded as within the range of natural variability for a given species in given environmental conditions. This is substantial for species in which deformities do not correlate with measured environmental parameters, such as for the majority of species from group 4 (deformed specimens found only at a single station) as well as for many species from groups 2, 3 and even from group 1.

2. Quantitative Distribution of Live Non-Deformed and Deformed Foraminifera

Many of the measured oceanographic (e.g., depth, salinity, temperature, DO, pH), sedimentological (e.g., distribution of coarse and silt-clay fractions, concentration of $CaCO_3$ and C_{org} in sediments) and geochemical (concentrations of heavy metals from the second geochemical association) parameters are rather similar in both regions. There is a significant difference in the concentrations of heavy metals of the first geochemical association between the two compared regions. In the HB region the maximum concentrations exceeded: (a) the local background of Cd by 10 times, As—7 times, Pb—5 times; (b) the crustal averages of Cd—21 times, As—17 times, Pb—11 times; (c) the average values of Cd in Mediterranean carbonates—133 times, As—17 times, Pb—11 times. Moreover, there is an inverse correlation between the amount of dissolved oxygen and C_{org} in sediments in HB. The above parameters point to seafloor conditions that are clearly stressed. Therefore, we consider the HB region as a biogeochemical province that might be potentially dangerous for the biota.

Heavy metals are certainly detrimental to benthic organisms in general (e.g., Aschan and Skullerud, 1990), and to the foraminifera in particular. We previously demonstrated that high concentrations of heavy metals in the environment cause pathological processes in the foraminiferal cell. They affect the defense systems of the foraminifera (Yanko and

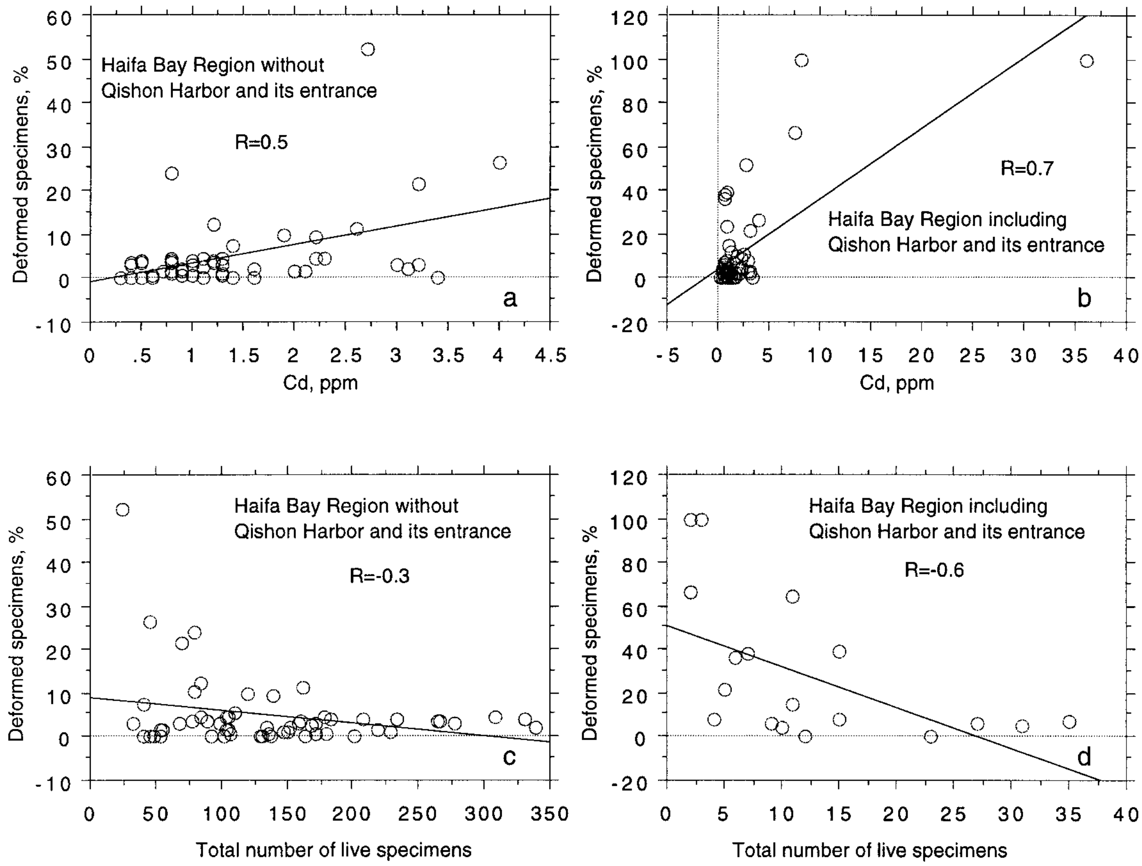

FIGURE 5. Deformed specimens (taken as percentage from total live population of foraminifera, P_d) versus: (a, b) Cd content in sediments, (c, d) total number of live specimens.

others, 1994a) and disrupt their membrane permeability (Bresler and Yanko, 1995a). In extreme cases of heavy metal pollution, the organism devotes its energy to protect itself. As a result, such an individual has little ability left for protein synthesis. This inhibits its energy budget, reproduction cycle, and also harms its cytoskeleton. Therefore, the live foraminiferal population in HB region is impoverished in the number of specimens but enriched in the proportion of deformed tests compared with our control area, the AB region. This is especially visible if data from heavily polluted Qishon Harbor (Yanko, 1994) are included (Fig. 5b, d).

There is a discrepancy between the percentage of deformed foraminifera in our study and the data set on deformed foraminifera from the heavily polluted Sørfjord (Alve, 1991) and Southampton waters, U.K (Sharifi, 1991, Sharifi and others, 1991), as well as with our previous results (Yanko and others, 1994b). In spite of the much lower concentrations of heavy metals in the Mediterranean sediments examined in this study, the percentage of deformed foraminifera is much higher. Alve (1991) found that the percentage of deformed foraminifera (calculated in dead assemblages) in Sorfjord with high concentrations of heavy metals in sediments (e.g., Cd = 850 ppm) ranged between 3% and 5%, with a maximum of 7% in the zone of high stress and oxygen depletion. Sharifi (1991) discovered that the percentage of deformed foraminifera (calculated in total live + dead assemblages) varied from 5% to 20% in Southampton, where the concentration of Cd in sediments ranged between 7 and 14 ppm. In our previous research, we reported that deformed foraminifera comprised only 2–3% of the total (live + dead) foraminiferal assemblage at the entrance to the Qishon Harbour, where the concentration of Cd in sediments was 2 ppm (Yanko and others, 1994b).

We propose that the observed difference in the percentage of deformed foraminifera is a result of the quantitative approach used by different researchers. In this study we calculated the number of deformed foraminifera in the live population only, while in the other studies the percentages were calculated from live + dead (Sharifi and others, 1991; Yanko and others, 1994b) or dead assemblages (Alve, 1991). We believe that our data would be more comparable to Sharifi's data as well as our own previous results, if calculations of deformed foraminifera were carried out on live populations only. At the same time, we believe that an environment with an enormously high concentration of heavy metals in sediments, e.g., Cd = 850 ppm, would not be suitable for living foraminifera. In our acute ecotoxicological experiments with foraminifera (carried out with a concentration of Cd in sea water that ranged between 1 and 1,000 μM) we observed that Cd strongly affects enzymatic activity in the cytoplasm and the functional activity of lysosomes. A concentration of Cd = 1 μM decreased membrane permeability which became almost impermeable at Cd = 100 μM. A concentration of Cd = 1,000 μM kills the foraminiferal cell immediately (Bresler and Yanko, 1995a).

It appears that the deformed foraminifera reported by

TABLE 8. Types of test deformities shown in Plates 1–7.

Species	Types of test deformities										
	1	2	3	4	5	6	7	8	9	10	11
Adelosina cliarensis		Pl. 7, Fig. 13, 14, 15					Pl. 7, Fig. 12				
Adelosina elegans	Pl. 6, Fig. 13	Pl. 6, Fig. 14, 15	Pl. 6, Fig. 13								
Adelosina intricata	Pl. 7, Fig. 2, 3, 10	Pl. 7, Fig. 2, 3, 5, 9		Pl. 7, Fig. 2, 3, 10			Pl. 7, Fig. 4, 6, 7, 8				
Adelosina pulchella	Pl. 4, Fig. 12	Pl. 4, Fig. 14		Pl. 4, Fig. 13			Pl. 4, Fig. 11				
Ammonia compacta	Pl. 2, Fig. 2										
Ammonia tepida	Pl. 2, Fig. 5					Pl. 2, Fig. 6			Pl. 2, Fig. 3		
Amphistegina lobifera								Pl. 3, Fig. 15		Pl. 3, Fig. 16	
Asterigerinata mamilla	Pl. 1, Fig. 11										
Brizalina spathulata		Pl. 2, Fig. 14									
Challengerella bradyi		Pl. 2, Fig. 9	Pl. 2, Fig. 10						Pl. 2, Fig. 8		
Cribroelphidium poeyanum		Pl. 1, Fig. 14									
Eggarelloides advenus				Pl. 1, Fig. 17							
Hauerina diversa	Pl. 5, Fig. 2			Pl. 5, Fig. 2			Pl. 5, Fig. 7				
Haynessina depressula		Pl. 3, Fig. 13									
Miliolinella subrotunda	Pl. 3, Fig. 4										
Nonionella atlantica		Pl. 1, Fig. 12									
Parrina bradyi	Pl. 4, Fig. 10										
Peneroplis pertusus					Pl. 3, Fig. 11		Pl. 3, Fig. 11				
Peneroplis planatus									Pl. 2, Fig. 12		
Pararotalia spinigera		Pl. 1, Fig. 8	Pl. 1, Fig. 7						Pl. 1, Fig. 9		
Pseudotriloculina subgranulata		Pl. 6, Fig. 10, 11	Pl. 6, Fig. 10								
Quinqueloculina disparalis	Pl. 5, Fig. 8, 9	Pl. 5, Fig. 5, 6, 7, 12	Pl. 5, Fig. 5	Pl. 5, Fig. 6, 8	Pl. 5, Fig. 13		Pl. 5, Fig. 10, 11				
Quinqueloculina phoenicia	Pl. 4, Fig. 2, 5, 6, 7	Pl. 4, Fig. 4, 5, 6		Pl. 4, Fig. 2, 3			Pl. 4, Fig. 2, 3				Pl. 4, Fig. 5, 6, 8
Sigmoilinita costata		Pl. 3, Fig. 9									
Triloculina schreiberiana					Pl. 3, Fig. 1		Pl. 3, Fig. 1				
Triloculina earlandi		Pl. 3, Fig. 6			Pl. 3, Fig. 7						
Triloculina marioni	Pl. 6, Fig. 2, 4, 7, 8	Pl. 6, Fig. 3, 5, 6, 7, 8	Pl. 6, Fig. 2	Pl. 6, Fig. 3		Pl. 6, Fig. 5, 6					

1. Wrong coiling; 2. Aberrant chamber shape and size. 3. Poor development of the last whorl; 4, Twisted chamber arrangement; 5. Additional chambers; 6. Protuberances; 7. Multiple apertures; 8. Irregular keel; 9. Twinning; 10. Lateral asymmetry; 11. Lack of sculpture.

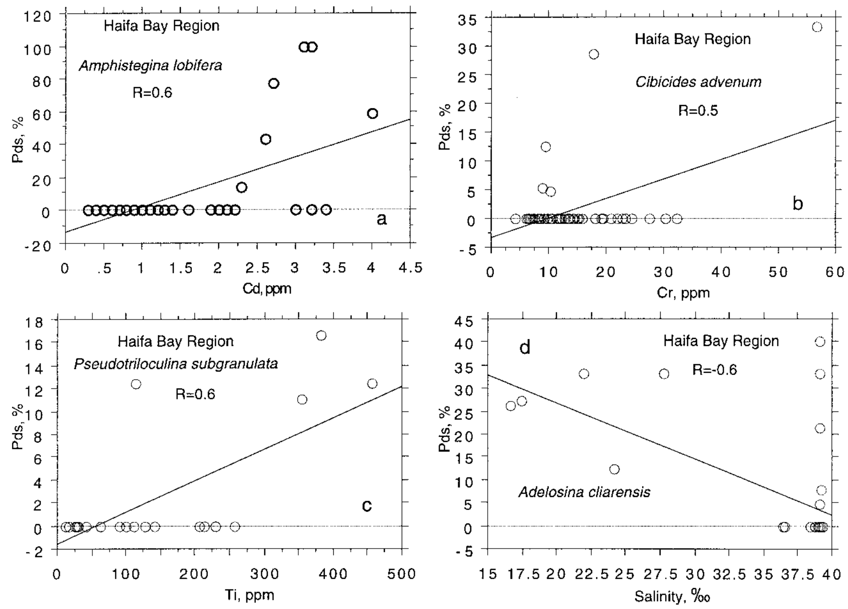

FIGURE 6. Deformed species-indicators (taken as percentage of a given species from total deformed population of foraminifera, P_{ds}) versus Cd, Cr, Ti content in sediments (a–c) and salinity (d).

Alve (1991) were not alive at the time of collection. They may represent some earlier (historical) stage of pollution when the concentration of Cd in Sorfjord was much lower than 850 ppm.

3. SIZE OF LIVE DEFORMED FORAMINIFERA AND TYPES OF MORPHOLOGICAL DEFORMITIES

In the HB region, the total population of live foraminifera (non-deformed + deformed) is dominated by larger specimens compared to those from AB. There are two possible explanations for this: (1) the HB region is enriched with nutrients (high concentrations of Chl-α, and, therefore, the higher primary productivity in sea water); (2) there is a taxonomic bias in the current sample set. The fauna includes numerous *Amphistegina lobifera,* which is among the largest of the species occurring in the area, and dominates on hard ground substrates. This substrate is associated with elevated concentrations of Cd, As, and Pb.

This observation seems to be in contradiction with our previous data. We observed that in areas polluted by heavy metals live foraminifera, including deformed specimens, are stunted. Moreover, an increase in the abundance of deformed specimens corresponds to a decrease in the mean size of the population (Yanko, 1994; Yanko and others, 1994b). If deformed *Amphistegina lobifera* are excluded from regression analysis, the stunting effect is observed as before (Fig. 7b).

The majority of deformed specimens were megalospheric. This observation is similar to our previous studies (Yanko and others, 1994b) as well as data of other investigators (e.g. Seiglie, 1971; Setty, 1976; Setty and Nigam, 1984). We believe that these abnormalities were caused by stressed conditions on the sea bottom related to heavy metal contamination. It is known that in stressed conditions asexual reproduction is preferable as opposed to sexual (Furssenko, 1978). Heavy metals inhibit metabolism and protein synthesis (Ganote and Van der Heide, 1987). As a result, the life-support systems function at a lower level (Baserga, 1985).

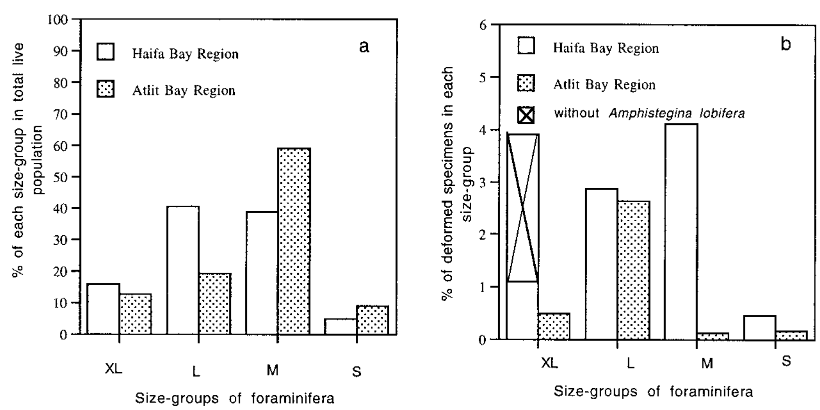

FIGURE 7. Size groups of live foraminifera: (a) non-deformed + deformed, (b) deformed.

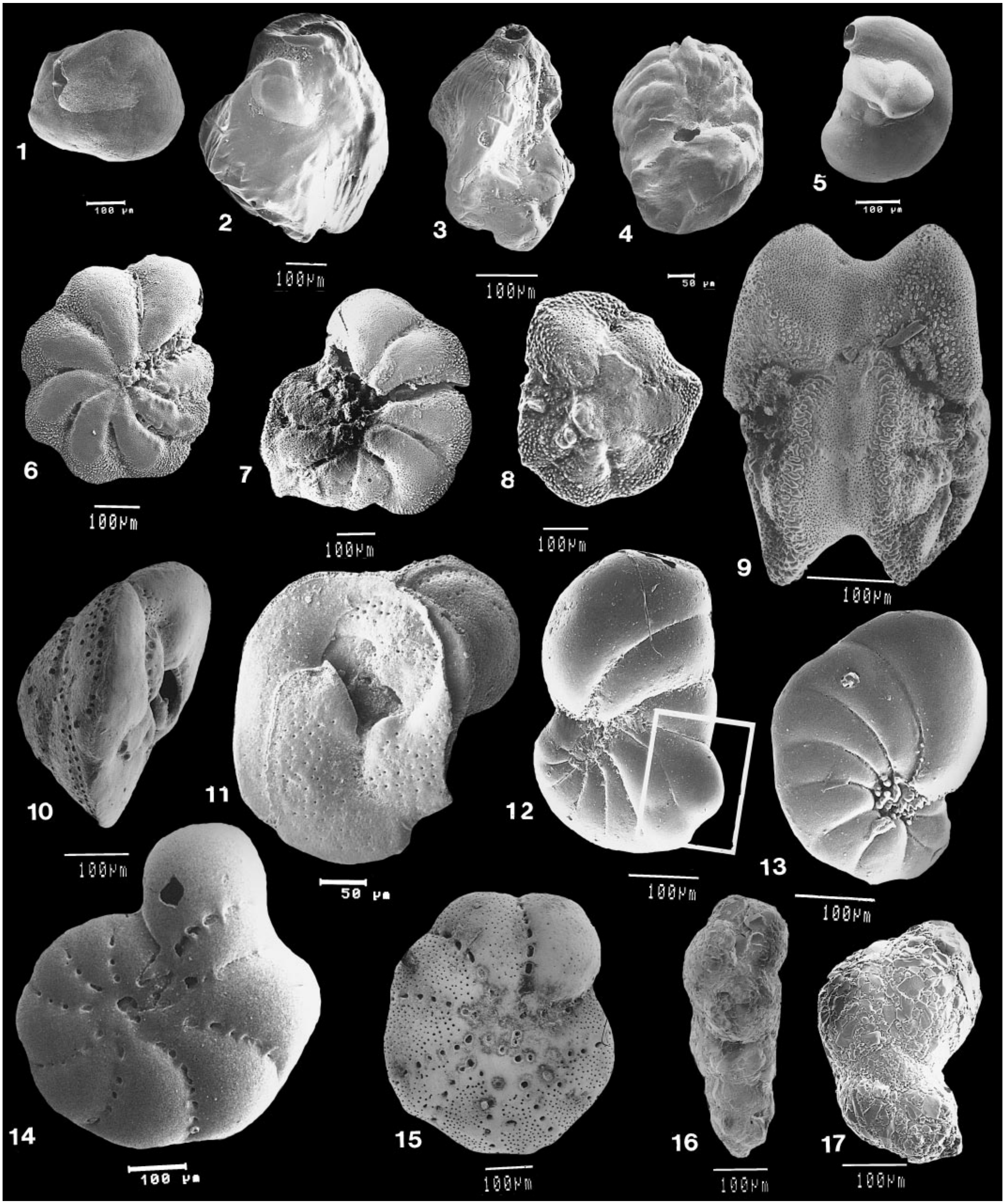

PLATE 1

Examples of test deformities in live foraminifera found in the Haifa Bay region, Israeli shelf, eastern Mediterranean. **1–5** Severely deformed tests of Miliolidae. **6–9** *Pararotalia spinigera* (Le Calvez), ventral side (**6–8**), normal specimen (**6**), specimen with poor development of the last whorl (**7**), aberrant chamber shape (**8**) and twinning of two specimens by dorsal side (**9**). **10, 11** *Asterigerinata mamilla* (Williamson), normal specimen (**10**), specimen with wrong coiling (**11**). **12, 13** *Nonionella atlantica* Cushman, normal specimen (**13**), specimen with aberrant chamber shape and size (**12**). **14, 15** *Cribroelphidium poeyanum* (d'Orbigny), specimen with aberrant chamber shape and size (**14**), normal specimen (**15**). **16, 17** *Eggerelloides advenus* (Cushman), normal specimen (**16**), specimen with twisted chamber arrangement (**17**).

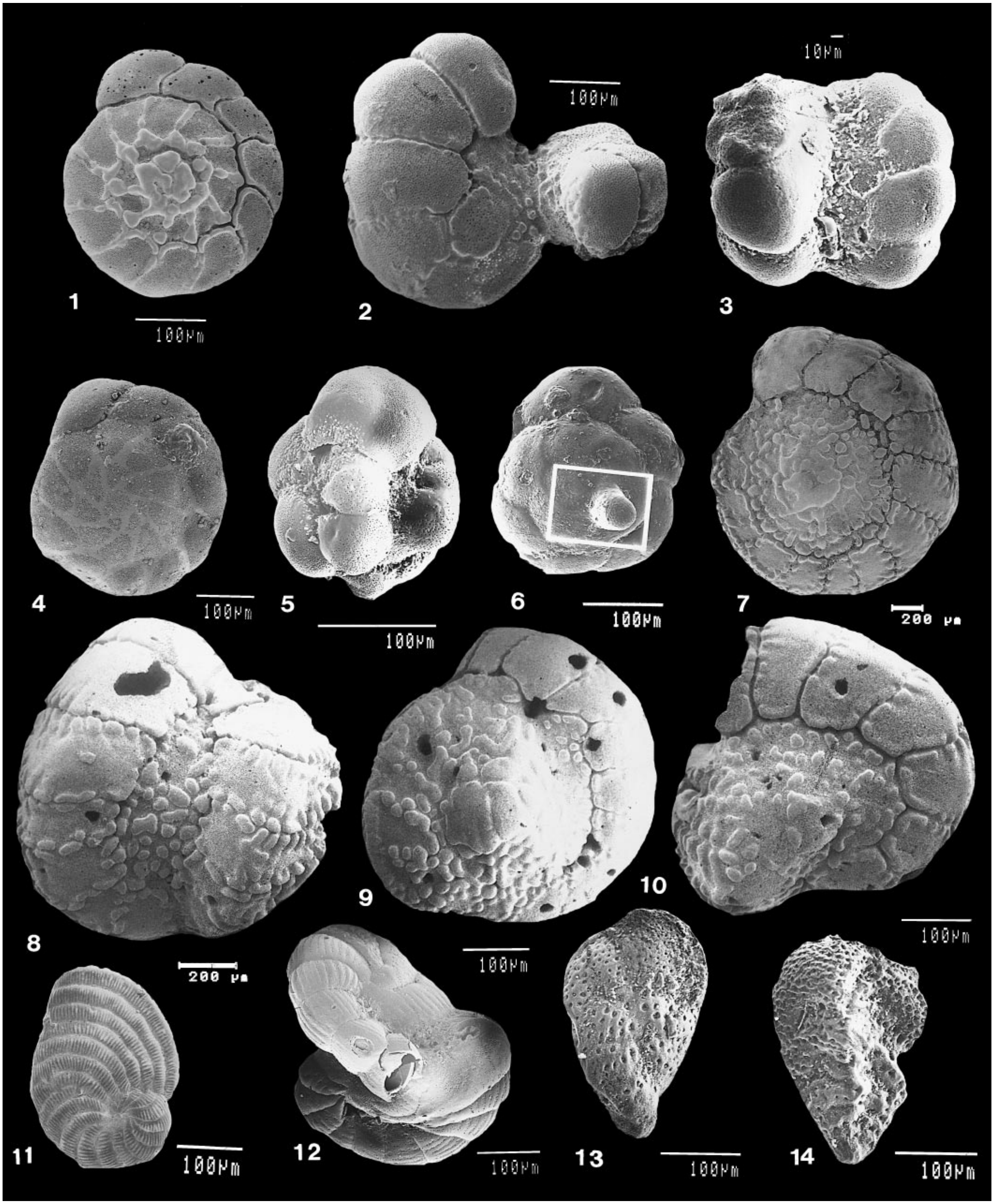

PLATE 2

Examples of test deformities in live foraminifera found in the Haifa Bay region, Israeli shelf, eastern Mediterranean. **1, 2** *Ammonia compacta* Hofker, normal specimen (**1**), specimen with wrong coiling (**2**). **3–6** *Ammonia tepida* (Cushman), normal specimen (**4**), specimen with twinning of two specimens by ventral side (**3**), specimen with wrong coiling (**5**), specimen with anomalous protuberance on dorsal side (**6**). **7–10** *Challengerella bradyi* Billman, Hottinger and Oesterle, normal specimen (**7**), specimen with twinning of two specimens by dorsal side (**8**), specimen with aberrant chamber shape and size (**9**), specimen with poor development of the last whorl (**10**). **11, 12.** *Peneroplis planatus* (Fichtel et Moll), normal specimen (**11**), specimen with twinning of two specimens (**12**). **13, 14** *Loxostomina limbata* (Brady) *robusta* (Said), normal specimen (**13**), highly deformed specimen with aberrant chamber shape and size (**14**).

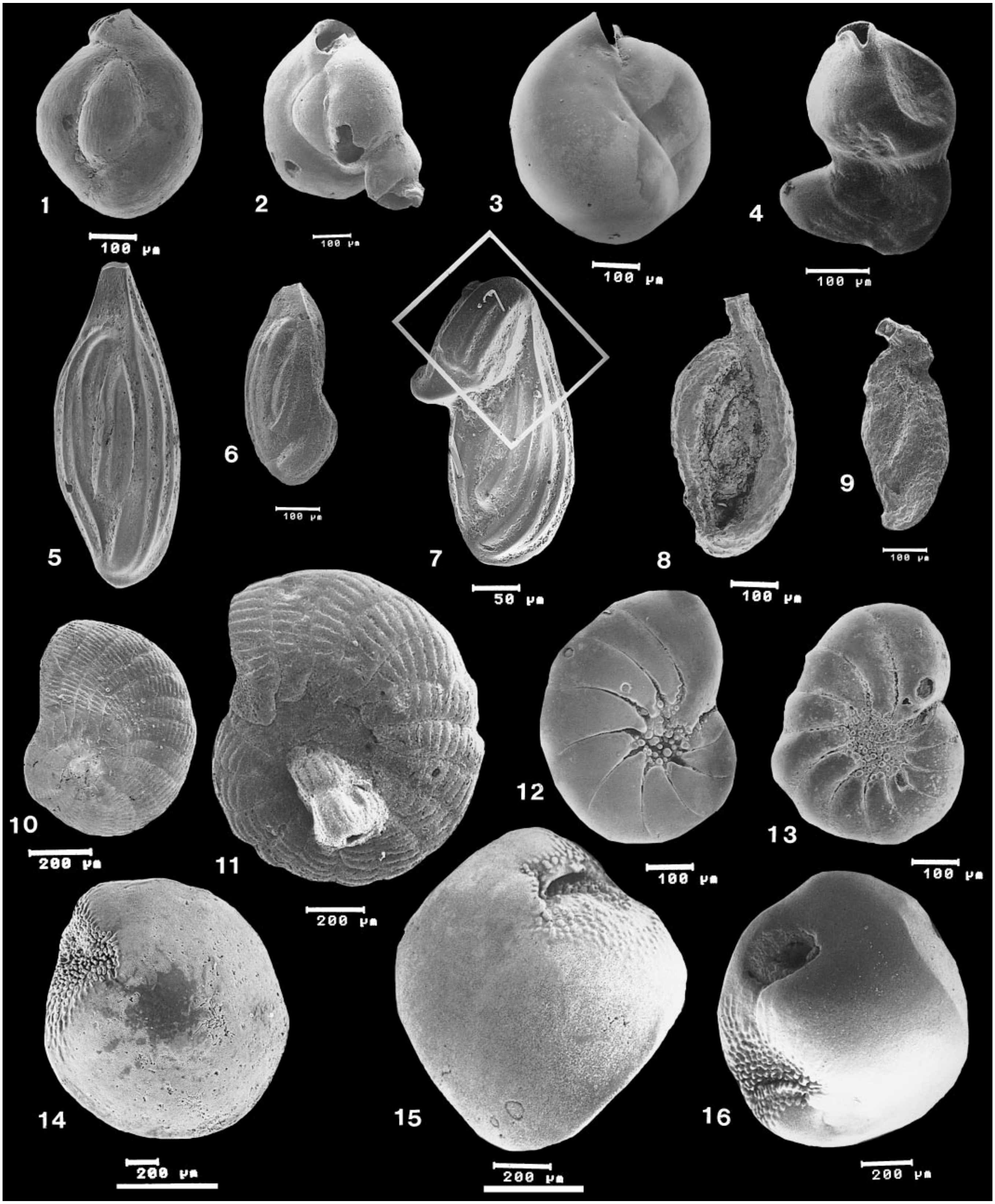

PLATE 3

Examples of test deformities in live foraminifera found in the Haifa Bay region, Israeli shelf, eastern Mediterranean. **1, 2** *Triloculina schreiberiana* d'Orbigny, normal specimen (**1**), specimen with additional chambers and double aperture (**2**). **3, 4** *Miliolinella subrotunda* Montagu, normal specimen (**3**), specimen with wrong coiling (**4**). **5–7** *Triloculina earlandi* Cushman, normal specimen (**5**), specimen with aberrant chamber shape (**6**), and specimen with additional chamber (**7**). **8, 9** *Sigmoilinita costata* (Schlumberger), normal specimen (**8**), specimen with aberrant chamber shape (**9**). **10, 11** *Peneroplis pertusus* (Forskal), normal specimen (**10**), specimen with additional chambers and double aperture (**11**). **12, 13** *Haynesina depressula* (Walker et Jacob), normal specimen (**12**), specimen with aberrant chamber shape and size (**13**). **14–16** *Amphistegina lobifera* Larsen, normal specimen (**14**), specimen with irregular keel and lateral asymmetry (**15, 16**).

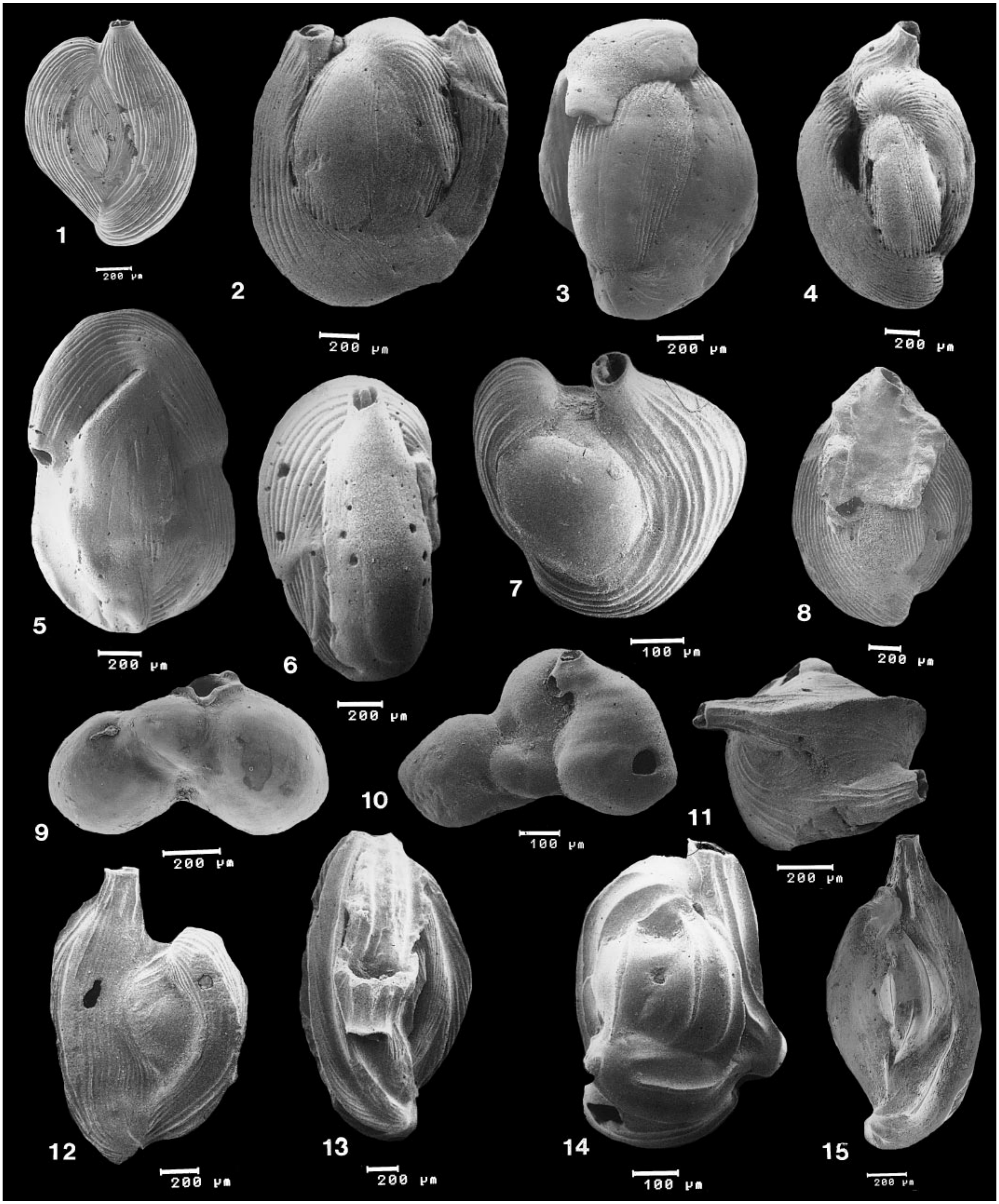

PLATE 4

Examples of test deformities in live foraminifera found in the Haifa Bay region, Israeli shelf, eastern Mediterranean. **1–8** *Quinqueloculina phoenicia* Colom, normal specimen (**1**), specimen with wrong coiling, twisted chamber arrangement and double aperture (**2, 3**), specimen with aberrant shape of the last chamber (**4**), specimens with wrong coiling, aberrant chamber shape and lack of sculpture (**5, 6**), specimen with wrong coiling (**7**), and specimen with lack of sculpture (**8**). **9, 10** *Parrina bradyi* (Millett), normal specimen (**9**), specimen with wrong coiling (**10**). **11–15** *Adelosina pulchella* d'Orbigny. Normal specimen (**15**), specimen with double aperture on the first whorl (**11**), specimen with wrong coiling (**12**), specimen with twisted chamber arrangement of the last whorl (**13**), and specimen with aberrant shape of the last chamber (**14**).

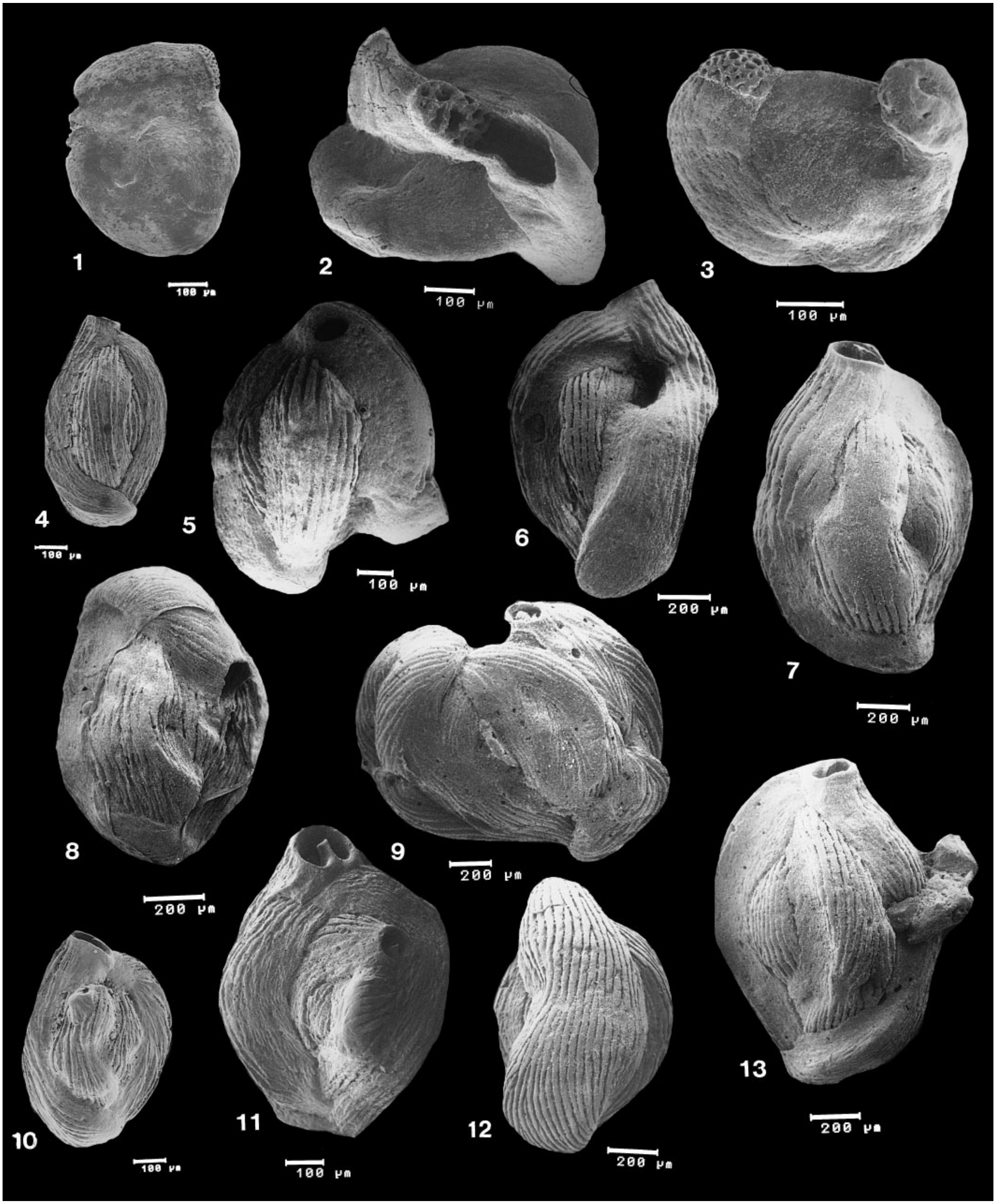

PLATE 5

Examples of test deformities in live foraminifera found in the Haifa Bay region, Israeli shelf, eastern Mediterranean. **1–3** *Hauerina diversa* Cushman, normal specimen (**1**), specimen with wrong coiling and twisted chamber arrangement (**2**), and specimen with double aperture (**3**). **4–13** *Quinqueloculina disparalis* d'Orbigny, normal specimen (**4**), specimen with poor development of the last whorl and aberrant chamber shape (**5**), specimen with twisted arrangement and aberrant shape of the last chamber (**6**), specimen with aberrant shape of several chambers (**7**), specimen with wrong coiling and twisted chamber arrangement (**8, 9, 12**), specimen with double aperture (**10, 11**), and specimen with additional chamber (**13**).

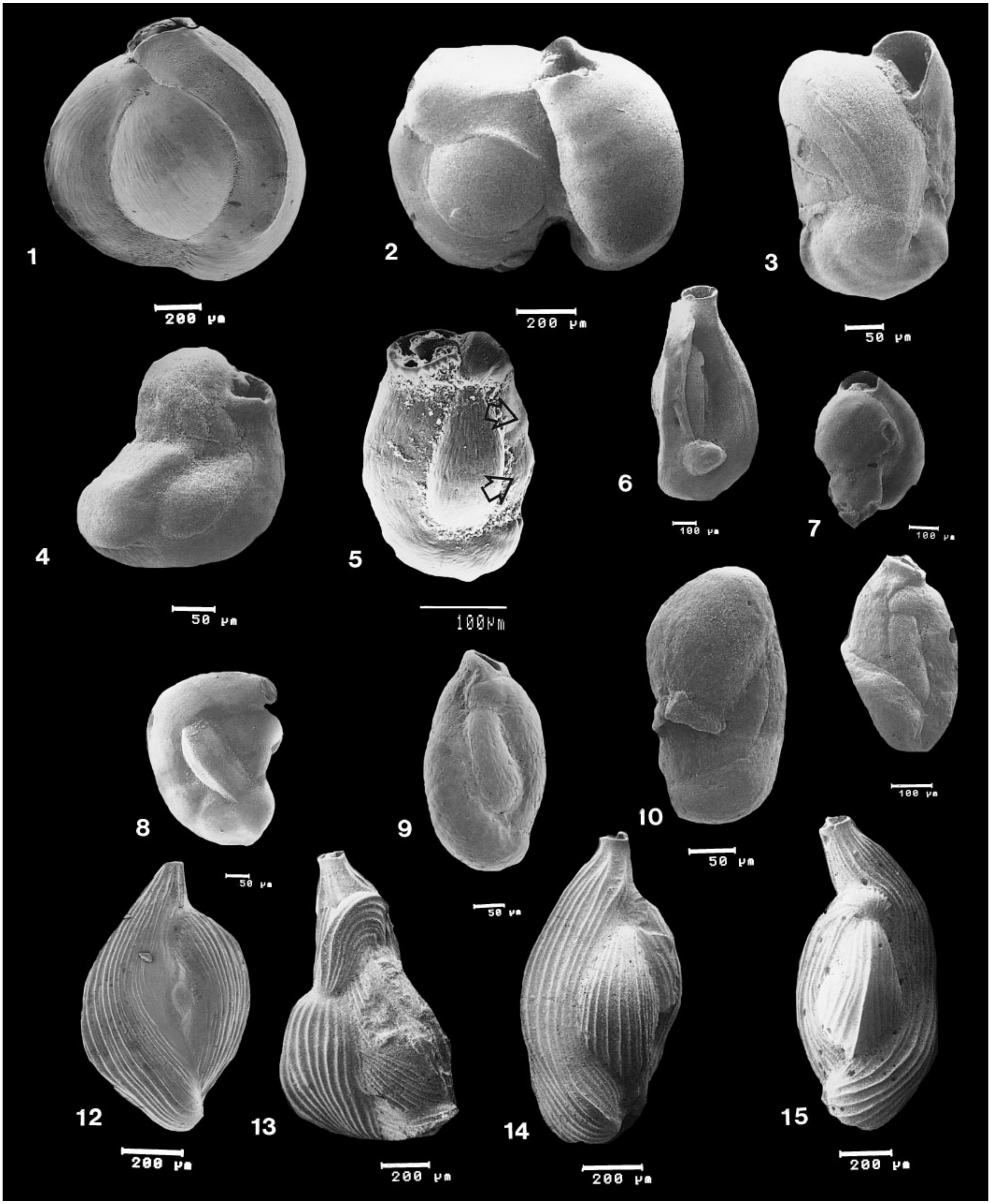

PLATE 6

Examples of test deformities in live foraminifera found in the Haifa Bay region, Israeli shelf, eastern Mediterranean. **1–8** *Triloculina marioni* Schlumberger, normal specimen (**1**), specimen with poor development and wrong coiling of the last whorl (**2**), specimen with twisted arrangement and aberrant chamber shape (**3**), young specimen with wrong coiling (**4**), aberrant shape and protuberance on the second chamber (**5, 6**), highly deformed specimen with wrong coiling and aberrant shape of several chambers (**7, 8**). **9–11** *Pseudotriloculina subgranulata* (Cushman), normal specimen (**9**), specimen with poor development (**10**) and aberrant shape of the last chamber (**10, 11**). **12–15** *Adelosina elegans* (d'Orbigny), normal specimen (**12**), specimen with poor development, wrong coiling and lack of sculpture (**13**), specimen with aberrant shape of the last two chambers (**14, 15**).

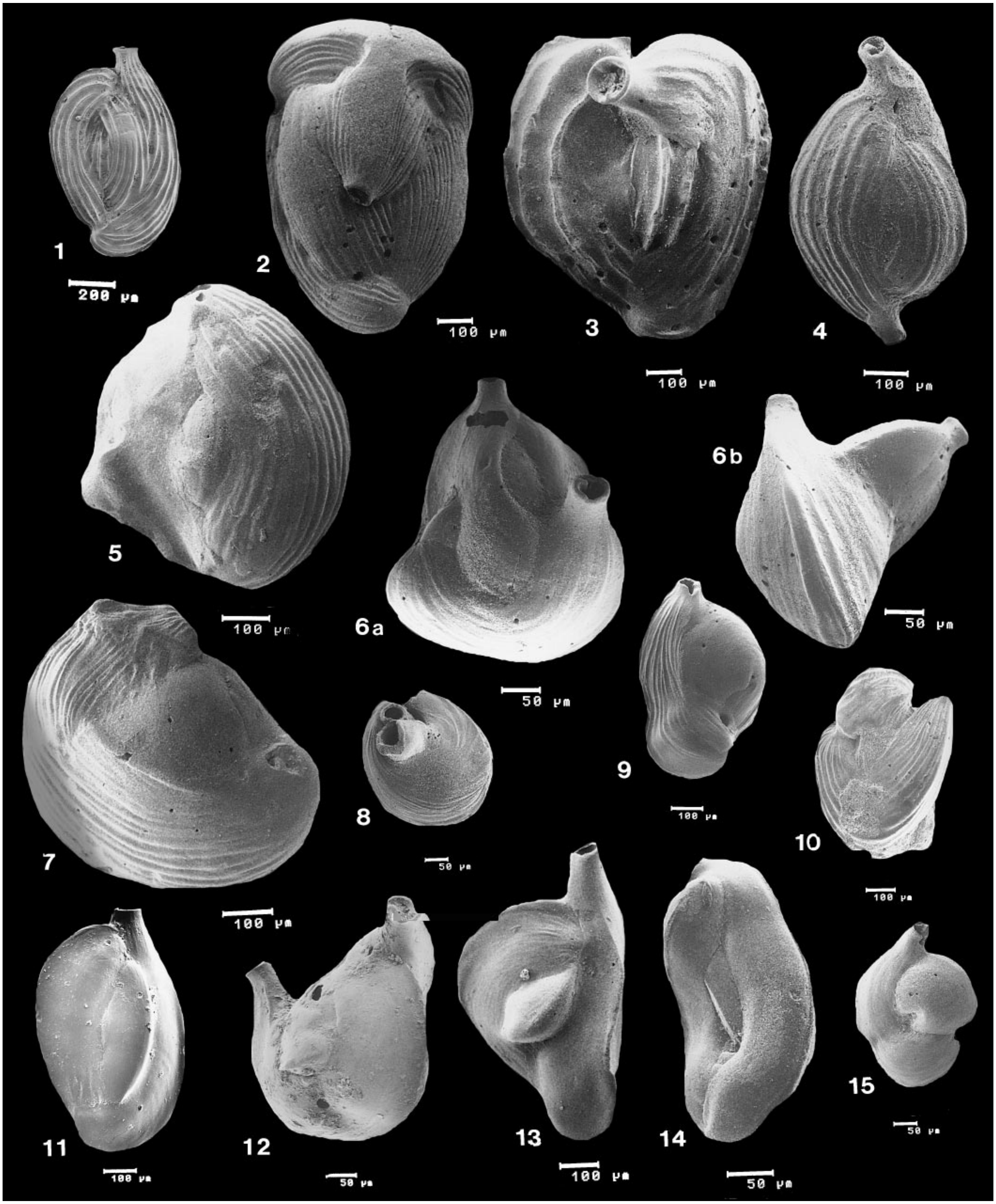

PLATE 7

Examples of test deformities in live foraminifera found in the Haifa Bay region, Israeli shelf, eastern Mediterranean. **1–10** *Adelosina intricata* (Terquem), normal specimen (**1**), specimen with wrong coiling, twisted chamber arrangement and aberrant chamber shape (**2, 3**), specimen with double aperture (**4**), specimen with aberrant chamber shape and lack of sculpture (**5**), specimens with triple apertures (**6a**-front view, **6b**-back view), specimens with double (**7**) and triple (**8**) apertures on early stage, specimen with aberrant second chamber (**9**), specimen with wrong coiling and twisted chamber arrangement (**10**). **11–15** *Adelosina cliarensis* (Heron-Allen et Earland), normal specimen (**1**), specimen with double apertures on early stage (**12**), specimens with aberrant chambers on latest (**13, 14**) and earliest stage of test development (**15**).

In such extreme situations, the organism devotes its energy to protecting itself and, therefore, prefers mitosis to meiosis. The latter may be considered as a luxury (Effrussi and Farber, 1975). Therefore, foraminifera in polluted areas in general and deformed foraminifera in particular are mainly megalospheric.

At present no correlation was found between the type of morphological deformity and heavy metal influence. The fibers of the cytoskeleton permeate the whole foraminiferal cell and form a bedding around the membrane. Heavy metals incorporated into the cell interact with proteins of the cytoskeleton and harm them. Each part of the cytoskeleton is responsible for the development of a certain part of the foraminiferal test. It is possible that in the event that any one part of the cytoskeleton is destroyed by heavy metals, various different types of deformities may be produced. This is still a speculative subject which remains to be studied by means of accurate experimental work carried out under controlled conditions.

4. Response of Live Deformed Foraminifera to Oceanographic Parameters

It is important to emphasize that foraminiferal deformities caused by heavy metal pollution occur independently of latitude or water temperature. Both Alve (1991) and Sharifi (1991), Sharifi and others (1991), worked in temperate cold water environments, while our study was carried out in the warm Mediterranean Sea. However, we recognize the possibility that higher temperatures may increase the rate of metabolic processes in foraminiferal cells, and consequently, even more strongly affect the cytoskeleton. Therefore, this may be an additional explanation for the high percentage of aberrant foraminifera observed in our area.

Sharifi (1991) found that variations in salinity (ranged between 29.9‰ and 33.0‰) were not responsible for test deformities in foraminifera. On the contrary, we discovered that at least one species (*Adelosina cliarensis*) is very sensitive to salinity, and exhibits morphological deformities (up to 30% of all deformed specimens) when salinity decreases up to 16–17‰. In our previous study we found that in an area with permanent high salinity, 39–40‰, but high concentration of heavy metals in sediments, e.g., Cd = 40 ppm, *Adelosina cliarensis* comprised about 50% of the total deformed population.

Each organism has its own threshold of sensitivity to different environmental parameters. This is well known for metazoans (e.g., fish). The threshold of sensitivity to Cd for different fishes varies greatly (1,000 times according to Majewski and Giles, 1981). It would appear that at the concentrations encountered in the current study, the influence of heavy metals for this species is not as important as the effects of naturally occurring water mass properties. In other words, that *Adelosina cliarensis* is a tolerant species to pollution by Cd = 4 ppm, but very sensitive to decrease in salinity up to 16–17‰.

5. Response of Live Deformed Foraminifera to Heavy Metals. Species-Indicators of Marine Pollution

Heavy metals can penetrate into the foraminiferal cell together with food (e.g., algae, bacteria). They also can be incorporated from sea water as imitators of more benign ions. It is likely the transport systems, ferments and centers for Ca^{++} binding can not easily distinguish Ca^{++}, and Mg^{++} ions from similar bivalent heavy metal ions such as Cd^{++}, Zn^{++}, Cu^{++}. Once incorporated into the foraminiferal cell, heavy metals affect the defense systems of the foraminifera (Yanko and others, 1994a; Bresler and Yanko, 1995b) and upset membrane permeability (Bresler and Yanko, 1995a, b). It is possible that trace metals strongly affect the foraminiferal cytoskeleton, which defines the shape of the organism and which is located very close to the membrane. The process of carbonate calcification includes the development of a glicoprotein organic matrix, the ''anlagen'', followed by the mineralization of Ca^{++} and carbonate (Fursenko, 1978; Hemleben and others, 1977). The calcium carbonate crystallizes in the glycoprotein matrix. It has been determined that in addition to calcium, other elements (e.g., Ba) can be included in the crystal structure of the test (Fritz et al., 1992; Lea and Boyle, 1989). Probably, this also holds true for bivalent ions of heavy metals, e.g. Cd^{++}, Cu^{++}, etc. Trace metals may also affect the ratio of the major elements, e.g. Ca and Mg uptake (Yanko and Kronfeld, 1992, 1993). Any of the above processes may deform the crystal structure and produce deformed tests. This has already been demonstrated for the ciliates (Anderheide et al., 1977) and experimentally for *Ammonia beccarii* (Sharifi, 1991).

Heavy metals are especially deleterious to symbiotic foraminifera such as *Amphistegina lobifera*. Symbiotic algae that do not have defense mechanisms, cannot protect themselves from heavy metals, which have the effect of inhibiting photosynthesis. Such inhibition reduces the amount of energy available to the foraminifera, and consequently lowers metabolic processes.

Out of 217 species found in our study area, only 65 species (30%) exhibit morphological deformities. Only a few of these display a strong positive correlation between the number of deformed tests and the concentration of heavy metals in sediments. We consider these species as indicator species of certain types of heavy metal pollution. In our opinion, an increase in the amount of deformed *Amphistegina lobifera* indicates pollution of bottom sediments by Cd. This metal has an affinity to coarse carbonate substrate of hard grounds that sustain a foraminiferal assemblage dominated by *Amphistegina lobifera* (Yanko and Kravchuk, 1996).

An increase in the amount of deformed *Cibicides advenum* indicates pollution by Cr, which has an affinity to muddy-clay substrate dominated by smectite and enriched with organic matter (Yanko and Kravchuk, 1996).

An increase in the proportion of deformed *Pseudotriloculina subgranulata* indicates pollution by Ti, which usually accumulates in muddy-clay substrate in a manner similar to Cr.

It is necessary to emphasize the fact that the above-mentioned indicator species only reflect the limits of heavy metal concentrations found in the present study (Table 2). Other deformed species might assume the role of indicator species at different levels of sediment heavy metal concentrations. For example, *Triloculina marioni* produced about 50% of deformed tests and played the role of indicator species when pollution of Cd in sediments reached 40 ppm (Yanko, 1994).

CONCLUSIONS

Benthic foraminifera exhibit morphological deformities of their tests independently of their taxonomic affinities, mode of life, and test morphotype. Some deformities are spontaneous or naturally-occurring and within the range of natural variability for given species in given environmental conditions.

Deformities in some species appear to be related to oceanographic parameters such as salinity. These species show no correlation between the proportions of deformed tests and concentrations of heavy metals in the sediment. However, there are three indicator species which do exhibit a strong positive response of their deformed tests to elevated concentrations of particular heavy metals in sediment. For example, an increase of Cd concentration in sediments (up to 4 ppm in present study) produces a significant amount of deformities in *Amphistegina lobifera.* Increased Cr (up to 60 ppm) causes deformities in *Cibicides advenum,* while Ti (up to 400 ppm) affects *Pseudotriloculina subgranulata.*

Test deformities of live benthic foraminifera are regarded to be sensitive *in situ* monitors of marine pollution by heavy metals. However, the biochemical and crystallographic mechanisms of the development of such deformities remains to be studied by culture experiments under controlled conditions.

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