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29. QUANTITATIVE ANALYSIS OF BENTHIC FORAMINIFERAL ASSEMBLAGES FROM PLIO-PLEISTOCENE SEQUENCES IN THE TYRRHENIAN SEA, ODP LEG 107[1]

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ABSTRACT

Plio-Pleistocene benthic foraminiferal assemblages from Holes 652A, 653A, and 654A of ODP Leg 107 (Tyrrhenian Sea, Western Mediterranean) are examined by means of Q-mode factor analysis. As a result, seven assemblages (A, B, Ca, Cb, D, Ea, and Eb) are distinguished in four zones (I–IV). The relationship between zones and assemblages and their stratigraphic ranges are as follows:

Zone I. Assemblage A; MPl1 biozone in the lowest Pliocene,
Zone II. Assemblage B; MPl2 biozone to lower part of MPl5 biozone in the Pliocene,
Zone III. Assemblages Ca (Sites 652 and 653) and Cb (Site 654); middle of MPl5 biozone to middle of MPl6 biozone in the upper Pliocene, and
Zone IV. Assemblages D, Ea, and Eb; upper of MPl6 (uppermost Pliocene) and the Pleistocene.

These faunal changes suggest that the whole Tyrrhenian Basin has become deeper from upper epibathyal to lower mesobathyal depths since the beginning of the Pliocene. This increasing depth was the differential that become more and more with the advance of time: Site 652 was deepest and Site 654 was shallowest, consistently. This basin sank rapidly during late Pliocene (Zone III).

The assemblages in Zone III and lower part of Zone IV indicate that the Tyrrhenian Basin has been occupied by the modern Mediterranean-type warmer deep water since the late Pliocene. At the same time, these assemblages also suggest that this region was affected in some degree by cool deep water like NADW in the Atlantic during late Pliocene to early Pleistocene.

Less oxygenated bottom conditions are represented by Assemblage E which prevailed in the three-site area as early as early Pleistocene time.

INTRODUCTION

The benthic foraminiferal study using the previous DSDP material in the Mediterranean Sea showed Neogene paleobathymetric trends in the deep-sea basins (Wright, 1978b). On post-Messinian sequences, however, they were roughly estimated, because only a small number of samples were available for the study. At a single site (Site 373) drilled in the Tyrrhenian Basin, only two cores of Plio-Pleistocene yielded benthic foraminifera.

During ODP Leg 107, many cores penetrating the Plio-Pleistocene were retrieved with good recovery at three sites (652, 653, and 654) in the central and western parts of the Tyrrhenian Sea (Table 1). They contain well-preserved benthic foraminiferal tests enough for quantitative analysis, particularly in Pliocene and lower Pleistocene sequences. Chronostratigraphic framework has been made on the basis of planktonic foraminiferal and calcareous nannofossil biostratigraphy and magnetostratigraphy (Kastens, Mascle, et al., 1987). The benthic foraminiferal biostratigraphy has revealed several bioevents correlative among the sites. Some of them occur during the same time as demonstrated by planktonic datum levels, but the rest are diachronic (Sprovieri and Hasegawa, this volume).

The present study intends to delineate quantitatively a history of the change in benthic foraminiferal faunas during the Pliocene-Pleistocene interval in the Tyrrhenian deep basin. Several studies of foraminifera in modern oceans have shown that foraminiferal biofacies are well correlated with water masses (Lohmann, 1978; Corliss, 1979; Burke, 1981). Such a relationship, however, is not clear in the Mediterranean Sea today. Several workers, on the contrary, reported relationships between species and physicochemical properties as dissolved oxygen (Mullineaux and Lohmann, 1981) or depth distributions of important species occurring in Mediterranean sequences (Parker, 1958; Bandy and Chierici, 1966; Blanc-Vernet, 1969; Colom, 1974; Wright, 1978a; Cita and Zocchi, 1978; Bizon and Bizon, 1984a-c; Jorissen, 1987; etc.). These Mediterranean data are employed to interpret paleoenvironmental change through faunal analysis.

MATERIAL AND METHODS

The materials used in this study were collected from the three holes located in lower (Holes 652 and 653) and middle (Hole 654) mesobathyal depth. Core catcher samples were excluded from the analysis. All the samples about 10 cm^3 each were washed on 63-μm sieve, and dried. Further, they were dry-sieved with a mesh of 125 μm.

Benthic foraminifera exist in 699 samples in total, two to three samples per section of a core. All the samples were used in biostratigraphic analysis (Sprovieri and Hasegawa, this volume). For faunal analysis, benthic foraminifera were picked up, identified, and counted from fractions larger than 125 μm. Specific identification was based on descriptions and illustrations of previous studies of the Mediterranean and the Atlantic species, as well as the original authors' works: Phleger et al. (1953), Parker (1958), Todd (1958), Cita et al. (1974), Cita and Zocchi (1978), Wright (1978a), Agip (1982), Parisi (1981), Bizon and Bizon (1984), Caralp (1984), and Ross and Kennett (1984). On generic position of species, we followed the taxonomy by Loeblich and Tappan (1964) and some subsequent authors including Lipps (1965), Seiglie (1965), Belford (1966), and McCulloch (1981). They are all included in the revised classification by Loeblich and Tappan (1988). See Plates 1–5 for SEM photomicrographs.

[1] Kastens, K. A., Mascle, J., et al., 1990. *Proc. ODP, Sci. Results*, 107: College Station, TX (Ocean Drilling Program).

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Table 1. Location of three holes studied.

Hole	Latitude	Longitude	Depth (m)	Geographic position	Depth of the base of Pliocene (mbsf)
652A	40°21.30′N	12°08.59′E	3446	Lower part of western Sardinian margin of central Tyrrenian Sea	188
653A	40°15.86′N	11°26.99′E	2817	Eastern rim of Carnaglia Basin in western Tyrrenian Sea	230
654A	40°34.76′N	10°41.80′N	2208	Upper part of eastern Sardinian margin	243

For quantitative analysis, a Q-mode factor analysis using CABFAC program (Imbrie and Kipp, 1971; Klovan and Imbrie, 1971) was employed. Forty-seven taxa groups were selected from the original data (269 species belonging to 104 genera). The occurrence of taxa groups in each site is shown in Table 2. Samples containing less than 50 specimens of these taxa groups were omitted from the analysis. Finally, 499 samples remain for the analysis. Incidentally, a long blank interval is made in the middle part of the Pleistocene at Site 652.

FAUNAL ANALYSIS

The computations of factor analysis were separately performed to determine in detail the stratigraphic variability at each site. The sum of the variances for the first six factors is about 80% at each site.

Meaning of each varimax factor can be explained based on distribution of higher factor loadings (more than 0.5) and on highly contributing taxa group represented by higher scores. The higher varimax factor loadings, either positive or negative for each factor, are distributed within a restricted stratigraphic interval at each site. The following lines are summarized results of the Q-mode factor analysis: cumulative variance (Cum. var.) for the first six factors for each site, and variance, taxa group with high contribution and its factor score (Taxa group), and distribution of higher factor loadings for each factor (Distribution). The stratigraphic distribution is represented by MPl biozone for the Pliocene using a scheme described by Glaçon et al. (this volume). There are a few samples with extremely low communality (less than 0.3) for the first six factors at each site. These samples have peculiar faunal compositions, and cannot be explained by the first six factors. Dominant species in such samples are also shown with their stratigraphic position.

Site 652

Cum. var. = 82.7% (Fig. 1, Table 3)

Factor 1 (Variance = 26.9%)
Taxa group: *Oridorsalis* spp. (6.11)
Distribution: MPl1 biozone; basal part of MPl4 biozone to middle part of MPl6 biozone.

Factor 2 (Variance = 23.6%)
Taxa group: *Siphonina reticulata* (5.86).
Distribution: Middle part of MPl2 biozone to basal part of MPl5 biozone.

Factor 3 (Variance = 12.4%)
Taxa group: *Parrelloides* spp. (4.62) and *Cibicidoides(?) italicus* (2.93).
Distribution: Lower part of MPl2 biozone to middle part of MPl4 biozone.

Factor 4 (Variance = 8.0%)
Taxa group: Miliolina (5.70).
Distribution: Upper part of MPl6 biozone to lower part of Pleistocene; uppermost part of Pleistocene.

Factor 5 (Variance = 7.6%)
Taxa group and Distribution: *Globocassidulina* spp. (1.97) in MPl1 biozone; *Gyroidina* group (4.98) in MPl1 biozone

Table 2. Taxa groups used for faunal analysis and their occurrence in each of the three sites. The number of samples used in the analysis for each site is shown at the bottom.

Taxa group	Sites 652	653	654
Anomalinoides helicinus	X	X	X
Articulina tubulosa	X	X	X
Astrononion spp.	X	X	X
Bigenerina nodosaria	X	X	X
Bolivina group (*Bolivina* spp. + *Brizalina* spp.)	X	X	X
Smooth *Bulimina* (*Bulimina* spp., *B. aculeata*-type)	X	X	X
Costate *Bulimina* (*Bulimina* spp., costate type)	X	X	X
Cassidulina carinata	X	X	X
Chilostomella spp.		X	X
Cibicides spp. (*C. lobatulus C. refulgens*)	X	X	X
Cibicides wuellerstorfi	X	X	X
Cibicidoides spp. (*C. agrigentinus* + *C. ornatus* + *C. ungerianus*)	X	X	X
Cibicidoides(?) italicus	X	X	X
Cibicidoides kullenbergi	X	X	X
Cibicidoides pachyderma	X	X	X
Eggerella bradyi	X	X	X
Globobulimina group (*Globobulimina* spp. + *Praeglobobulimina* spp.)	X	X	X
Globocassidulina group (*Globocassidulina* spp. + *Paracassidulina minuta*)	X	X	X
Gyroidina group (*Gyroidina* spp. + *Gyroidinoides* spp.)	X	X	X
Hanzawaia rhodiensis	X	X	X
Hoeglundina elegans			X
Hyalinea balthica			X
Karreriella spp.	X	X	X
Nodosariidae (all Nodosariidae)	X	X	X
Laticarinina pauperata	X	X	X
Martinottiella spp.	X	X	X
Miliolina (all Miliolina, if not specified)	X	X	X
Nonionella spp.	X	X	X
Oridorsalis spp.	X	X	X
Parrelloides spp.	X	X	X
Planulina ariminensis	X	X	X
Pleurostomella alternans	X	X	X
Pseudoparrella group (*P. exigua bathyalis* + *Quadrimorphina laevigata*)	X	X	X
Pullenia spp.	X	X	X
Pyrgo spp.	X	X	X
Rutherfordoides tenuis		X	X
Sigmoilopsis schlumbergeri	X	X	X
Siphonina reticulata	X	X	X
Sphaeroidina bulloides		X	X
Stainforthia complanata	X	X	X
Stilostomella spp.	X	X	X
Trifarina spp.	X	X	X
Spinose *Uvigerina* (*Uvigerina* spp., spinose type)		X	X
Costate *Uvigerina* (*Uvigerina* spp., costate type)	X	X	X
Valvulineria spp.	X	X	X
Textulariina (all agglutinated forms, if not specified)	X	X	X
Number of samples	91	245	162

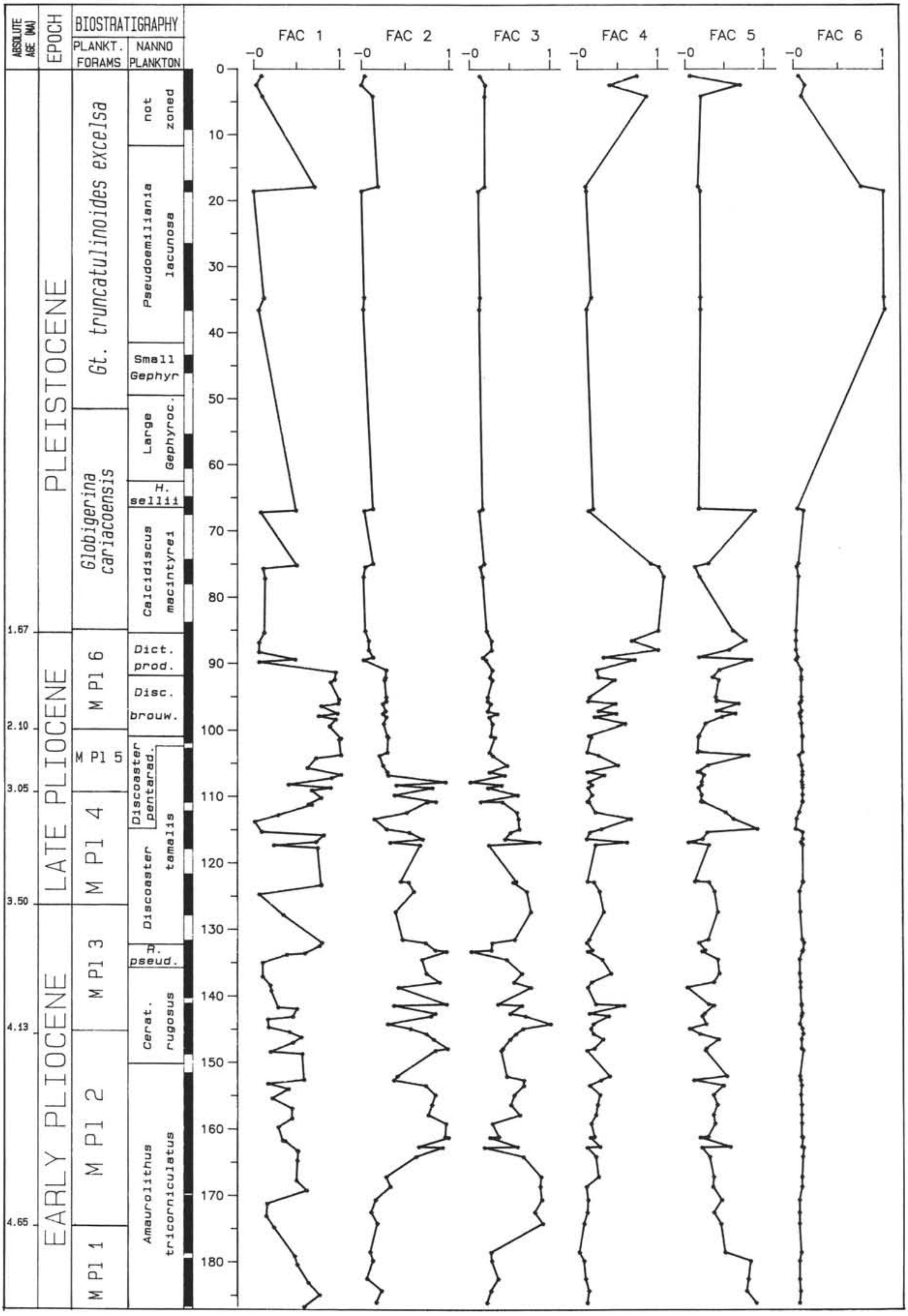

Figure 1. Stratigraphic distribution of varimax loadings of each factor for the first six factors at Site 652.

Table 3. Factor scores at Site 652.

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Anomalinoides helicinus	0.0051	−0.0076	−0.0071	−0.0275	0.0645	−0.0035
Articulina tubulosa	−0.3830	−0.2616	−0.1171	−0.1072	0.1860	6.3533
Astrononion spp.	−0.0170	0.0462	0.3455	0.0213	−0.0402	0.0033
Bigenerina nodosaria	0.1116	0.1161	0.6033	0.0918	0.0144	−0.0175
Bolivina group	0.0495	−0.0499	−0.0770	−0.1500	0.4498	−0.0197
Smooth *Bulimina*	−0.0359	0.0029	−0.0316	0.1211	0.0928	0.0591
Costate *Bulimina*	−0.0160	−0.0026	−0.0286	0.0557	0.0953	0.0266
Cassidulina carinata	−0.0729	0.0160	−0.1175	0.6392	0.0353	0.1661
Cibicides spp.	−0.0054	0.0652	−0.0608	0.2443	−0.0324	0.0379
Cibicides wuellestorfi	0.0948	−0.0220	−0.0046	−0.0029	−0.0656	−0.0075
Cibicidoides spp.	0.0644	−0.0196	0.1149	0.0587	−0.1122	−0.0009
Cibicidoides (?) *italicus*	−0.5546	1.4156	2.9335	0.0696	−1.2587	0.1550
Cibicidoides kullenbergi	0.2691	−0.0939	−0.1234	0.4442	−0.1927	−0.0525
Cibicidoides pachyderma	0.2951	−0.0257	−0.1586	0.1532	−0.0112	−0.0370
Eggerella bradyi	−0.1772	−0.3226	0.4400	1.9173	2.1754	0.0588
Globobulimina group	−0.0399	−0.0225	−0.0413	0.1654	0.0546	0.4342
Globocassidulina group	0.1493	−0.2413	−0.2366	−0.6773	1.9736	0.1221
Gyroidina group	0.2824	0.0805	0.0550	0.2556	4.9789	−0.2156
Hanzawaia rhodiensis	−0.2639	0.3812	0.4233	1.1558	1.3526	−0.1000
Karreriella spp.	−0.0145	0.1796	1.5463	−0.1390	1.1830	−0.0945
Nodosariidae	0.0357	−0.0354	0.0167	−0.0693	0.4560	0.0243
Laticarinina pauperata	−0.0090	0.0062	0.0076	−0.0098	0.0396	−0.0021
Martinottiella spp.	−0.1157	−0.0187	0.3933	0.1994	0.1442	−0.0040
Miliolina	0.3133	−0.0546	0.0559	5.6970	−0.8769	0.1069
Nonionella spp.	0.1553	−0.3389	1.0847	−0.4830	0.7041	−0.0480
Oridorsalis spp.	6.1134	1.5828	0.6066	−0.1730	−0.1146	0.4667
Parrelloides spp.	−0.6901	0.6136	4.6179	−0.5767	−0.0107	0.0686
Planulina ariminensis	−0.0097	0.0165	−0.0194	0.1043	−0.0262	0.0155
Pleurostomella alternans	0.0181	−0.0047	−0.0922	0.0679	0.4152	−0.0099
Pullenia spp.	−0.5668	0.9912	1.5886	1.0456	0.1850	0.0905
Pyrgo spp.	−0.0941	−0.0051	0.0163	0.1382	0.5265	0.1002
Pseudoparrella group	0.0587	−0.0690	0.0329	−0.1868	0.3066	−0.0115
Sigmoilinita tenuis	0.0164	0.0224	0.2523	0.0447	0.3286	−0.0252
Sigmoilopsis schlumbergeri	0.1040	0.0410	0.0223	0.0511	−0.1088	−0.0213
Siphonina reticulata	−1.3427	5.8692	−1.5905	−0.0809	0.3700	0.1189
Stainforthia complanata	−0.0075	−0.0176	0.0186	−0.0163	0.0251	0.1490
Stilostomella spp.	−0.0213	−0.0052	−0.0070	−0.0449	0.1396	0.0234
Trifarina spp.	−0.0206	0.0020	−0.0268	0.1164	0.0512	0.0440
Costate *Uvigerina*	−0.0910	−0.3289	0.9127	−0.2935	0.1584	0.0273
Valvulineria spp.	−0.0373	0.0347	0.0302	0.0243	0.0286	0.0099
Textulariina	0.0213	−0.0055	−0.0590	0.5349	−0.2452	0.0499

and upper part of MPl4 biozone to lower part of Pleistocene.

Factor 6 (Variance = 4.1%)
  Taxa group: *Articulina tubulosa* (6.35).
  Distribution: Middle to upper part of Pleistocene.

Low communality samples: *Cibicidoides kullenbergi* in upper part of MPl6 biozone and lower part of Pleistocene.

Site 653

Cum. var. = 77.0% (Fig. 2, Table 4)

Factor 1 (Variance = 30.0%)
  Taxa group: *Siphonina reticulata* (6.06).
  Distribution: Middle part of MPl2 biozone to basal part of MPl5 biozone.

Factor 2 (Variance = 11.6%)
  Taxa group: *Oridorsalis* spp. (6.15).
  Distribution: Lower part of MPl2 biozone; lower part of MPl5 biozone to basal part of Pleistocene.

Factor 3 (Variance = 10.0%)
  Taxa group: *Gyroidina* group. (6.53).
  Distribution: Upper part of MPl5 biozone to lower part of Pleistocene; upper part of Pleistocene.

Factor 4 (Variance = 9.4%)
  Taxa group: *Parrelloides* spp. (4.61).
  Distribution: Basal part of MPl2 to middle part of MPl5 biozone.

Factor 5 (Variance = 9.3%)
  Taxa group: *Cibicidoides pachyderma* (6.13).
  Distribution: Middle part of MPl5 biozone to middle part of MPl6 biozone.

Factor 6 (Variance = 7.2%)
  Taxa group and Distribution: Miliolina (4.50) and *Pyrgo* spp. (2.38) in upper part of MPl6 biozone; *Articulina tubulosa* (3.54) in Pleistocene. Continuous in middle to upper part, but sporadic in lower part.

Low communality samples: *Globocassidulina* spp. in MPl1 biozone; *Cibicides wuellerstorfi* in MPl5 biozone; *Globobulimina* spp. in middle to upper part of Pleistocene.

Site 654

Cum. var. = 79.1% (Fig. 3, Table 5)

Factor 1 (Variance = 46.9%)
  Taxa group: *Siphonina reticulata* (5.71).
  Distribution: Middle part of MPl2 biozone to lower part of MPl5 biozone.

Factor 2 (Variance = 11.8%)
  Taxa group: *Sigmoilopsis schlumbergeri* (2.80), Miliolina (2.62) and *Parrelloides* spp. (2.10), *Cibicidoides pachyderma* (1.45) and *Oridorsalis* spp. (1.97).
  Distribution: Middle part of MPl5 biozone to lower part of Pleistocene.

Factor 3 (Variance = 7.9%)
  Taxa group: Costate *Uvigerina* (5.21) and *Globocassidulina* spp. (2.29).
  Distribution: MPl1 biozone to basal part of MPl2 biozone.

Factor 4 (Variance = 6.2%)

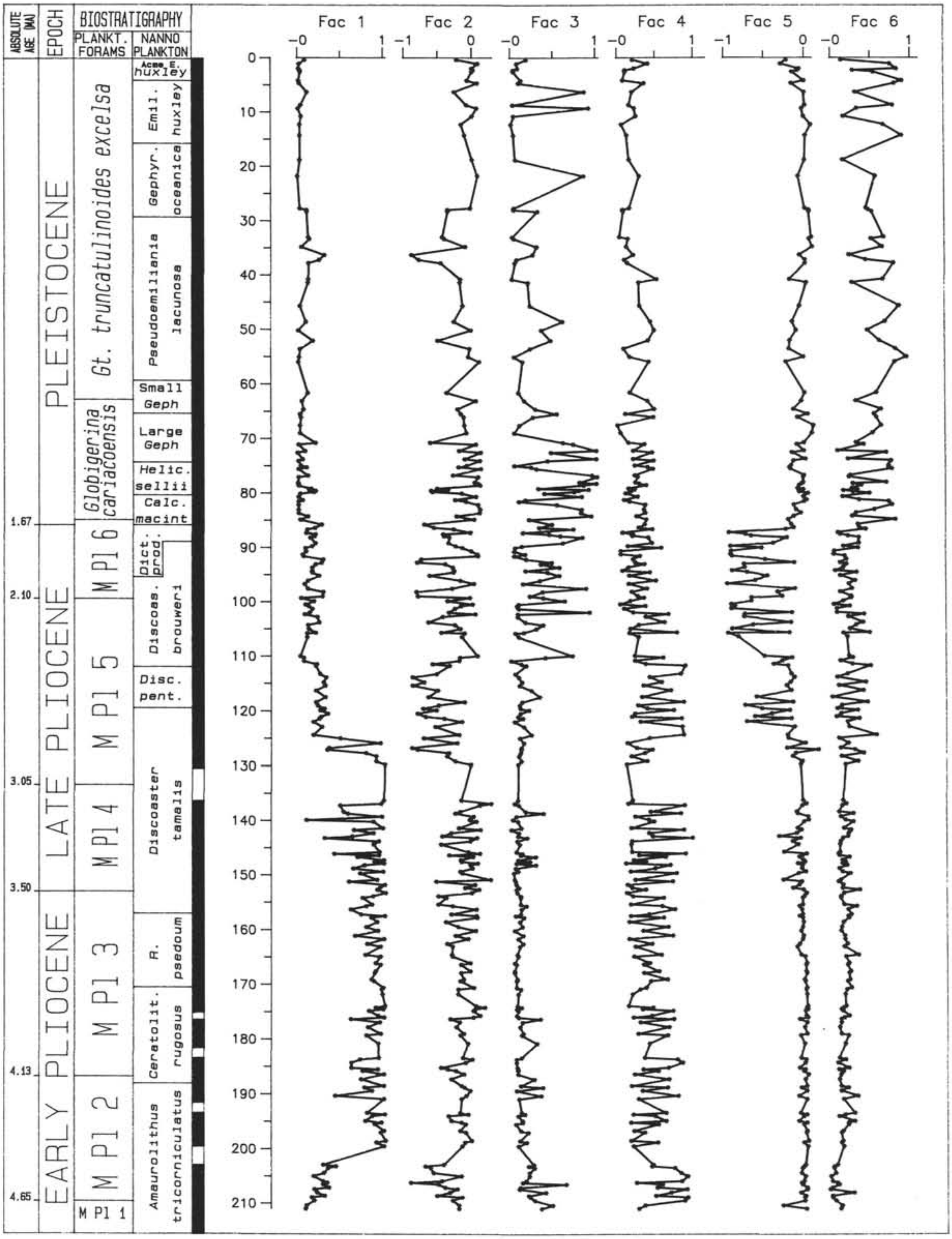

Figure 2. Stratigraphic distribution of varimax loadings of each factor for the first six factors at Site 653.

Taxa group: *Articulina tubulosa* (4.57) and *Gyroidina* group (3.46).

Distribution: Pleistocene.

Factor 5 (Variance = 3.2%)

Taxa group: *Cibicidoides pachyderma* (4.40) and *Cassidulina carinata* (3.93).

Distribution: Middle to upper Pleistocene.

Factor 6 (Variance = 3.1%)

Taxa group: Miliolina (3.61) and *Bolivina* group (3.23).

Distribution: Upper part of MPl6 biozone to lower part of Pleistocene.

Low communality samples: *Cibicidoides kullenbergi* in lower part of Pleistocene; *Globobulimina* spp. in upper part of Pleistocene.

Table 4. Factor scores at Site 653.

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Anomalinoides helicinus	0.0903	−0.0255	0.1445	0.1399	0.0848	−0.1008
Articulina tubulosa	−0.0290	−0.8887	−0.3522	−1.1172	0.6554	3.5424
Astrononion spp.	0.1943	0.0161	0.0320	0.9140	0.1499	−0.2115
Bigenerina nodosaria	0.4408	0.2403	−0.0556	1.3041	−0.0160	0.0527
Bolivina group	−0.0089	−0.0563	0.0935	0.0366	0.0428	−0.0046
Smooth *Bulimina*	−0.0105	0.0445	−0.0343	0.0402	0.0094	0.2265
Costate *Bulimina*	−0.0147	−0.2076	−0.0853	−0.1363	0.1354	0.5362
Cassidulina carinata	0.0118	0.0862	−0.0463	−0.2486	−0.0436	1.1053
Chilostomella spp.	−0.0113	0.0407	0.0346	0.0475	0.0024	0.0826
Cibicides spp.	0.0046	−0.0012	0.0126	0.0190	−0.0041	0.0002
Cibicides wuellestorfi	−0.1142	−0.4016	−0.3295	0.1825	−0.9463	−0.0053
Cibicidoides spp.	0.1081	−0.0752	−0.1836	0.5593	−0.0494	0.0853
Cibicidoides (?) *italicus*	1.7797	0.4463	0.0343	0.7757	0.1710	−0.4430
Cibicidoides kullenbergi	−0.0783	−0.7291	0.1094	−0.5042	0.2794	1.2066
Cibicidoides pachyderma	0.2268	0.4892	−0.0581	−0.9985	−6.1286	−0.5446
Eggerella bradyi	−0.3059	0.0976	−0.0350	1.9714	−0.5881	0.9308
Globobulimina group	0.0010	−0.0057	0.1852	−0.0942	0.0825	0.1610
Globocassidulina group	−0.0907	0.0555	0.7374	0.2818	0.0495	−0.1005
Gyroidina group	−0.1367	0.4185	6.5274	0.2304	0.0349	−0.1604
Hanzawaia rhodiensis	0.1121	0.4943	0.3389	1.8904	−0.2703	0.1230
Karreriella spp.	0.1010	0.1427	−0.2664	1.8470	−0.9294	0.3948
Nodosariidae	0.0716	−0.0704	0.0401	0.3369	−0.0204	0.0461
Laticarinina pauperata	0.0120	−0.0086	−0.0120	0.0323	−0.0102	0.0020
Martinottiella spp.	0.1734	0.0539	0.0349	0.4422	0.0463	−0.1465
Miliolina	−0.1256	0.6809	0.5285	1.5408	−1.2859	4.5013
Nonionella spp.	0.0088	−0.0199	0.0325	0.7784	0.1092	−0.1457
Oridorsalis spp.	1.9181	−6.1512	0.6438	0.1065	−0.5248	−0.2405
Parrelloides spp.	0.6295	−0.2673	−0.4715	4.4615	0.2080	−0.9801
Planulina ariminensis	−0.0209	0.0253	−0.0006	0.0122	−0.0099	0.3411
Pleurostomella alternans	0.1327	−0.0842	0.2750	0.0464	0.0492	0.0925
Pullenia spp.	0.7188	−0.1741	−0.4894	1.7584	0.0139	0.6314
Pyrgo spp.	−0.0149	−0.4639	0.0253	−0.4462	0.4149	2.3751
Pseudoparrella group	−0.0111	−0.0224	0.0522	0.0585	0.0246	−0.0258
Rutherfordoides tenuis	−0.0023	0.0377	0.0747	0.0097	0.0045	0.0020
Sigmoilinita tenuis	0.0166	0.1494	0.1763	0.3955	0.0196	0.1618
Sigmoilopsis schlumbergeri	0.1698	−0.6475	−0.0764	0.3135	−1.5451	0.1178
Siphonina reticulata	6.0555	1.8428	0.0533	−0.9915	0.3163	0.4225
Sphaeroidina bulloides	−0.0182	−0.0173	−0.0092	0.1354	0.0332	−0.0100
Stainforthia complanata	0.0107	−0.0010	−0.0454	0.0428	0.0097	0.0948
Stilostomella spp.	−0.0227	−0.0752	−0.0266	0.0826	0.0351	0.1085
Trifarina spp.	−0.0018	−0.0429	0.0436	−0.0322	0.0257	0.0042
Spinose *Uvigerina*	−0.0011	0.0083	0.0048	0.0028	−0.0176	−0.0006
Costate *Uvigerina*	−0.0675	−0.1469	0.0245	0.2890	0.0729	−0.1624
Valvulineria spp.	−0.0150	−0.0100	−0.0377	0.2165	0.0067	0.0138
Textulariina	0.0135	0.0507	−0.0397	0.0286	−0.0467	0.1167

Based on the stratigraphic distribution of varimax factors with higher factor loadings, the sequence is divided into four zones in respective sites. The zonal boundary in each sequence is located roughly at the same level among three sites (Fig. 4). Every zone is at a similar interval and correlative among the three sites based on similarity of characteristic taxa groups, recognized by higher factor scores. Consequently, four stratigraphic intervals are recognized among the three sites, and are named Zone I to Zone IV in stratigraphically ascending order (Table 6).

The lowest zone, Zone I, is recognized by Factor 5 at Site 652, and by Factor 3 at Site 654. A faunal assemblage recognized by these factors at both sites is named Assemblage A. It is characterized by dominant *Globocassidulina* spp. This taxa group is accompanied by *Gyroidina* group at Site 652, and costate *Uvigerina* at Site 654. At Site 653, no similar assemblage is extracted by any of the first six factors, but is recognized in a few samples with low communalities, which *Globocassidulina* spp. dominate.

Zone II is recognized by two factors at every site as shown in Table 6. These factors are related to either *Siphonina reticulata* or *Parrelloides* spp. Both species occur in the same sample, together with *Cibicidoides(?) italicus* throughout the sequences within the zone. This fauna is named Assemblage B. At Site 652, *S. reticulata* and *Parrelloides* spp. dominate alternatively through this zone. Samples dominated by *S. reticulata* are more frequent at Site 653 than Site 652. At Site 654, this zone is occupied by the same species. *Parrelloides* spp. are abundant only in the lower part of the zone.

In Zone III, the fauna is dominated by *Oridorsalis* spp. at Sites 652 and 653 and is named Assemblage Ca. It is accompanied by *Cibicidoides pachyderma* only at Site 653. *Oridorsalis* spp. and *C. pachyderma* are also contained at Site 654. The fauna is, however, characterized by more frequency occurrences of *Sigmoilopsis schlumbergeri* and Miliolina, named Assemblage Cb.

The highest zone, Zone IV, is roughly divided into lower and upper parts, though criteria and levels of boundaries between both parts differ from site to site. In the lower part of the zone, faunas are dominated by Miliolina and *Gyroidina* spp. at the three sites. These two taxa groups occur in the same sample within the zone, dominating alternatively. This fauna is named Assemblage D. In this zone at Site 652, *Cibicidoides kullenbergi* dominates a few samples which have low communalities. The assemblage contains *Pyrgo* spp. and *C. kullenbergi* as subordinate species at Site 653, and the *Bolivina* group at Site 654, respectively.

In the upper part of Zone IV, the fauna, named Assemblage Ea, is dominated by *Articulina tubulosa* at the three sites. At Site 652, this assemblage occurs at about 37 mbsf (meters below seafloor) in the middle part of the Pleistocene. For about 30 m

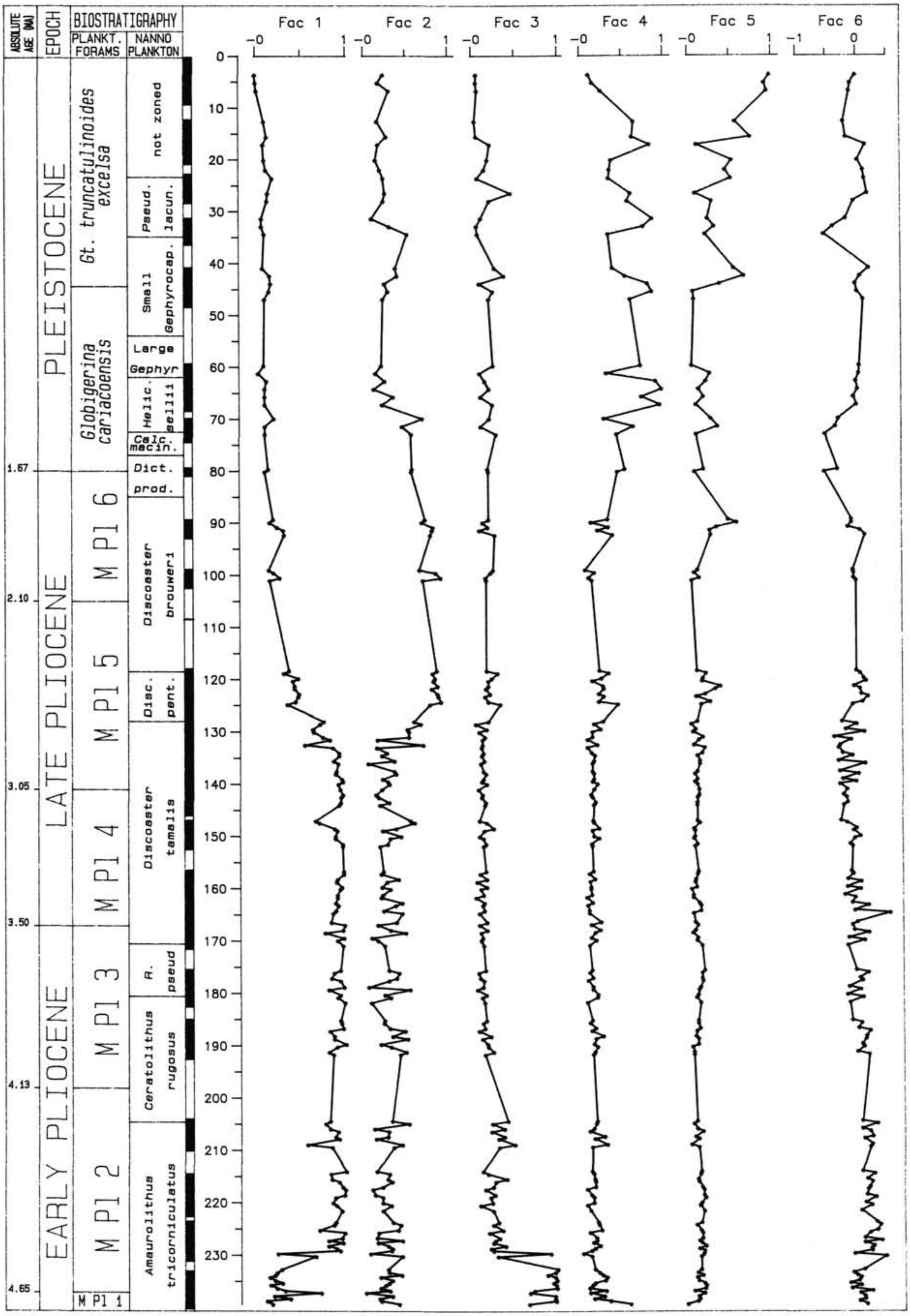

Figure 3. Stratigraphic distribution of varimax loadings of each factor for the first six factors at Site 654.

Table 5. Factor scores at Site 654.

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Anomalinoides helicinus	0.1798	0.0841	0.2324	−0.0167	−0.0364	0.4796
Articulina tubulosa	0.0766	−1.0800	−0.6587	4.5670	1.1237	−0.0573
Astrononion spp.	1.2226	−0.1215	0.7572	−0.3007	−0.3359	−0.7411
Bigenerina nodosaria	0.8723	1.2916	−0.0309	−0.2966	−0.5147	0.8173
Bolivina group	0.3218	1.6404	0.4474	0.1904	0.6230	−3.2283
Smooth *Bulimina*	0.0431	0.2233	0.0372	−0.0462	−0.1073	0.0453
Costate *Bulimina*	0.0288	−0.1562	0.3334	0.5908	1.0341	0.1321
Cassidulina carinata	0.0163	−0.2990	−0.0328	0.2940	3.9317	−0.1600
Chilostomella spp.	0.0038	−0.0231	−0.0028	0.0601	0.0757	0.0417
Cibicides spp.	0.0569	0.1714	0.1796	−0.0741	−0.0104	−0.3754
Cibicides wuellestorfi	−0.0671	0.4147	0.0255	−0.1393	−0.0756	−0.0443
Cibicidoides spp.	0.6567	0.1750	0.0667	−0.2004	−0.4373	−0.9462
Cibicidoides (?) *italicus*	1.1296	−0.3562	−0.2152	0.0580	−0.1075	0.2501
Cibicidoides kullenbergi	−0.0033	−0.0710	−0.1060	0.5869	0.8368	0.0731
Cibicidoides pachyderma	−0.2881	1.4498	0.1068	−0.8028	4.4012	0.4782
Eggerella bradyi	0.2976	0.6885	−0.0399	0.0561	0.0081	0.2910
Globobulimina group	0.0169	−0.0799	0.0456	0.1335	0.5386	0.1938
Globocassidulina group	−0.1312	0.7220	2.2881	0.9819	−0.7052	0.0692
Gyroidina group	0.5275	1.0142	1.3803	3.4574	−0.7787	1.4179
Hanzawaia rhodiensis	0.7835	1.4433	0.1204	0.1681	−0.9068	−1.4328
Hoeglundina elegans	−0.0028	0.0079	−0.0021	0.0075	0.0060	−0.0224
Hyalinea baltica	0.0011	−0.1018	0.0008	0.4692	0.0766	0.0729
Karreriella spp.	0.7704	0.8882	0.2617	0.1559	0.1604	0.7198
Laticarinina pauperata	0.0034	0.0098	−0.0062	−0.0025	−0.0098	−0.0151
Martinottiella spp.	0.1557	−0.1028	0.1860	0.0797	−0.0425	−0.1272
Miliolina	0.3352	2.6170	−0.5525	0.4712	0.2469	−3.6083
Nodosariidae	0.5348	−0.0350	1.1251	0.0746	−0.0729	0.3337
Nonionella spp.	0.1821	0.1119	0.7137	−0.1187	−0.1462	−0.0435
Oridorsalis spp.	1.2333	1.9719	1.3114	−0.4191	1.0030	1.7494
Parrelloides spp.	1.5518	2.1048	−0.5889	−0.4906	−0.5563	2.0340
Planulina ariminensis	0.2157	0.3435	−0.0483	−0.0991	−0.1660	−0.0656
Pleurostomella alternans	0.4108	−0.0437	0.6769	0.1007	−0.1007	−1.0273
Pullenia spp.	1.8837	1.5958	−0.4270	0.2991	0.4388	1.9651
Pyrgo spp.	0.0602	0.1849	−0.2090	0.8228	1.4591	−0.3075
Pseudoparrella group	−0.3473	1.4562	1.0338	−0.5981	−0.5055	−0.0006
Rutherfordoides tenuis	0.0096	−0.0517	0.0134	0.0608	0.2921	0.1059
Sigmoilinita tenuis	0.0768	0.0436	0.6240	2.4605	−0.8140	−0.5945
Sigmoilopsis schlumbergeri	0.1201	2.8013	−0.6409	0.2794	−0.7014	−0.2474
Siphonina reticulata	5.7066	−2.2793	−0.0756	−0.4672	0.3582	−1.1174
Sphaeroidina bulloides	0.2095	−0.2770	2.0303	0.1875	−0.1591	1.0584
Stainforthia complanata	0.0301	0.2115	−0.0273	1.0009	0.1399	−0.1340
Stilostomella spp.	0.0014	0.0071	0.3282	0.8790	−0.0086	−0.1648
Trifarina spp.	0.0049	−0.0421	0.0073	0.4586	0.2286	−0.0275
Spinose *Uvigerina*	0.0106	0.1638	−0.0462	0.0012	−0.0748	−0.0987
Costate *Uvigerina*	−0.3546	−0.6821	5.2110	−0.8243	0.5977	−0.8000
Valvulineria spp.	0.1507	0.1484	0.3455	0.1164	−0.1952	0.0227
Textulariina	0.3769	0.1569	−0.2024	0.9857	0.1079	−0.4223

below this horizon, we did not use the samples for this analysis owing to the very scarce occurrence of benthic foraminifera. The lowest occurrence of this assemblage is in the lowermost part of the Pleistocene at Sites 653 and 654. At Sites 652 and 653, *Globobulimina* spp. dominate a few samples with low communality. At Site 654, the dominant species changed alternatively between *A. tubulosa* and both *Cibicidoides pachyderma* and *Cassidulina carinata* in the middle and upper parts of the Pleistocene. This fauna is named Assemblage Eb.

DISCUSSION

Faunal changes through the Plio-Pleistocene sequences are quite similar at the three sites. This suggests that basin-wide changes of environment occurred in the Tyrrhenian Sea region. Interpretation of paleoenvironment based on foraminiferal fauna is made by analogy with the modern Mediterranean fauna and additional ones, mainly in the Atlantic Ocean. In this paper, paleodepth is represented with a bathymetric zonal scheme in the modern Mediterranean by Wright (1978b) as well as water depth.

Paleoenvironment Deduced from Assemblages

In Zone I, Assemblage A is characterized by the *Globocassidulina* group (mainly *G. subglobosa*) and accompanying taxa, *Gyroidina* group (mainly *G. soldanii*) and costate *Uvigerina* (*U. pigmea*). The upper depth limit (UDL) of *Globocassidulina subglobosa* is about 150 m (Bandy and Chierici, 1966). This species is a typical bathyal form, common in epibathyal zone and below. *Gyroidina soldanii* occurs below 400 m in the Gulf of Naples (Wright, 1978b). Off Catalonia, it occurs in upper epibathyal zone, and common in 240–300 m (Colom, 1974). *Uvigerina pigmea* occurs in deposits of shelf to over 2500 m (Boersma, 1984). In the Tyrrhenian sites, it is characterized by typically fusiform tests with lower costae and hispid final chambers. Such a form is typical in shallower sediment in the bathymetric range of this species (Boersma, 1984). Among the low costate forms of *Uvigerina*, *U. peregrina* has an UDL at about 100 m (Bandy and Chierici, 1966). *Uvigerina mediterranea* is reported from 104 to 1378 m in the Eastern Mediterranean (Parker, 1958). Consequently, Assemblage A is considered as a fauna in upper epibathyal zone (150–200 m to 500–700 m).

Assemblage B is characterized by two elements opposing to each other, *Siphonina reticulata* and *Parrelloides* spp. (both *P. robertsonianus* and *P. bradyi*). *Siphonina reticulata* is recorded at depths of 81–1000 m off western Corsica (Bizon and Bizon, 1984c) and 104–1016 m in the Eastern Mediterranean (Parker, 1958). The related species, *S. bradyana*, occurs from the upper Pleistocene at lower epibathyal depth in the Alboran Sea, westernmost Mediterranean (Caralp, 1988). *S. bradyana* is also re-

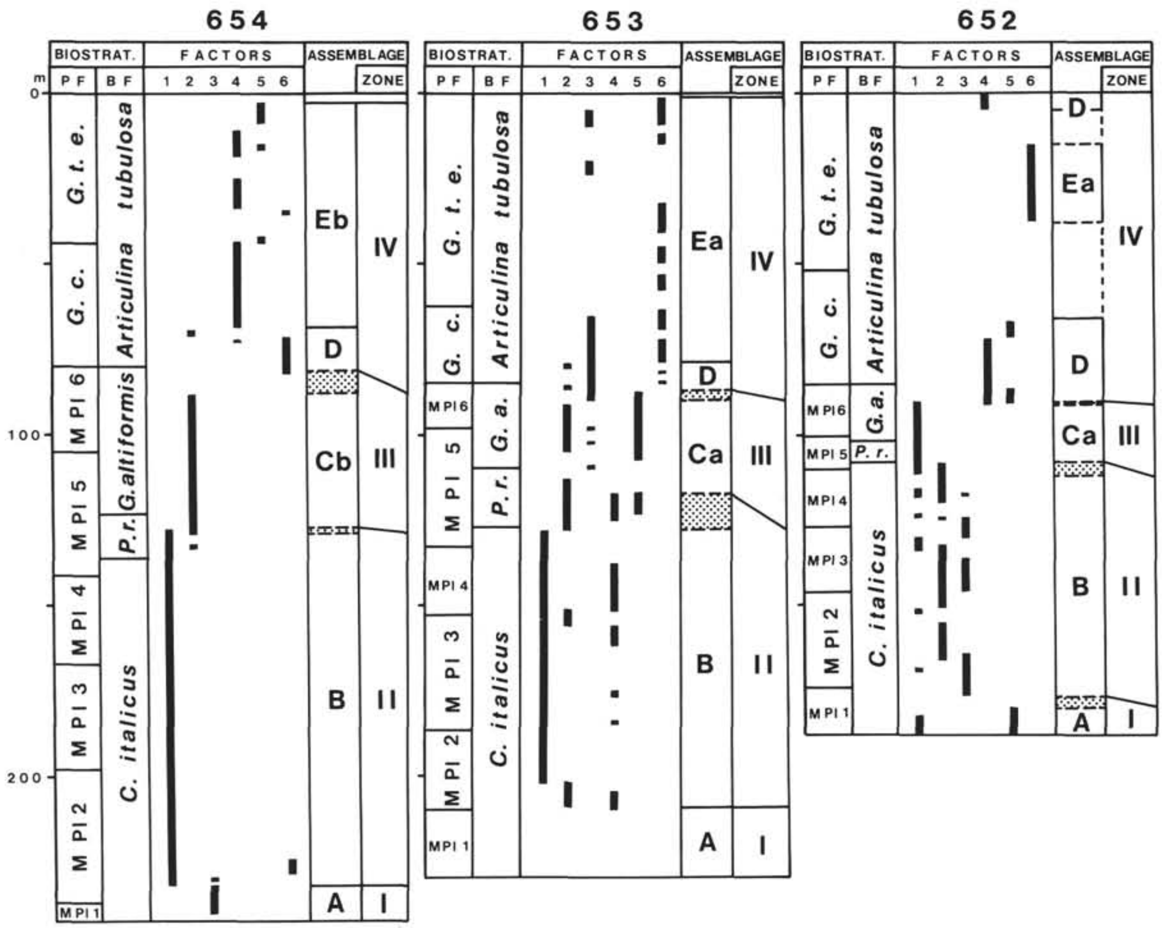

Figure 4. Stratigraphic distribution of Plio-Pleistocene benthic foraminiferal assemblages and zones extracted from varimax factor loadings at Sites 652, 653, and 654. Planktonic and benthic foraminiferal zones (Glaçon et al., this volume; Sprovieri and Hasegawa, this volume) are shown on the left.

Table 6. Benthic foraminiferal assemblages and their characteristic taxa groups in four zones detected by factor analyses at Sites 652, 653, and 654. Corresponding factors are also shown at each site.

<table>
<tr><th>Zone</th><th>Site 654</th><th>Site 653</th><th>Site 652</th></tr>
<tr><td>IV</td><td>Eb: Cibicidoides pachyderma + Cassidulina carinata + Articulina tubulosa
(Factors 4 and 5)</td><td>Ea: Articulina tubulosa
(Factor 6)</td><td>(Factor 4)</td></tr>
<tr><td></td><td>(Factor 4)</td><td colspan="2">+ Globobulimina spp.</td></tr>
<tr><td></td><td></td><td>(low communality)</td><td>(low communality)</td></tr>
<tr><td></td><td colspan="3">D: Miliolina + Gyroidina group</td></tr>
<tr><td></td><td>+ Bolivina group
(Factors 4 and 6)</td><td>+ Pyrgo spp. + Cibicidoides kullenbergi
(Factors 3 and 6)</td><td>(Factors 4 and 5)
+ Cibicidoides kullenbergi
(low communality)</td></tr>
<tr><td>III</td><td>Cb: Sigmoilopsis schlumbergeri + Miliolina + Oridorsalis spp. + Parrelloides spp.
(Factor 2)</td><td colspan="2">Ca: Oridorsalis spp.</td></tr>
<tr><td></td><td></td><td>Cibicidoides pachyderma
(Factors 2 and 5)</td><td>(Factor 1)</td></tr>
<tr><td>II</td><td colspan="3">B: Siphonina reticulata + Parrelloides spp. + Cibicidoides (?) italicus</td></tr>
<tr><td></td><td>(Factors 1 and 6)</td><td>(Factors 1 and 4)</td><td>(Factors 2 and 3)</td></tr>
<tr><td>I</td><td colspan="3">A: Globocassidulina spp.</td></tr>
<tr><td></td><td>+ Gyroidina group
(Factor 3)</td><td>(low communality)</td><td>+ costate Uvigerina
(Factor 5)</td></tr>
</table>

ported with *S. pulchra* from 150 to 750 m in the Gulf of Mexico (Pflum and Frerichs, 1976). All the data on living forms have come from the seas of rather higher salinity than normal marine water. In those seas, however, this genus is always rare in the fauna. On the contrary, *S. reticulata* is very abundant in the Tyrrhenian Pliocene and seems to be characteristic in this region (or the Mediterranean). This element assumed to indicate a hypersaline water in upper epibathyal zone (150–200 m to about 1000 m).

The other element of Assemblage B, *Parrelloides* spp. are absent in the modern Mediterranean, but live in the Atlantic. *Parrelloides robertsonianus* is one of the characteristic species of North Atlantic Deep Water (NADW), but its bathymetric range extends up to 790 m off northwest Africa (Lutze and Coulbourn, 1984). The UDL of *P. bradyi* is about 450 m in the Gulf of Mexico (Pflum and Frerichs, 1976). In Assemblage B, *P. robertsonianus* is always less frequent than *P. bradyi,* and is never common through Zone II. Therefore, this element represents the uppermost region of middle epibathyal zone (500–700 m to 1000–1300 m).

At Site 654, *S. reticulata* is more dominant than *Parrelloides* spp. This reveals that this site was situated at central depths of upper epibathyal zone. At Site 652, on the contrary, both elements affect the fauna in the same degree throughout the sequence. It is presumed that Site 652 was deeper and more affected by deeper water than Site 654 in transition between upper and lower epibathyal zones. Site 653 was situated at depth between Sites 652 and 654.

At Site 654, *Planulina ariminensis* is commonly found in Zone II, though it is statistically a minor element. This species is found from outer neritic depths to 800 m in modern oceans, and attains a maximum at 400–500 m (Berggren and Haq, 1976). It is less abundant at Sites 653 and 652. This fact supports the above estimation that Site 654 was the shallowest.

Assemblage Ca is characterized by *Oridorsalis* spp. in Zone III at Sites 652 and 653. This group consists of *O. stellatus, O. umbonatus,* and other forms. *Oridorsalis stellatus* has not been reported from the modern Mediterranean. This species is reported from the oxygen minimum layer in the Gulf of Mexico by Pflum and Frerichs (1976). However, the form of their figured specimen does not fall in the range of morphologic variation. In the Gulf of Gascogne, *Oridorsalis umbonatus* occurs at 850 m and below (Caralp et al., 1970). At Site 653, Assemblage Ca has an additional element represented by *Cibicidoides pachyderma* which is considered as a ubiquitous form (Arnold, 1983).

Assemblage Cb at Site 654 is characterized by the association of *Sigmoilopsis schlumbergeri*, Miliolina, and *Parrelloides* spp. in Zone III. *Oridorsalis* spp. and *C. pachyderma* are also included in this assemblage. *Sigmoilopsis schlumbergeri* occurs below 57 m to 1000 m; and attains maximum between 200 and 300 m in Ajaccio Bay (Bizon and Bizon, 1984c). In the northeast Atlantic, it occurs at 200 m, becoming common below 800 m and abundant below 2000 m (van Morkhoven et al., 1986). Miliolina in this analysis contain *Quinqueloculina bicarinata, Q. venusta,* and *Triloculina tricarinata,* as major components. They are regarded as important elements of NADW together with *Oridorsalis umbonatus* and *Parrelloides robertsonianus* (Lohmann, 1978). These species are also found in Assemblage Ca, though less abundant.

Cibicides wuellerstorfi, another important element of NADW, occurs as a minor element within Zone III, both Assemblage Ca and Cb. This species occurs below 800 m in the North Atlantic and becomes common below 3000 m (van Morkhoven et al., 1986). As a whole, the assemblages in Zone III include many elements of modern NADW, and suggest the presence of a water like NADW in the Tyrrhenian region. We call it Atlantic-type deep water as a tentative name.

The depth range of present NADW is 1800–3000 m off Northwest Africa, but becomes shallower to 1300 m toward the equator (Lutze and Coulbourn, 1984). Within the range, one of the components of the NADW fauna, *Cibicidoides kullenbergi,* becomes abundant below 2100 m in the Gulf of Gascogne (Wright, 1978b). Its UDL is 1400 m in the same sea (Caralp et al., 1970). This species, however, is not included in these assemblages.

Judging from the modern distribution of NADW and of species composing the assemblages in Zone III, Assemblages Ca and Cb are regarded as the faunas representing the upper region of upper mesobathyal zone (from 1000–1300 to 1800 m) under a slight influence of Atlantic-like deep water. In contrast with Site 654, Sites 652 and 653 were less affected by this deep water. In Zone II, in turn, the occurrence of *P. robertsonianus* seems to reveal the beginning of this deep-water invasion. In Zone III, Atlantic-type deep water became more effective in the Tyrrhenian region.

The lower part of Zone IV, upper Pliocene to lower Pleistocene, is characterized by Assemblage D which consists of two end members, Miliolina and the *Gyroidina* group. Miliolina are components of the Atlantic-like deep water as mentioned above. The *Gyroidina* group consists of *Gyroidina* cf. *neosoldanii, G. soldanii, Gyroidinoides altiformis,* and *G. altiformis delicata.* They live in the Mediterranean today. The UDLs of *G. soldanii* and *G. altiformis* are about 100 and 150 m, respectively (Bandy and Chierici, 1966). *Gyroidina* spp. are common at 2500–4000 m in the Western Mediterranean (Cita and Zocchi, 1978). This element of Assemblage D, then, is considered as Mediterranean-type deep water element.

The present deep water in the Mediterranean is characterized by a warm and extremely constant temperature (13°C), moderate oxygen contents (5 mL/L) and higher salinity (38‰) (compiled by Bandy and Chierici, 1966). On the contrary, NADW is characterized by cooler temperatures (2.5°–1.5°C), high oxygen contents, and high salinity, and is distributed between 1800 and 3000 m off northwest Africa (Lutze and Coulbourn, 1984).

Assemblage D is associated with *Cibicidoides kullenbergi,* which is a typical bathyal-abyssal species and correlates with NADW in the present Atlantic (Lohmann, 1984; Sen Gupta et al., 1982; Murray, 1984). Judging from these distribution data in modern ocean, Assemblage D is regarded as a lower mesobathyal fauna (2500–4000 m).

The depth distribution of deep water has been variable with time. At DSDP Site 548, 1256 m deep in the Northeastern Atlantic, *C. kullenbergi* occurs in upper Pliocene-lower Pleistocene sequence (Caralp, 1984). This suggests that NADW-like deep water rose up to 1250 m deep during this interval. Therefore, Assemblage D was possibly distributed at shallower depths as middle mesobathyal (1800–2500 m).

In the upper part of Zone IV, Assemblage E is characterized by *Articulina tubulosa* which is a remarkable deep-water species in the present Mediterranean. It is rare below 1300 m, but becomes common below 1800 m (Wright, 1978b). In the Eastern Mediterranean where bottom environment is more or less ill ventilated, *A. tubulosa* replaces *Gyroidina* spp. from 1800 to 3000 m (Massieta et al., 1976) and becomes abundant. In the well ventilated western Mediterranean, for example the Balearic Basin, faunal assemblages are more diversified, and *A. tubulosa* is never a dominant component (Cita and Zocchi, 1978; Bizon and Bizon, 1984c).

Articulina tubulosa is relatively tolerant of oxygen-depletion, and has been found near the sapropel horizons in cores from the Eastern Mediterranean (Mullineaux and Lohmann, 1981). On the contrary, *Gyroidinoides* spp. are common in the intervals between sapropel layers and seems to represent more oxygenated conditions. Therefore, the transition from Assemblage D to Assemblage E at the three sites indicates the beginning of oxygen-depletion in the Tyrrhenian Basin, though we do not have samples from sapropel layers.

A few samples from the middle to upper Pleistocene contain faunas dominated by *Globobulimina* spp. at Sites 652 and 653. This indicates severe low oxygenation. Further, at Site 652, a long interval (about 30 m) with poor benthic foraminifera is found in the middle part of the Pleistocene. It suggests that bottom was under conditions of true stagnant water. On the other hand, Assemblage D occupied again several horizons in the upper Pleistocene at both sites. This suggests that ventilation has revived in lower bathyal basin. This assemblage, however, consists of Mediterranean-type deep water element, but any species indicating NADW-like deep water is excluded.

At Site 654, Assemblage Ea is replaced by Assemblage Eb in the middle Pleistocene. This assemblage is characterized by the association of two elements opposing to each other: *A. tubulosa* vs. *Cassidulina carinata* and *Cibicidoides pachyderma*. The latter element occurs below the outer neritic zone to lower mesobathyal in the Mediterranean today (Parker, 1958; Cita and Zocchi, 1978). In upper Pleistocene sequences, *C. carinata* and *Cibicidoides pachyderma* are dominant components, and their proportions in the fauna fluctuates in the opposite manner to that of *A. tubulosa* element. Therefore, it is regarded as an indicator of oxygen-rich conditions at middle mesobathyal zone (1800–2500 m).

Paleoceanographic Implication

Through the Plio-Pleistocene sequence, comparable faunal changes have been recognized among the three sites. Some differences in faunal composition and also time lags of faunal change are detected among these sites (Fig. 5). They are ascribed to the different paleodepth of each site and probably to differential movements of the basement.

The transition from Assemblage A to Assemblage B occurred in MPl1 biozone at Site 652 (4.7 Ma), the earliest among the three sites. At the other sites, it occurred near the base of MPl2 biozone (about 4.7 Ma). During Zone II, which corresponds to most of the *Cibicidoides(?) italicus* benthic foraminiferal zone (Sprovieri and Hasegawa, this volume), the Tyrrhenian region was the most stable throughout the sequences. Through this period (about 1.9 m.y.), the three sites sank about 200–400 m by the end of *C.(?) italicus* biozone (Fig. 5). Zone II terminated with a long transition period in the lower of MPl5 biozone; 3.1–2.7 Ma at Site 652, 2.9–2.6 Ma at Site 653, and 2.8–2.6 Ma at Site 654. In Zone III, these sites rapidly deepened more than 1000 m during 1.0-m.y. interval. The fauna changed from Assemblages Ca (Sites 652 and 653) and Cb (Site 654) to Assem-

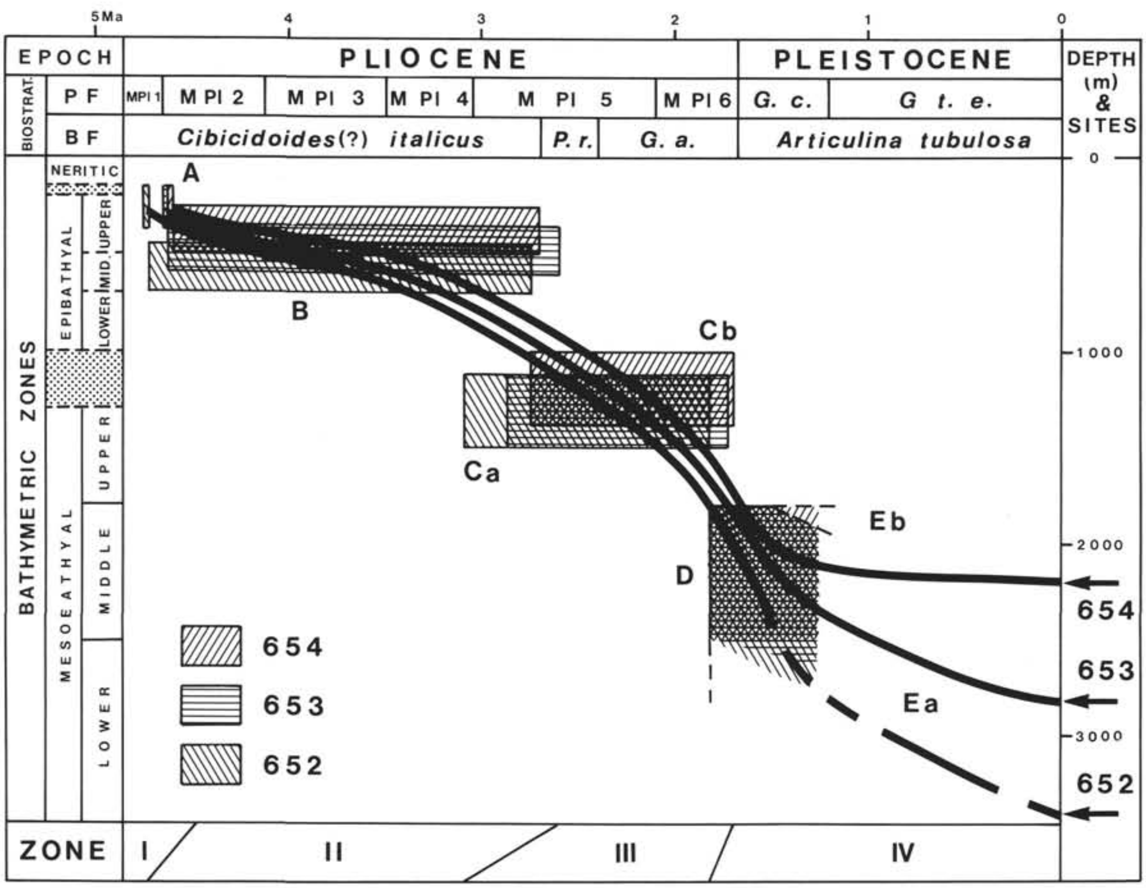

Figure 5. Assumed paleobathymetric curves for the Plio-Pleistocene at Sites 652, 653, and 654. Broken parts stand for intervals not examined for benthic foraminifera. Hatched areas represent stratigraphic ranges (horizontal) and estimated bathymetric ranges (vertical) of each assemblage. Characteristic taxa groups in assemblages: A = *Globocassidulina* spp.; B = *Siphonina reticulata* and *Cibicidoides(?) italicus*; Ca = *Oridorsalis* spp.; Cb = *Sigmoilopsis schlumbergeri*, Miliolina, *Oridorsalis* spp., and *Parrelloides* spp.; D = Miliolina and *Gyroidina* group; Ea = *Articulina tubulosa*; Eb = *Cibicidoides pachyderma, Cassidulina carinata,* and *Articulina tubulosa*. Stippled areas stand for overlapping intervals of adjacent two zones.

blage D in the upper of MPl6 biozone (about 1.8 Ma) at the three sites. During the Pleistocene (Zone IV), Site 652 at 3446 m, deepest site, has continued to subside. On the contrary, Site 654 at 2208 m, shallowest site, becomes stable. At Site 653 at 2817 m, subsidence is estimated at about 600 m.

In the upper Pliocene to lower Pleistocene, many species indicating Atlantic-type cool deep water are found in Zone III and lower part of Zone IV. They suggest that the Tyrrhenian basin was affected in some degree by such a deep water in that time.

One of the peculiar features of the Mediterranean is its circulation pattern of "shallow-in and deep-out." Water-loss caused by evaporation at the surface is compensated by the inflow of surface water of the Atlantic. Dense deeper water spills over the sill at the Strait of Gibraltar into the Atlantic Ocean where it is recognized as the Mediterranean Outflow Water (Vergnaud Grazzini et al., 1986). This pattern seems to have formed only during the Pleistocene. The element of Mediterranean-type deep water, Assemblage D, occupied this region in the late Pliocene. It is seen, however, from the dominance of Assemblages Ca and Cb, and Assemblage D that Atlantic-type deep water was effective even in later time of period.

Additional evidence comes from the Balearic sites of the previous DSDP Leg 42A (Sites 371 and 372), where faunas comparable to Assemblages C and D are reported in the upper Pliocene and lower Pleistocene (Bizon et al., 1978). They listed all the species characterizing this Atlantic-type deep water: *Oridorsalis umbonatus, Sigmoilopsis schlumbergeri*, Miliolina (*Quinqueloculina* spp. and *Triloculina* spp.), *Parrelloides* spp. (*Cibicidoides robertsonianus* and *C. bradyi*), *Cibicidoides wuellerstorfi,* and *Cibicidoides kullenbergi*. This suggests that a uniform deep water expanded from the deep Balearic region to, at least, the deep Tyrrhenian Sea region. Sills between both seas did not play the role of barrier for the deep-sea fauna or for the passage of deep water itself.

If this deep water were of true "Atlantic" origin, it is assumed that the Balearic Sea was connected with the Atlantic, with no effective barrier for deep water circulation: a shallow sill like that at the Strait of Gibraltar was not active during the late Pliocene and early Pleistocene, and Atlantic deep water flowed into the Mediterranean Sea. Occurrence of Assemblage E at the three sites suggests that this deep-water circulation has been interrupted, at least, in the Tyrrhenian Basin since the early Pleistocene. It possibly led to low oxygenation at deep bottom. These phenomena may have been caused by either lowering of the NADW in the Atlantic or activated barriers at the Strait of Gibraltar and/or around the Tyrrhenian Basin, or both during the middle Pleistocene.

CONCLUSION

By means of Q-mode factor analysis, Plio-Pleistocene benthic foraminifera were examined at Sites 652, 653, and 654. Among the three sites, comparable faunal changes were delineated through the sequences. A paleoenvironmental trend at the three sites was delineated as follows:

After the reestablishment of open-marine condition at the beginning of Pliocene, the three sites in the Tyrrhenian Basin were located in upper epibathyal zone (MPl1 biozone). Every site, then, deepened slowly to lower epibathyal zone during most of the Pliocene (MPl2 biozone to lower MPl5 biozone). This period was the most stable for the entire Plio-Pleistocene interval in the Tyrrhenian Basin.

Rapid deepening occurred in the late Pliocene (middle MPl5 biozone to middle MPl6 biozone), and all the sites sank into upper mesobathyal zone. Mediterranean-type deep water occupied this deep bottom. At the same time, some species suggest that Atlantic-like deep water affected the faunas in some degree. Continuous deepening led to more effective Atlantic-like deep water prevailing at the three sites. During the Pleistocene, Sites 652 and 653, deeper sites, continued to sink to the present depth of lower mesobathyal (3446 and 2817 m, respectively). On the contrary, Site 654, the shallowest site, stopped sinking at the present depth (2208 m) of middle mesobathyal zone.

As compared with NADW in the present Atlantic, the temperature of the present Mediterranean deep water is extremely high. On the analogy of faunal composition, a similar degree of difference in water temperature was expected between Atlantic-like deep water and Mediterranean-type deep water in Pliocene-Pleistocene time. Both types of element are contained in faunal assemblages of the upper Pliocene to lower Pleistocene. They occur from the same sections, but dominant elements in each horizon change alternatively. This fact suggests that Atlantic-like deep water intermittently flowed into the Tyrrhenian region which Mediterranean-type deep water usually occupied. This influx may be led by the rise of NADW in the Atlantic.

Both types of deep water seem to have been well oxygenated. On the contrary, low oxygenated deep water has occurred since the early Pleistocene. Such a bad ventilation was caused by either lowering of the NADW in the Atlantic or activated barriers for deep water circulation.

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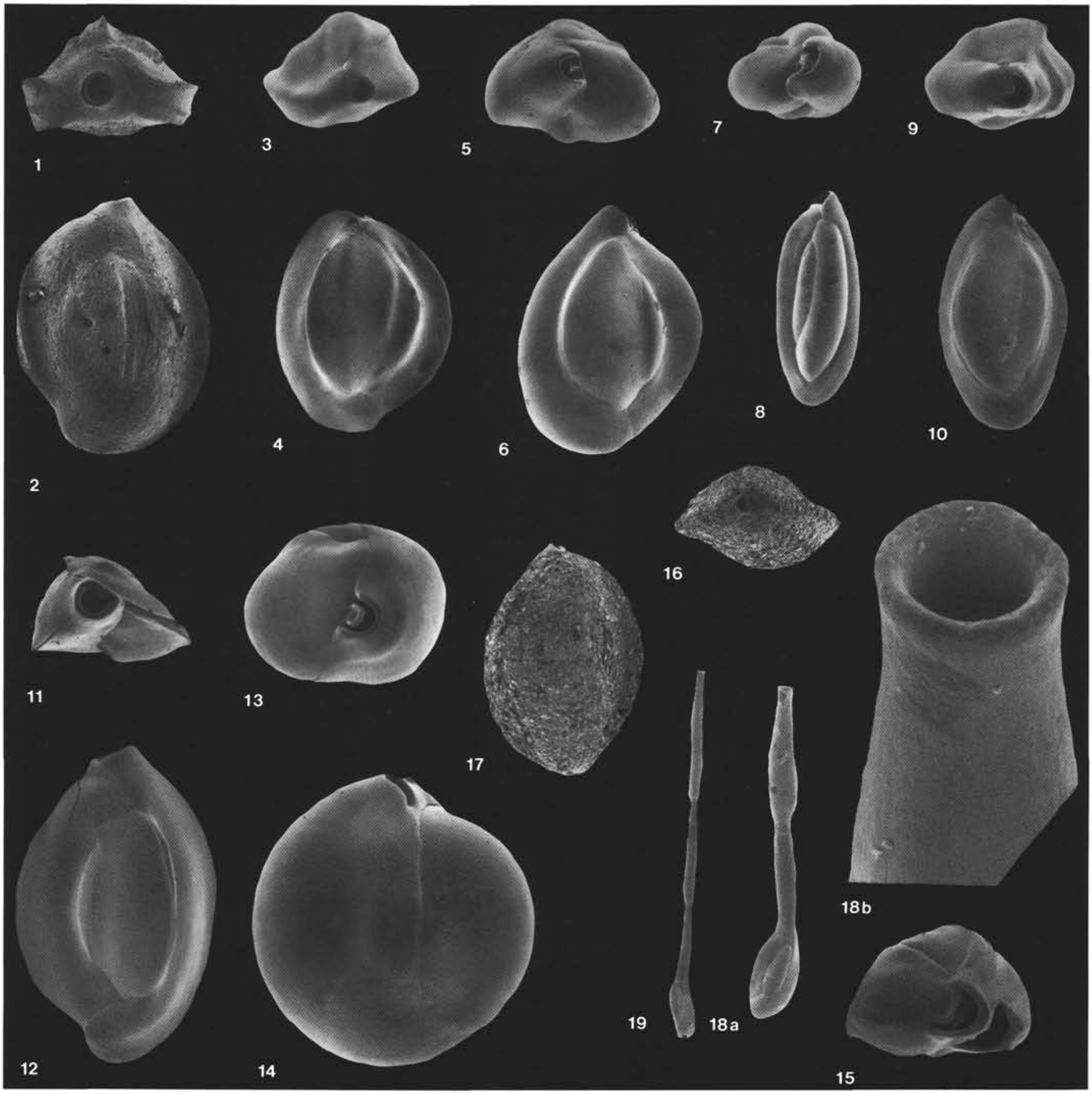

Plate 1. **1, 2.** *Quinqueloculina bicarinata* d'Orbigny. **1.** Sample 107-654A-15R-5, 70–72 cm (48X). **2.** Sample 107-653A-15X-1, 45–47 cm (48X). **3–6.** *Quinqueloculina viennensis* J. and Y. Le Calvez. **3, 4.** Sample 107-653A-1H-2, 45–47 cm (67X). **5, 6.** Sample 107-653A-11H-6, 105–107 cm (48X). **7, 8.** *Quinqueloculina oblonga* (Montagu). Sample 107-653A-10H-2, 45–47 cm (7-99X; 8-67X). **9, 10.** *Quinqueloculina padana* Perconig. Sample 107-653A-2H-3, 105–107 cm (100X). **11, 12.** *Quinqueloculina venusta* Karrer. Sample 107-654A-10R-1, 116–120 cm (100X). **13, 14.** *Miliolinella subrotunda* (Montagu). Sample 107-653A-3H-6, 105–107 cm (67X). **15.** *Miliolinella circularis* (Bornemann). Sample 107-652A-2R-1, 56–59 cm (99X). **16, 17.** *Sigmoilopsis schlumbergeri* (Silvestri). Sample 107-654A-8R-6, 70–72 cm (68X). **18a, b, 19.** *Articulina tubulosa* (Seguenza). **18a, b.** Sample 107-653A-5H-4, 45–47 cm (a-47X; b-apertural view of the same specimen, magnified, 466X); **19.** Sample 107-653A-3H-2, 105–107 cm (46X).

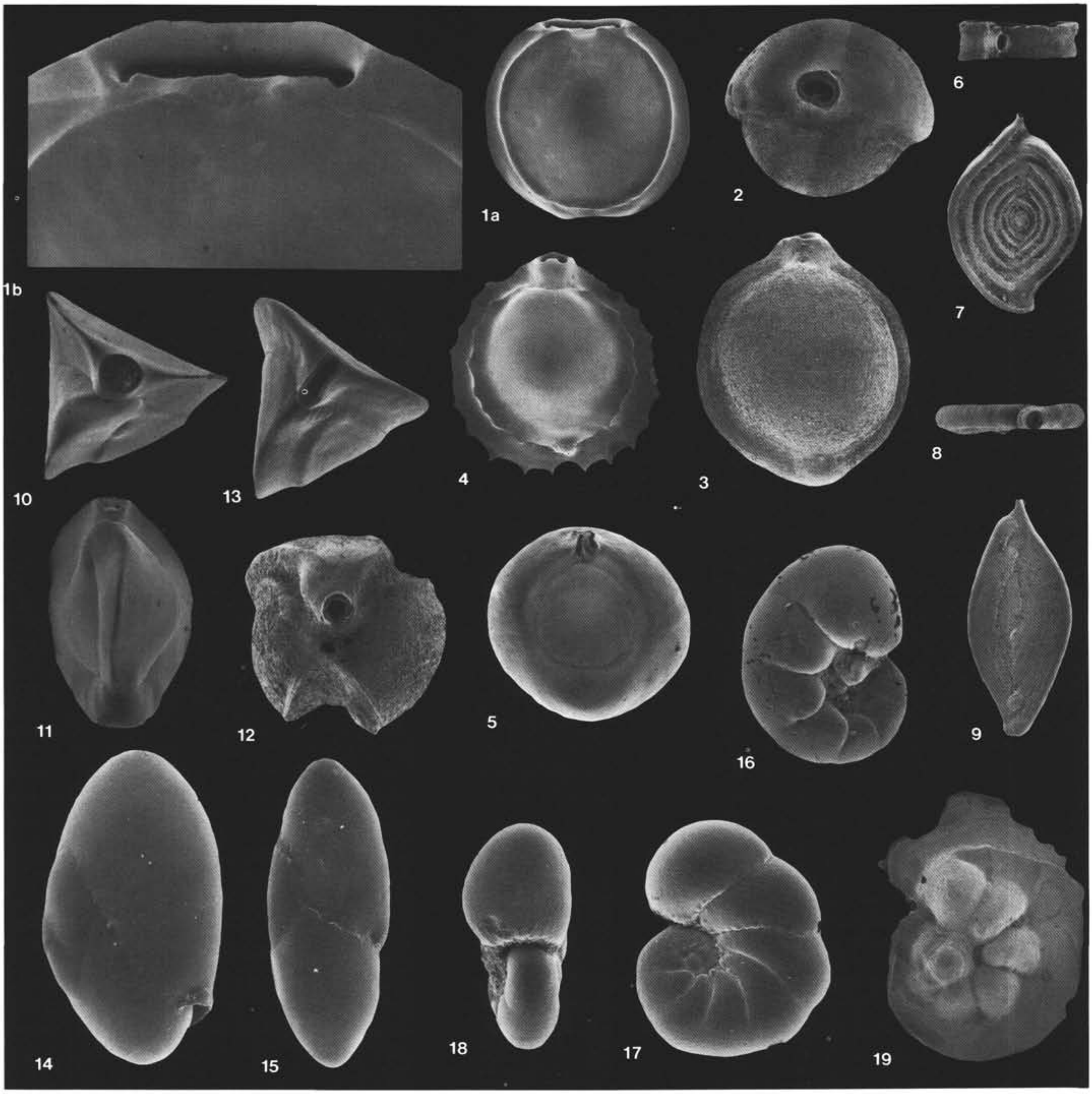

Plate 2. **1a, b.** *Pyrgo depressa* d'Orbigny. Sample 107-653A-1H-2, 45–57 cm (a-30X; b-99X). **2, 3.** *Pyrgo lucernula* (Schwager). Sample 107-653A-5H-2, 105–107 cm (31X). **4.** *Pyrgo serrata* (Bailey). Sample 107-653A-4H-4, 105–107 cm (31X). **5.** *Pyrgoella sphaera* d'Orbigny. Sample 107-653A-2H-4, 45–47 cm (48X). **6, 7.** *Spiroloculina canaliculata* d'Orbigny. Sample 107-653A-7H-1, 105–107 cm (48X). **8, 9.** *Sigmoilinita tenuis* (Czjzek). Sample 107-653A-9H-2, 105–107 cm (8-101X; 9-66X). **10, 11.** *Triloculina tricarinata* d'Orbigny. Sample 107-653A-8H-1, 105–107 cm (10-135X; 11-100X). **12.** *Triloculina gibba* d'Orbigny. Sample 107-653A-8H-3, 105–107 cm (48X). **13.** *Cruciloculina staurostoma* (Schlumberger). Sample 107-653A-2H-3, 105–107 cm (100X). **14.** *Chilostomella mediterranensis* Cushman and Todd. Sample 107-653A-2H-5, 105–107 cm (97X). **15.** *Chilostomella oolina* Schwager. Sample 107-653A-9H-6, 105–107 cm (97X). **16-18.** *Valvulineria marmorea* Conato. Sample 107-653A-14X-1, 105–107 cm (136X). **19.** *Laticarinina pauperata* (Parker and Jones). Sample 107-652A-16R-3, 105–107 cm (65X).

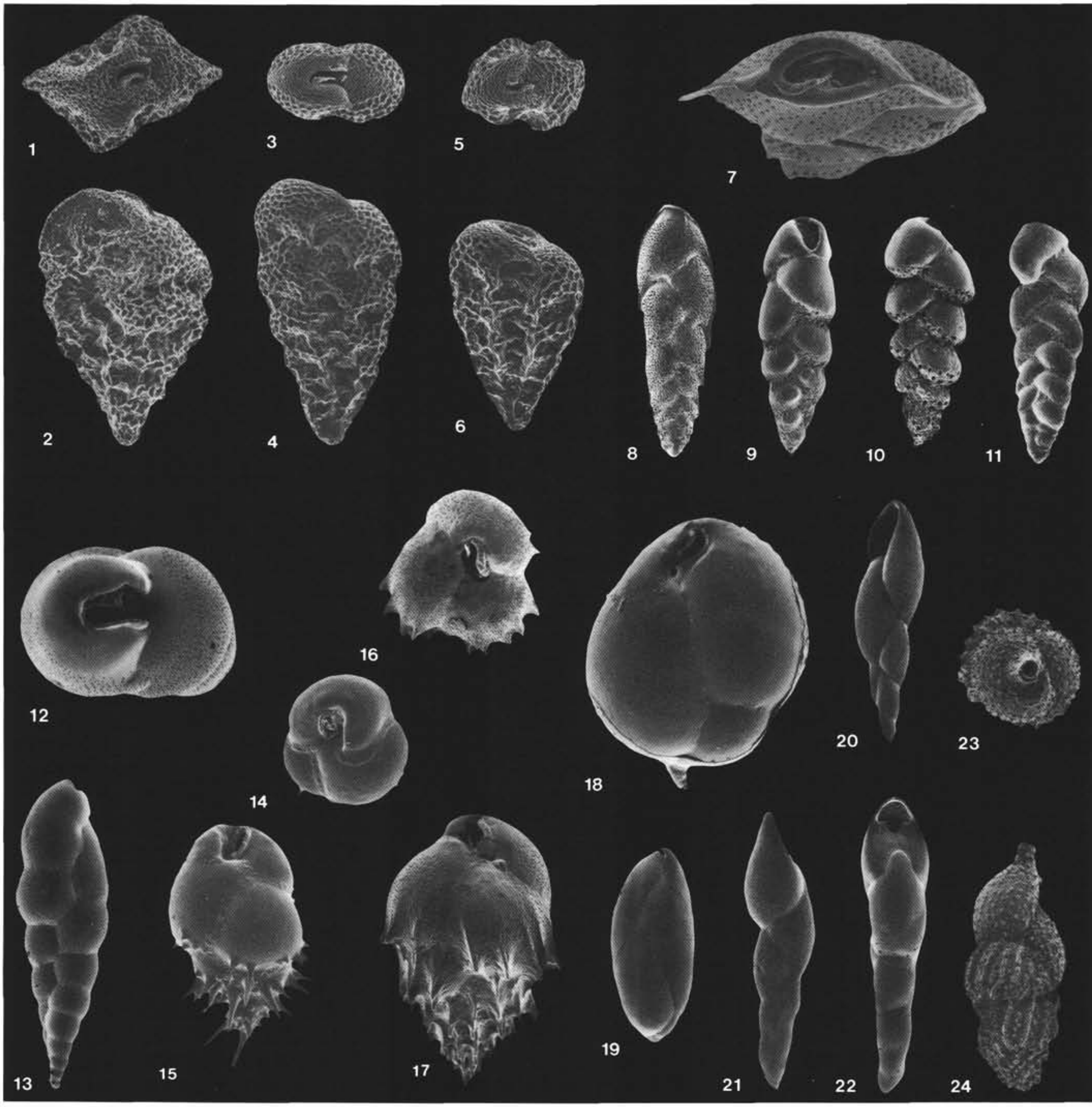

Plate 3. **1, 2.** *Bolivina cistina* Cushman. Sample 107-654A-11R-2, 132–134 cm (132X). **3, 4.** *Bolivina plicatella* Cushman. **3.** Sample 107-652A-20R-5, 21–23 cm (132X); **4.** Sample 107-653A-7H-5, 105–107 cm (132X). **5, 6.** *Bolivina pseudoplicata* Heron-Allen and Earland. Sample 107-654A-10R-1, 116–118 cm (132X). **7, 8.** *Brizalina alata* (Seguenza). Sample 107-653A-9H-6, 105–107 cm (7-201X; 8-97X). **9.** *Brizalina spinescens* (Cushman). Sample 107-654A-10R-1, 116–118 cm (97X). **10.** *Brizalina subspinescens* (Cushman). Sample 107-653A-8H-6, 101–103 cm (97X). **11.** *Brizalina lucidopunctata* (Conato). Sample 107-653A-23X-5, 105–107 cm (135X). **12, 13.** *Brizalina translucens* (Phleger and Parker). Sample 107-653A-4H-4, 105–107 cm (12-204X; 13-99X). **14, 15.** *Bulimina aculeata* d'Orbigny. Sample 107-653A-3H-4, 105–107 cm (66X). **16, 17.** *Bulimina clava* Cushman and Parker. Sample 107-653A-2H-4, 45–47 cm (99X). **18.** *Globobulimina ovula* (d'Orbigny). Sample 107-653A-8H-6, 101–103 cm (99X). **19.** *Praeglobobulimina glabra* (Cushman and Parker). Sample 107-653A-2H-4, 105–107 cm (67X). **20.** *Stainforthia complanata* (Egger). Sample 107-654A-11R-1, 132–136 cm (99X). **21, 22.** *Pleurostomella alternans* Schwager. Sample 107-653A-23X-4, 105–107 cm (67X). **23, 24.** *Uvigerina pigmea* d'Orbigny. Sample 107-652A-19R-2, 105–107 cm (100X).

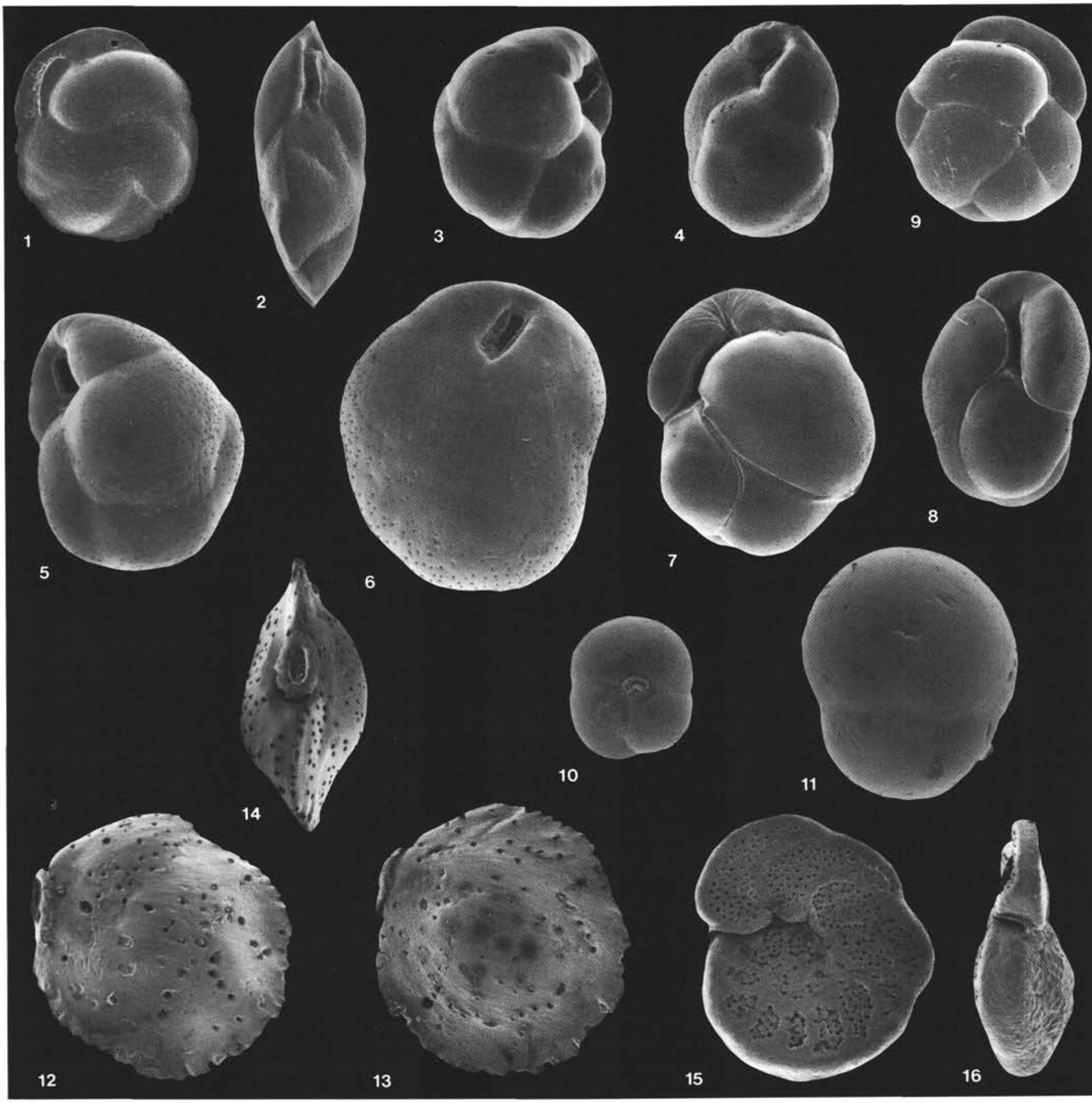

Plate 4. **1, 2.** *Cassidulina carinata* Silvestri. **1.** Sample 107-653A-1H-2, 102–104 cm (132X). **2.** Sample 107-653A-2H-1, 45–47 cm (132X). **3, 4.** *Globocassidulina oblonga* (Reuss). Sample 107-653A-14X-2, 105–107 cm (134X). **5, 6.** *Globocassidulina subglobosa* (Brady). Sample 107-654A-23R-3, 110–112 cm (198X). **7, 8.** *Globocassidulina* aff. *crassa* (d'Orbigny). Sample 107-652A-8R-2, 80–83 cm (129X). **9.** *Paracassidulina minuta* (Cushman). Sample 107-653A-22X-3, 105–107 cm (132X). **10, 11.** *Sphaeroidina bulloides* d'Orbigny. **10.** Sample 107-653A-23X-6, 45–47 cm (100X). **11.** Sample 107-654A-14R-5, 116–120 cm (100X). **12–14.** *Siphonina reticulata* (Czjzek). Sample 107-653A-22X-3, 105–107 cm (99X). **15, 16.** *Planulina ariminensis* d'Orbigny. **15.** Sample 107-654A-18R-1, 116–118 cm (67X). **16.** Sample 107-654A-18R-5, 116–118 cm (67X).

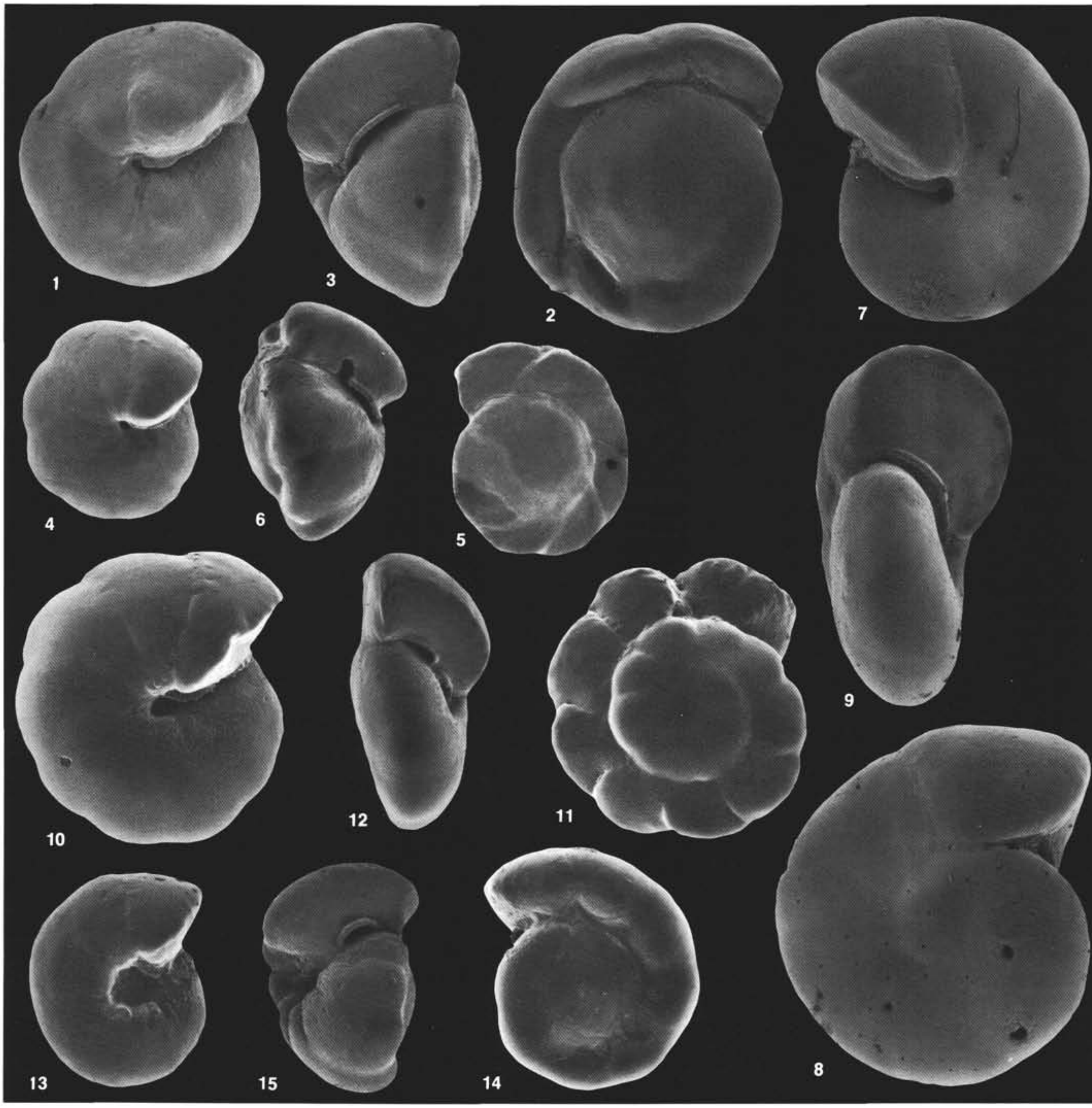

Plate 5. **1-3.** *Gyroidinoides altiformis* (K.C. and R.E. Stewart). Sample 107-653A-9H-5, 105–107 cm (132X). **4–6.** *Gyroidinoides altiformis delicata* (Parker). Sample 107-653A-2H-2, 105–107 cm (138X). **7–9.** *Gyroidinoides laevigata* (d'Orbigny). **7.** Sample 107-653A-23X-5, 45–47 cm (134X). **8, 9.** Sample 107-653A-23X-3, 105–107 cm (8-134X; 9-132X). **10–12.** *Gyroidina* cf. *neosoldanii* Brotzen (sensu Parker, 1958). **10, 12.** Sample 107-653A-4H-1, 105–107 cm (137X). **11.** Sample 107-652A-4R-4, 120–122 cm (137X). **13–15.** *Gyroidina soldanii* d'Orbigny. Sample 107-652A-10R-4, 114–116 cm (13, 14-135X; 15-134X).