

17. STRONTIUM-ISOTOPE STRATIGRAPHY FROM SITES 918 AND 919¹

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ABSTRACT

A detailed Sr-isotope stratigraphy has been established for the Cenozoic sediments drilled during Leg 152. The Sr-isotope record is disturbed in several intervals due to reworking of foraminifers and reaction between pore waters and carbonate. A Sr-isotope chronology based on well-preserved samples has been established for the Neogene sediments drilled, while diagenesis and low abundance of carbonate fossils hindered age determination in older sediments. Ages have been calculated by comparing our results with previously published, well-dated ⁸⁷Sr/⁸⁶Sr records. At Site 918, which contains one of the most complete records of glaciation in the North Atlantic, more or less continuous Sr-isotope dating was possible back to 22.6 ± 0.8 Ma (early Miocene). Site 919 was found to contain Pleistocene sediment no older than 1.0 Ma. The sedimentation rate at the two studied sites is about 11.0 cm/k.y. in the Pliocene–Pleistocene part of the sequence (2.9 Ma until today). In the older sediment deposited between 22.5 and 10.4 Ma, the sedimentation rate has been calculated to 2.4 cm/k.y. The higher sedimentation rate in the Pliocene–Pleistocene sediment probably reflects the buildup of glaciers in southern Greenland followed by increasing amounts of ice-rafted detritus into the Greenland Sea sediments.

INTRODUCTION

The Cenozoic, and especially the Neogene, part of the Sr-isotope seawater curve has received attention recently (DePaolo, 1986; Hess et al., 1989; Hodell et al., 1989, 1990, 1991; Miller et al., 1991; Hodell and Woodruff, 1994; Oslick et al., 1994; Farrell, 1995; Mead and Hodell, 1995). This has allowed the development of a detailed marine Sr-isotope chronology for the Neogene and the Oligocene based on high precision measurements of well-dated Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) sites. It has been shown that the Sr-isotope composition of the oceans has increased during the Neogene from a ⁸⁷Sr/⁸⁶Sr value of about 0.7082 at the Oligocene/Miocene boundary to 0.7092 in the modern ocean (Hodell et al., 1991).

The purpose of this study was to establish a Sr-isotope chronology for the Oligocene and Neogene sediments from ODP Sites 918 and 919. Dating of the upper Neogene sediments found at these sites is especially interesting because they contain a detailed record of the glacial history of the North Atlantic Ocean and East Greenland.

The abundance and diversity of microfossils at Sites 918 and 919 are generally less than that of low latitude sites, and precise magnetostratigraphic age assignments were a problem due to the low recovery, especially at Site 918 (Shipboard Scientific Party, 1994a). Sr-isotope stratigraphy can thus provide a valuable supplement to the biostratigraphy. However, the occurrence of turbidites causes mixing of foraminifers of different ages and reversals in the Sr-isotope curves in certain intervals (Shipboard Scientific Party, 1994a). Reversals are defined as downhole increases in ⁸⁷Sr/⁸⁶Sr values; that is, the opposite of what should be expected for a Neogene sequence (Hodell et al., 1991). Diagenetic alteration of the original Sr-isotope signal is also a problem in some intervals, especially in the deeper part of Hole 918D.

LOCATION AND DRILLING SUMMARY

The two sites studied are located in the Greenland Sea near latitude 63°N, 40 km (Site 918) and 115 km (Site 919) off the East Greenland coast (see location map inside front cover of this volume).

Site 918

Hole 918A is located at 63°5.569'N, 38°38.336'W and penetrated 332.7 meters below seafloor (mbsf) with a core recovery of 78.2% using the hydraulic piston corer (APC). Hole 918D is only slightly offset from 918A at 63°5.572'N, 38°38.334'W. The hole was washed down to 253.2 mbsf, but no core was recovered above 325.0 mbsf. Thereafter, the rotary core barrel (RCB) was used to a total depth of 1310 mbsf with an average recovery of 25.1%. The oldest sediment recovered before the drill went into basement was at 1189.4 mbsf. Altogether 56 samples were analyzed for Sr isotopic composition at Site 918.

Site 919

Eighteen samples were analyzed from both Holes 919A and 919B. Hole 919A is situated at 62°40.200'N, 37°27.611'W and was drilled to 93.5 mbsf with 100% recovery. Hole 919B (62°40.201'N, 37°27.618'W) was cored to 18.7 mbsf, washed down to 90.0 mbsf, and thereafter cored to a total depth of 147 mbsf. Recovery at Hole 919B was also 100%.

SEDIMENTS

At Site 918, the most complete record of Miocene and Pliocene glacial sediments was obtained (Shipboard Scientific Party, 1994a; Larsen et al., 1994). The upper 550 m of sediment comprise abundant silts and muds, within which numerous granule- to pebble-size clasts are suspended. Two sediment facies have been identified in the upper 550 m of Site 918. The first is interpreted as hemipelagic sediment with dropstones and the second as massive glaciomarine diamictons. Both sediment types reflect a glacial environment characterized by high sedimentation rates, which were estimated at up to 19.9 cm/k.y. (Shipboard Scientific Party, 1994a). From 550 to 600 mbsf, the sediment consists of silt and siliciclastic terrigenous debris containing

¹Saunders, A.D., Larsen, H.C., and Wise, S.W., Jr. (Eds.), 1998. *Proc. ODP, Sci. Results, 152*: College Station, TX (Ocean Drilling Program).

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volcaniclastic components. From 600 to 806 mbsf, the sediment consists of moderately to heavily bioturbated nannofossil chalk and very dark gray silt with nannofossils. The average nannofossil content is 35%, but values up to 90% occur in some intervals. From 806 to 1011 mbsf, the lithology consists of interbeds of nannofossil chalk and massive to faintly laminated silt and sand. The silt and sand beds are composed of quartz, feldspar, and volcaniclastic grains. Below 1011 and down to 1108 mbsf is a coarse terrigenous sediment consisting of massive, highly bioturbated sand. Nannofossils and other microfossils are almost absent. The last sedimentary unit at Site 918 that concerns this study is composed of nannofossil chalk enriched in clay or altered volcaniclastic grains and silt with nannofossils (up to 50%). This unit extends down to 1157 mbsf.

Sediment at Site 919 was assigned to a single lithologic unit primarily composed of silty clay or clayey silt. Nearly 200 separate thin beds with fining-upward grain size and sharp basal contacts were identified in this sediment sequence. These beds ranged in thickness from 5 cm to several meters and have been interpreted as turbidites (Shipboard Scientific Party, 1994b).

SAMPLES AND ANALYTICAL PROCEDURE

All samples were washed in distilled water and dried at room temperature in order to avoid any contamination or Sr exchange (Spezzaferrri, this volume). Three kinds of fauna were analyzed for Sr isotopic ratios: planktonic foraminifers, benthic foraminifers, and fragments of mollusk shells. The fauna were picked from the same samples used for biostratigraphy. The planktonic foraminifer *Neogloboquadrina pachyderma* was mainly used. In those samples where this species was not abundant, *Neogloboquadrina dutertrei*, *Neogloboquadrina acostaensis*, *Neogloboquadrina humerosa*, *Neogloboquadrina atlantica* (dextral and sinistral forms), and rarely *Globigerina bulloides*, *Globorotalia scitula*, and *Globorotalia inflata* were also selected. In Sample 152-918D-24R-2, 68–70 cm, a few specimens of *Orbulina universa* were also analyzed. Only the most abundant genera of benthic foraminifers were analyzed for Sr isotopes. They include *Pullenia*, *Cassidulina*, *Globocassidulina*, *Cibicides*, *Melonis*, *Oridorsalis*, *Planulina*, *Pseudoparrella*, *Gyroidinoides*, *Buliminella*, *Elphidium*, and *Astrononion*.

Planktonic foraminifers were preferentially used for Sr-isotope stratigraphy and chronology. When possible only the best preserved and in situ foraminifer specimens with little or no sign of recrystallization were used (Plates 1, 2). Specimens with sediment trapped inside the shell were avoided.

Leached sediments were only used in the interval below 700 mbsf at Site 918 where no foraminifer material was available and where CaCO₃ content was greater than 5%. In an attempt to minimize the potential reaction with noncarbonate sediments, samples with the highest carbonate concentration were preferred.

For isotopic analysis, between 0.1 and 1 mg of sample was dissolved and Sr separated from solution by ion exchange before loading onto a single W or Re filament. Sediment samples were leached in 0.1 N HCl or 10% acetic acid before being centrifuged. The supernate was removed with a pipette and evaporated before being redissolved in HNO₃ for ion exchange chemistry. The purpose of the leaching approach was to dissolve only the carbonate fraction of the sediment. The dissolved carbonate fraction was between 5% and 10% of the leached sediment sample (Shipboard Scientific Party, 1994a).

The samples of Sr were analyzed in dynamic multicollector mode on a VG Sector mass spectrometer. Samples were analyzed both at the Danish Center for Isotope Geology at the University of Copenhagen and at the Radiogenic Isotope Geochemistry Laboratory at the University of Michigan. A NBS987 standard was analyzed for every five or 10 samples. Internal precision was normally $\pm 10^{-5}$ or less; the mean error (2 s.d.) for the NBS987 was 0.710242 ± 15 ($n = 17$) for standards analyzed in Copenhagen and 0.710245 ± 10 ($n = 13$) for the

standards analyzed in Michigan. Sr-isotope data were corrected to NBS987 = 0.710248, using the average of appropriate in run standards (Tables 1, 2).

Four samples were analyzed at both laboratories to test for inter-laboratory differences. Three of these were leached sediment samples (Table 1); the fourth was a Jurassic belemnite sample. These duplicates were subjected to the total analytical procedure, including leaching of the sediments in 0.1 M HCl. The difference between the four duplicates ranged from 1×10^{-6} to 23×10^{-6} , with an average of 11×10^{-6} (Table 1). The difference is within laboratory reproducibility.

Sample 152-918D-60R-1, 26–28 cm, was also leached in 10% acetic acid. The result was not significantly different from the aliquot of the sample leached in 0.1 M HCl (Table 1). Duplicate analyses of foraminifer samples were not often possible because samples were too small to split. One duplicate analysis of Sample 152-918D-39R-6, 73–75 cm (benthic foraminifer), gave a difference of only 1×10^{-6} . This is obviously not representative of sample duplicates, but duplicates generally were comparable to the precision of the NBS standard. We, therefore, used error bars of $\pm 15 \times 10^{-6}$, which is 2 s.d. of the NBS987 standard at the laboratory at the University of Copenhagen. Data from Site 919, however, were analyzed over a short time interval at the University of Michigan and with very reproducible NBS987 standard values. We therefore used error bars of only $\pm 10 \times 10^{-6}$ for Site 919 ⁸⁷Sr/⁸⁶Sr values.

RESULTS

Site 918

The results of the Sr-isotope analysis of samples from Site 918 are shown in Figure 1 and Table 1. From 0 to 700 mbsf, foraminifers and, in two cases, mollusk fragments have been analyzed for Sr-isotope composition. From the top of the hole to the deepest sample analyzed (1098 mbsf), there is a general downhole decreasing trend in ⁸⁷Sr/⁸⁶Sr ratios. The Sr-isotope values decreased from modern seawater values (0.7092) at the top of the sequence to middle Miocene values (0.7088) at 1098 mbsf (Hodell et al., 1991). There is a major discontinuity in the record, between 320 and 485 mbsf, where no suitable foraminifers or other carbonate material were available.

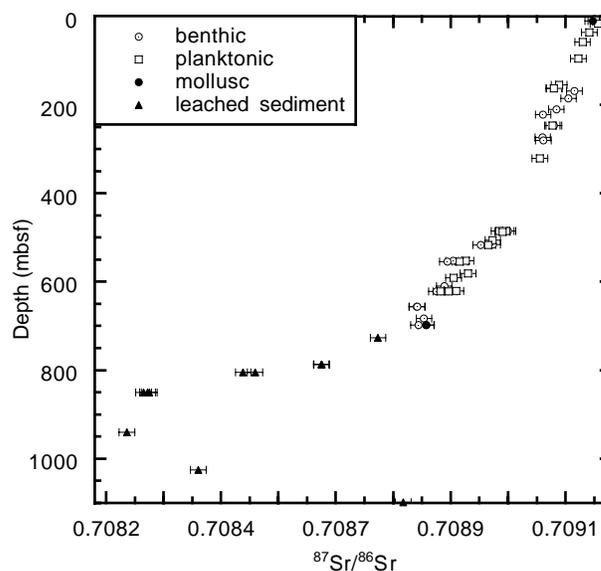


Figure 1. Strontium isotope variations in planktonic and benthic foraminifers, mollusk fragments, and leached sediments at Site 918.

Table 1. Results of the Sr-isotope analyses from Site 918.

Core, section, interval (cm)	Type	Preservation	Depth (mbsf)	$^{87}\text{Sr}/^{86}\text{Sr}$	Age (Ma)	Age err. +	Age err. -
152-918A-							
2H-6, 95-97	mol	G	10.26	0.709173	0.4	0.6	
2H-6, 95-97	pl	G	10.26	0.709178	0.3	0.7	
3H-5, 30-32	pl	G	16.26	0.709183	0.0	0.8	
5H-4, 120-122	pl	G	36.01	0.709166	0.6	0.5	
7H-6, 126-128	pl	G	58.07	0.709153	0.9	0.5	
10H-6, 64-65	pl	G	95.45	0.709145	1.0	0.5	0.6
18H-4, 120-122	pl	P	154.77	0.709107	1.7	0.9	0.5
19H-4, 95-97	pl		162.41	0.709098	1.9	1.7	0.6
19H-4, 95-97	bt		162.41	0.709098	1.9	1.7	0.6
19H-5, 95-97	bt	M	168.76	0.709137	1.1	0.6	0.5
21X-3, 46-48	bt	M/P	184.97	0.709126	1.3	0.6	0.5
24X-1, 96-98	bt	M	209.67	0.709102	1.8	1.1	0.6
25X-3, 94-98	bt	P	221.55	0.709076	2.7	2.3	1.0
28X-2, 96-98	bt	G/M	246.57	0.709097	1.9	1.8	0.6
28X-2, 96-98	pl	G/M	246.57	0.709107	2.3	2.4	0.7
31X-2, 95-97	bt	P	273.06	0.709076	2.7	2.3	1.0
32X-1, 96-98	bt	M/P	280.47	0.709077	2.6	2.3	0.9
37X-4, 95-97	pl	G	320.56	0.709083	4.4	0.9	2.3
152-918D-							
22R-1, 134-136	bt		485.15	0.709009	5.8	0.6	0.6
22R-1, 134-136	pl		485.15	0.709018	6.0		0.6
22R-2, 8-10	pl	M/P	485.40	0.709004	6.3		0.6
22R-3, 8-10	pl	M	486.90	0.709011	6.2		0.5
24R-2, 68-70	pl	P	505.39	0.708992	6.6		0.6
25R-4, 72-74	bt		515.83	0.708979	6.4		0.6
25R-5, 3-4	pl	M	516.93	0.708970	6.6		0.6
25R-5, 3-5	bt	M/P	516.93	0.708955			
29R-1, 95-97	bt	M/P	552.36	0.708903			
29R-1, 95-97	pl	M/P	552.36	0.708927	10.1	0.8	0.8
29R-2, 95-97	pl	M	553.86	0.708915	10.6	0.8	0.8
29R-2, 95-97	bt	M	553.86	0.708891			
32R-1, 95-97	pl	M	581.26	0.708931	10.0	0.8	0.8
33R-1, 93-95	pl	M/G	590.94	0.708903	11.0	0.8	0.8
35R-1, 68-69	bt	M	609.88	0.708885			
36R-1, 130-132	pl	M	620.21	0.708908	10.8	0.8	0.8
36R-2, 75-78	pl	M	621.16	0.708878	12.0	0.8	0.8
36R-2, 123-126	bt	M/G	621.66	0.708870			
36R-2, 123-126	pl	M/G	621.66	0.708894	11.3	0.8	0.8
39R-6, 73-75	bt	G	656.14	0.708832	13.7	0.8	0.8
		G	656.14	0.708833	13.7	0.8	0.8
42R-4, 127-129	bt	G	682.58	0.708846	13.2	0.8	0.8
44R-1, 96-98	bt		697.07	0.708850	13.0	0.8	0.8
44R-1, 96-98	mol		697.07	0.708851			
44R-1, 96-98	bt	P/M	697.07	0.708835	13.6	0.8	0.8
47R-2, 80-82	leac		726.01	0.708757	16.1	0.4	0.4
53R-3, 71-73	leac		786.22	0.708647	17.7	0.4	0.4
	leac		786.22	0.708648	17.7	0.4	0.4
55R-2, 68-70	leac		803.99	0.708496	19.9	0.4	0.4
	leac		803.99	0.708519	19.6	0.4	0.4
53R-3, 26-28	leac		850.27	0.708303	22.7	0.4	0.4
	leac		850.27	0.708314	22.6	0.4	0.4
	leac		850.27	0.708311	22.6	0.4	0.4
63R-1, 80-83	leac		940.27	0.708271			
72R-1, 9-12	leac		1025.27	0.708409			
86R-1, 5-7	leac		1098.64	0.708806			
89R-2, 13-15	bt	P	1128.64	0.707806			
10R-2, 113-115	bt	P	1138.53	0.707810			

Notes: All $^{87}\text{Sr}/^{86}\text{Sr}$ values are normalized to NBS987 = 0.710248. In age calculations are included differences in the NBS987 $^{87}\text{Sr}/^{86}\text{Sr}$ value used in this study and the NBS987 value used in the respective Sr isotope-age equations. pl = planktonic foraminifer, bt = benthic foraminifer, mol = mollusk shell, leac = leached sediment. Preservation: P = poorly, M = moderate, G = good.

In Hole 918A, the $^{87}\text{Sr}/^{86}\text{Sr}$ values of planktonic foraminifers decrease from about 0.70917 to 0.70907 from the top of the sequence to 320 mbsf, respectively. There are no reversals and no indications of major gaps in the planktonic Sr-isotope record. The $^{87}\text{Sr}/^{86}\text{Sr}$ values of benthic foraminifers, however, show one reversal at 240 mbsf and an offset toward higher $^{87}\text{Sr}/^{86}\text{Sr}$ values between 160 and 200 mbsf. There is a larger spread about the general trend decreasing downhole for the benthic foraminifers in this interval than expected for seawater Sr isotopic compositions (Hodell et al., 1991). From 485 to 700 mbsf, at Hole 918D, the Sr isotopic composition of planktonic and benthic foraminifers decreases rapidly from 0.70900 to 0.70882, respectively. There is a major barren interval between Cores 152-918D-26R and 29R, where no foraminifers or other suitable carbonate material were found. There is less scatter in $^{87}\text{Sr}/^{86}\text{Sr}$ values around the general trend decreasing downward than there is at Hole 918A; however, between 515 and 620 mbsf all benthic display lower $^{87}\text{Sr}/^{86}\text{Sr}$ values than do the planktonic foraminifers.

Below 700 mbsf (Hole 918D), only bulk carbonate samples were used for isotopic determination. The samples from Hole 918D show a trend decreasing downhole from 726 to 850 mbsf. From 850 to 1100 mbsf, bulk carbonate samples show a sudden trend increasing downhole.

Site 919

Samples from both Holes 919A and 919B were analyzed. Only planktonic foraminifers were used for Sr isotopic determination at Site 919 (Fig. 2; Table 2). In one case, benthic foraminifers from Section 152-919A-1H-1 were analyzed. These gave a $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.70884 (Table 2). Because of the large difference in isotope value between planktonic and benthic foraminifers from this interval, no further attempt was made to analyze benthic foraminifers from Site 919. The variation in $^{87}\text{Sr}/^{86}\text{Sr}$ values from the top of Hole 919A (Section 152-919A-1H-1) to the bottom of Hole 919B (Section 152-

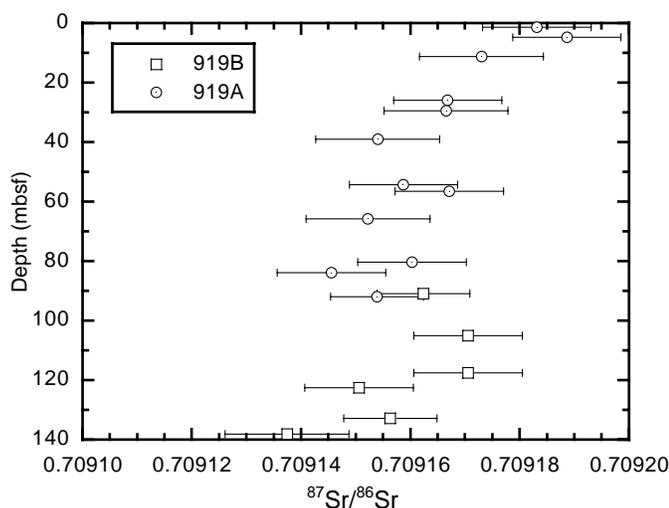


Figure 2. Strontium isotope variations in planktonic foraminifers at Site 919.

Table 2. Results of the Sr isotopes analyzed from Site 919.

Core, section, interval (cm)	Type	Preservation	Depth (mbsf)	$^{87}\text{Sr}/^{86}\text{Sr}$
152-919A-				
1H-1, 130-132	pl	G	1.31	0.709192
1H-1, 130-132	bt	G	1.31	0.708846
1H-4, 20-22	pl	G	4.71	0.709198
2H-3, 13-15	pl	G	11.14	0.709182
3H-6, 95-97	pl	G	25.96	0.709176
4H-2, 95-97	pl	G	29.46	0.709176
5H-2, 95-97	pl	G	38.96	0.709163
6H-6, 78-80	pl	G	54.29	0.709168
7H-1, 95-97	pl	G	56.46	0.709176
8H-1, 79-81	pl	G	65.8	0.709161
9H-4, 130-132	pl	G	80.3	0.709169
9H-7, 29-31	pl	G	83.8	0.709155
10H-6, 41-43	pl	G	91.92	0.709163
152-919B-				
3H-1, 94-96	pl	G	90.95	0.709171
4H-3, 95-97	pl	G	105	0.709180
5H-6, 97-99	pl	G	117.5	0.709180
6H-3, 96-98	pl	G	122.5	0.709160
7H-4, 30-32	pl	G	132.8	0.709165
8H-1, 56-58	pl	G	138.1	0.709146

Notes: All data are normalized to NBS987 = 0.710248. pl = planktonic foraminifer, bt = benthic foraminifer. Preservation: P = poorly, M = moderate, G = good.

919B-8H-1) is only 0.00005. However, because of the small error bars on Site 919 data, it is possible to resolve a slight trend decreasing downward in $^{87}\text{Sr}/^{86}\text{Sr}$ values at Hole 919A from 0.70917 at the top of the hole to 0.70915 at 84 mbsf. In Hole 919B, the $^{87}\text{Sr}/^{86}\text{Sr}$ value drops to 0.70914 at 138.1 mbsf, the lowest Sr-isotope value measured at Site 919.

DISCUSSION

Diagenesis and Pore Water

Careful consideration of diagenesis is necessary in order to use Sr-isotope values of carbonate material as an indicator of contemporaneous seawater Sr isotopic composition (Richter and DePaolo, 1988). Diagenetic alteration of foraminifers is mainly a problem in samples from Site 918. In general, preservation decreases and recrystallization increases with depth in the Pleistocene to upper Miocene sequence of Site 918 (Spezzaferrri, this volume). This trend has been observed previously in Sites 871 and 872 (Israelson et al., 1995). Plate 2 shows the poorly preserved lower-middle Miocene species *Zeaglobigerina woodi*, *Zeaglobigerina connecta*, *Globorota-*

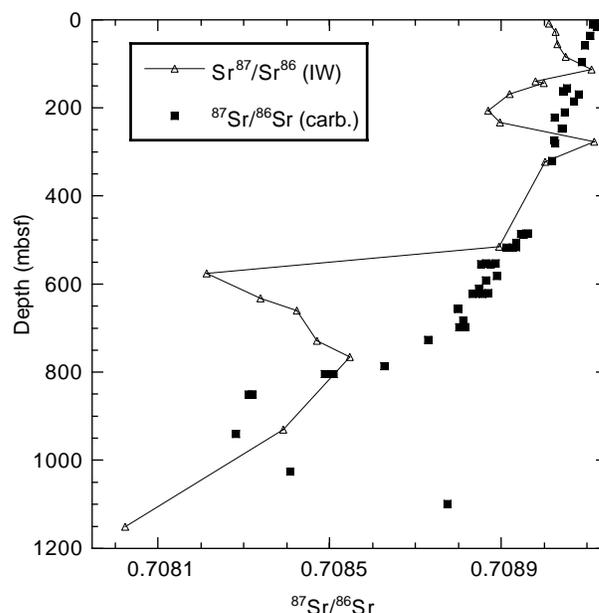


Figure 3. Carbonate and interstitial water isotopic composition at Site 918. Interstitial water data are from Gieskes et al. (this volume).

lia zealandica, and *Globigerinoides bisphericus*. All the specimens analyzed in this study were visually examined before selection for isotopic analyses to prevent erroneous results due to diagenesis, and several samples were inspected by Scanning Electron Microscope (SEM) (Plates 1, 2).

Special care needs to be taken if bulk carbonate material is used as an indicator of seawater Sr isotopic composition at the time of deposition of the carbonate. It was not possible to visually examine the samples, and there is the risk of dissolving Sr from the clastic component of the sediments when the samples are leached. A general problem with carbonate material is that reaction with pore waters and siliceous sediments can cause alteration of the original isotope signal (Richter and DePaolo, 1988; Gieskes et al., 1987). To further examine whether the original seawater Sr isotopic composition of carbonate material had been altered, we compared carbonate data with interstitial water Sr-isotope data (Fig. 3). A more complete discussion of pore water geochemistry at Sites 918 and 919 can be found in Gieskes et al. (this volume).

As mentioned previously, benthic foraminifers at Site 918 between 515 and 620 mbsf have lower $^{87}\text{Sr}/^{86}\text{Sr}$ values than the planktonic foraminifers. The difference is only between 0.000010 and 0.000025 and is close to the limit of analytical precision. However, because it is consistent, it could be an indication that one or another type of foraminifer is recording a Sr-isotope composition different from seawater at the time of deposition. Figure 3 shows that there is a significant decrease in interstitial water $^{87}\text{Sr}/^{86}\text{Sr}$ values from 0.70893 to 0.70819 in the interval between 515 and 575 mbsf. This sudden shift probably reflects alteration of volcanic material and indicates that the interstitial water has reacted with the sediment (Gieskes et al., this volume). Alteration of volcanic material has previously been shown to affect pore water Sr isotopic composition (Hawkesworth and Elderfield, 1978; Gieskes et al., 1987).

The lower than contemporaneous carbonate $^{87}\text{Sr}/^{86}\text{Sr}$ values continue until 765 mbsf where the isotopic composition of pore waters shifts to higher than contemporaneous carbonate values (Fig. 3). If only benthic foraminifers have reacted with the pore water, they would have systematically lower $^{87}\text{Sr}/^{86}\text{Sr}$ values than their planktonic counterparts. Alternatively, the benthic foraminifers could have incorporated dissolved Sr from pore water or detrital volcanic material

into their shells during growth, which could not be removed during sample preparation for Sr-isotope analyses. All three of these possibilities leave the planktonic foraminifers as the most reliable recorders of seawater Sr isotopic composition during deposition. Therefore, only planktonic foraminifers are used below to calculate Sr-isotope ages in the interval between 515 and 620 mbsf.

The leached sediments from depths between 720 and 850 mbsf at Site 918 are from a sediment sequence where the clastic component is mainly silt and clay (Shipboard Scientific Party, 1994a). Sr-isotope values of the carbonate fraction show a trend decreasing downhole as expected for a Neogene section (Hodell et al., 1991). The exchange of Sr between pore water and carbonate and silicate sediments has probably been small due to the low permeability of the sediments. It is, therefore, likely that the nannofossil chalk from this interval has also undergone little exchange of Sr between pore waters and sediment, and it has therefore retained its original seawater Sr-isotope signal.

The Sr isotopic composition of leached sediment below 850 mbsf in Hole 918D shows a downhole increase in $^{87}\text{Sr}/^{86}\text{Sr}$ values. This is the opposite of what should be expected from the Sr-isotope curve for Oligocene and Neogene seawater (Hess et al., 1989; Hodell et al., 1991; Mead and Hodell, 1995). In the same interval, the pore water Sr isotopic composition shifts from lower to higher than contemporaneous Neogene seawater values. This probably means that alteration of volcanic material is no longer as important as it was between 720 and 850 mbsf. The Sr isotopic composition of the pore water below 850 mbsf is probably more complex, involving diffusive processes and alteration of continental sediments with high $^{87}\text{Sr}/^{86}\text{Sr}$ (Gieskes et al., this volume). The interval also coincides with a change in lithology from nannofossil chalk and very dark gray silt to interbeds of nannofossil chalk with massive to faintly laminated silt and sand (Shipboard Scientific Party, 1994a). It is possible that the coarser and more permeable sandy sediments in this interval permit increased circulation of pore waters, which would facilitate a greater degree of exchange of Sr between the different lithologic components of the sediment and the pore water. Therefore, the Sr isotopic composition of bulk carbonate leached from sediments below 850 mbsf at Site 918 cannot be used as an indicator of seawater Sr isotopic composition at their time of deposition.

Reworking

Evidence of reworking has mainly been observed in the Pleistocene sequence at both Sites 918 and 919. At Site 918, reworking and mixing of foraminifers from different stratigraphic intervals are seen by a scatter in the $^{87}\text{Sr}/^{86}\text{Sr}$ values around the general trend decreasing downhole in the interval between 150 and 300 mbsf.

Reworking is also a problem at Site 919, where several reworked foraminifers have been found (Spezzaferri, this volume). The benthic foraminifers from Section 152-919A-1H-1 gave a $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.70884, which clearly indicates that the benthics have been reworked, probably from upper Miocene sediments. An alternative explanation to the low Sr-isotope values in benthics in Section 152-919A-1H-1 is that they have incorporated pore water with values lower than seawater $^{87}\text{Sr}/^{86}\text{Sr}$. However, it can be seen in Figure 4 that the pore water at 7.8 mbsf (Section 152-919A-2H-4) has a $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.709053. Although there are no pore water data from Section 152-919A-1H-1, it seems unlikely that pore water at this depth in the core should be even lower than at Section 152-919A-2H-4. The planktonic foraminifers from the same samples gave a present-day seawater value that would be expected from late Pleistocene foraminifer samples.

Another major reworking problem is found in Hole 919A at 71.96 mbsf, where the occurrence of *Neogloboquadrina atlantica* sinistral indicates the presence of the Pliocene sediments. Other indicators of Pliocene sediments occur deeper at Site 919 in Sections 152-919B-4H, 6H, and 8H where a few specimens of *Neogloboquadrina atlantica*

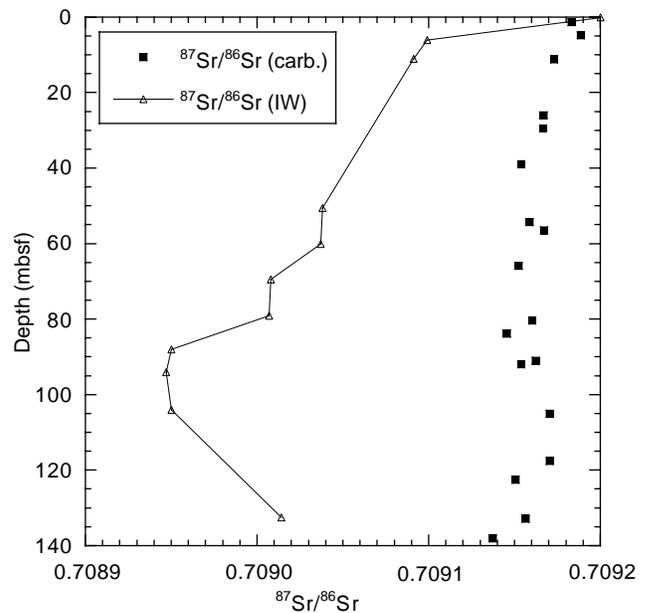


Figure 4. Strontium isotope variations in interstitial water and foraminifers from Site 919. Interstitial water data are from Gieskes et al. (this volume).

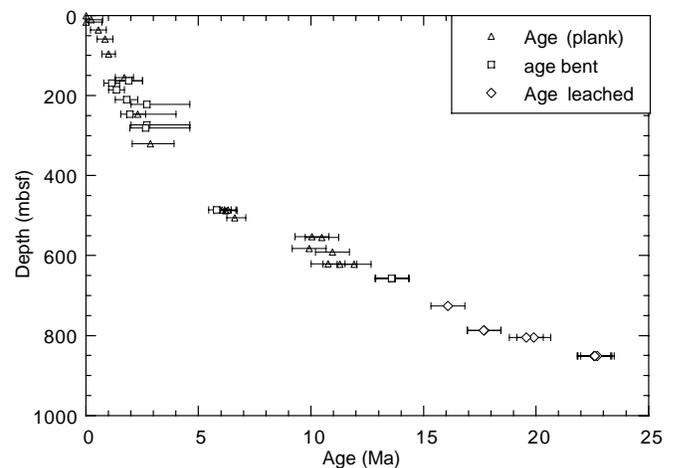


Figure 5. Age model from Site 918 based on published Sr vs. age equations (Oslick et al., 1994; Farrell et al., 1995). Note that the plus and minus error bars are not always the same due to changes in the slope of the reference curve.

tica dextral were found (Spezzaferri, this volume). However, Sr-isotope data give late Pleistocene $^{87}\text{Sr}/^{86}\text{Sr}$ values throughout Holes 919A and 919B (Fig. 2). The species of planktonic foraminifers analyzed in all Site 919 samples is *N. pachyderma*, which is by far the most abundant species at this site. If reworked *N. pachyderma* do occur in the samples analyzed (typically between 20 and 30 individuals), they are probably much less abundant than the in situ individuals. We, therefore, think that our Sr-isotope analyses of *N. pachyderma* at Site 919 record the Sr isotopic composition of seawater at the time of deposition of the sediments.

Sr-Isotope Ages

Site 918

The results of the Sr-isotope age calculations are shown in Figure 5. Sr-isotope ages for the late Neogene part of the record are calculat-

ed using the Sr-isotope reference curve of Farrell et al. (1995). This reference curve is based on sediments from ODP Site 758 and covers the time interval from 0 to 7 Ma. It has a higher resolution than previous late Neogene records published by Hodell et al. (1989, 1991). Sr-isotope ages are calibrated to the Geomagnetic Polarity Time Scale (GPTS) of Cande and Kent (1992). Ages from the Farrell et al. (1995) curve are determined by iteration of a fifth-order polynomial age equation to measured $^{87}\text{Sr}/^{86}\text{Sr}$ values. Upper and lower confidence intervals on the polynomial curve enclose 97% of the data and are $\pm 19 \times 10^{-6}$. The analytical error on $^{87}\text{Sr}/^{86}\text{Sr}$ for the samples of unknown age has been set to $\pm 10 \times 10^{-6}$. The variation in the slope of the age curve means that plus and minus errors do not always have the same magnitude (Fig. 4). Farrel et al. (1995) normalized their data to a NBS987 standard value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.710257$. For age calculations, we normalized our data to this value to make them directly comparable to their data set.

We have no data from the time interval between 6.6 and 10.4 Ma because this interval contains no foraminifers nor any other suitable material. For ages older than 9.9 Ma the age equation of Oslick et al. (1994) is used. This equation is valid for 9.9–15.2 Ma and is also based on the GPTS of Cande and Kent (1992). Before calculating ages we normalized our data from the relevant interval to a NBS987 value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.710255$, the value reported by Oslick et al. (1994). Ages are calculated using two linear regression equations; errors are ± 0.76 Ma for the equation that covers the interval from 9.9 to 15.2 Ma and ± 0.4 Ma for the equation that covers the interval from 15.5 to 22.5 Ma.

Site 919

The lowest $^{87}\text{Sr}/^{86}\text{Sr}$ value measured at Site 919 is in Sample 152-919B-8H-1, 56–58 cm (138.1 mbsf), and gives a value of 0.709146 when normalized to the NBS 987 standard value reported by Farrell et al. (1995). This corresponds to a maximum Sr-isotope age of 1.0 (+0.5/–0.6) Ma at this site. The variation in $^{87}\text{Sr}/^{86}\text{Sr}$ values at Site 919 is only 0.00005 and is too small to calculate meaningful sedimentation rates or to identify small hiatuses. The Sr isotopes, therefore, suggest that all sediments recovered at Site 919 are younger than 1.0 (+0.5/–0.6) Ma.

CONCLUSIONS

Planktonic foraminifers from Sites 918 and 919 yield Sr isotopic ratios that reflect the composition of seawater at the time of deposition. In certain intervals at Site 918, Sr isotopic ratios of benthic foraminifers were affected by Sr originating from alteration of volcanic material in the sediment. Both benthic and planktonic foraminifer were affected by reworking in other intervals. Bulk carbonate leached from sediments was in some cases, where sediments had low porosity, reliable as indicators of seawater contemporary with primary carbonate. In other intervals, where sediment had higher porosity, bulk carbonate was diagenetically altered and did not reflect original seawater values.

It has been possible to create an age model based on previously published Sr-isotope curves (Fig. 5). The oldest sediment dated with this method was 22.6 ± 0.8 Ma and was found at Site 918, 850.3 mbsf. From the age-depth plot from Site 918 (Fig. 5), the sedimentation rate was estimated to be 2.4 cm/k.y. in the interval from 850 to 540 mbsf (corresponding to 22.6 to 10.4 Ma). The data are too sparse in the interval between 540 and 320 mbsf to determine precise sedimentation rates; however, from 320 to 0 mbsf the sedimentation rate was estimated at 11.0 cm/k.y. The rapid increase in sedimentation rate from 2.9 Ma probably reflects increased influence of ice-rafted detritus associated with the major buildup of glaciers in Greenland.

Site 919 is characterized by upper Pleistocene sediment and a sedimentation rate slightly higher than the top sediments from Site 918.

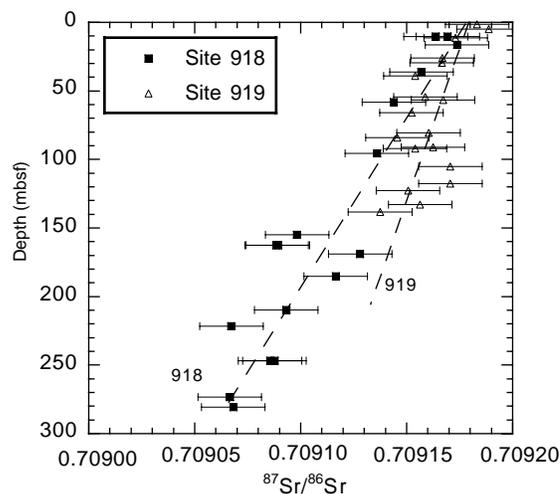


Figure 6. Strontium isotope variations in the upper 300 m at Sites 918 and 919. Sedimentation rates are slightly higher at Site 919.

The difference in sedimentation rates cannot be calculated precisely but can be illustrated by plotting the Sr-isotope data from the upper 300 and 140 m of sediments from Sites 918 and 919, respectively (Fig. 6). From the difference in slopes on the line interpolated through the data from the two sites, it can be seen that the sedimentation rate was higher at Site 919. This suggests that, during the late Pleistocene, Site 919 received a larger input of sediments from turbidite currents or that episodic erosion was more pronounced at Site 918.

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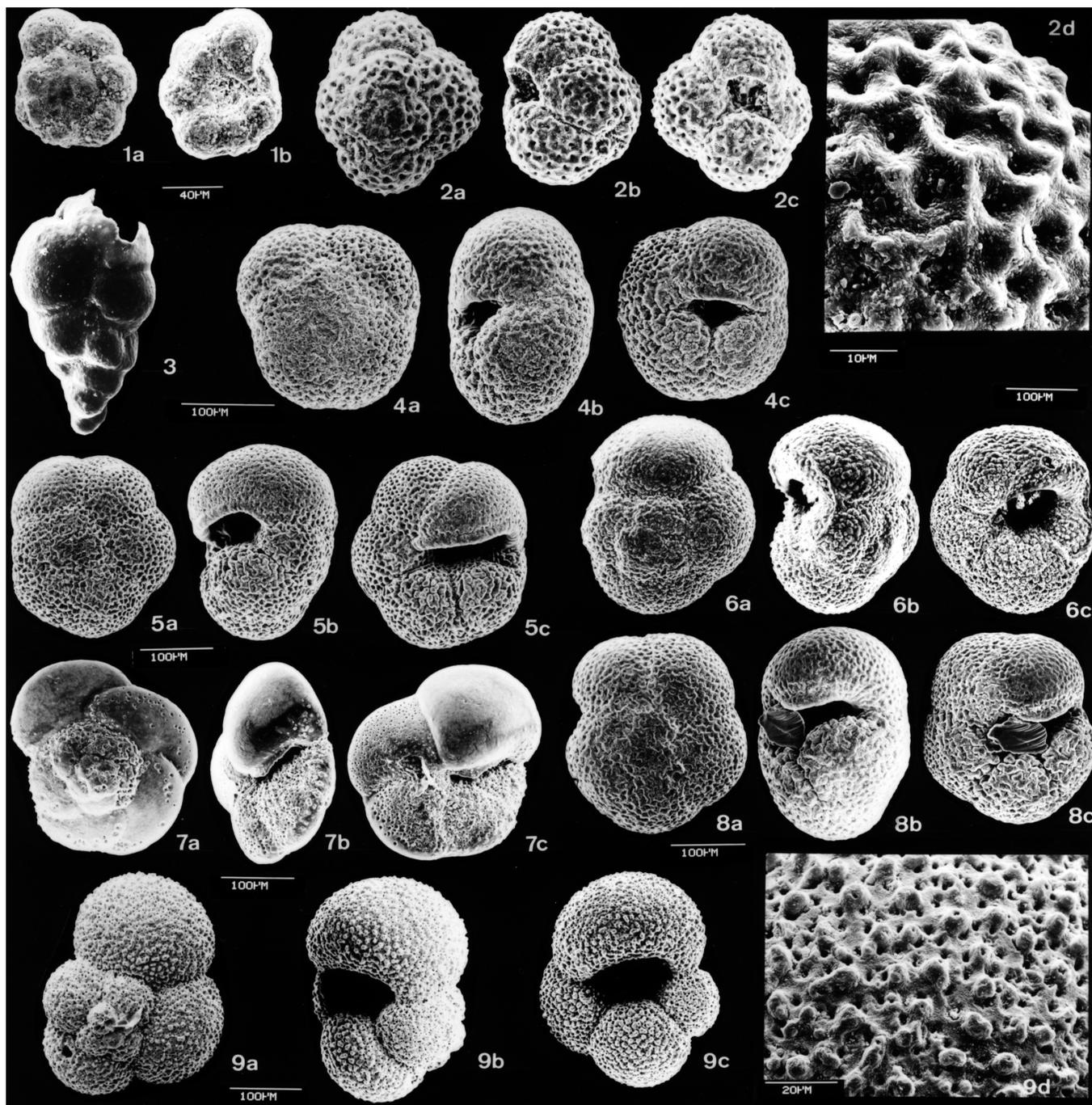


Plate 1. Examples of specimens used or avoided in Sr-isotope analyses. P = poor preservation (generally avoided in Sr-isotope analyses, used only when better preserved specimens were missing), M = medium preservation, G = good preservation. **1a–b.** *Tenuitella minutissima* Bolli, Sample 152-918A-4H-1, 141–143 cm, *N. pachyderma* sinistral Zone, Pleistocene, (a, spiral view; b, umbilical view), P. **2a–d.** *Globoturbotalita rubescens* (Hofker), Sample 152-918A-4H-1, 95–97 cm, *N. pachyderma* sinistral Zone, Pleistocene, M. **3.** *Streptochilus globigerum* (Boersma), Sample 152-918A-7H-7, 12–14 cm, *N. pachyderma* sinistral Zone, Pleistocene, M. **4a–c.** *Neogloboquadrina pachyderma* (Ehrenberg) sinistral coiling, Sample 152-918A-7H-4, 106–108 cm, *N. pachyderma* sinistral Zone, Pleistocene, M/G. **5a–c.** *Neogloboquadrina acostaensis* (Blow)/*Neogloboquadrina humerosa* (Takayanagi and Saito) transition, Sample 152-918A-6H-7, 34–36 cm, *N. pachyderma* sinistral Zone, Pleistocene, M/G. **6a–c.** *Globorotalia inflata* (d’Orbigny), Sample 152-918A-6H-4, 12–5 cm, *N. pachyderma* sinistral Zone, Pleistocene, M/G. **7a–c.** *Globorotalia scitula* Brady, Sample 152-918A-6H-4, 12–5 cm, *N. pachyderma* sinistral Zone, Pleistocene, M/G, with inclusion in the aperture. **8a–c.** *Neogloboquadrina acostaensis* (Blow), Sample 152-918A-5H-5, 14–16 cm, *N. pachyderma* sinistral Zone, Pleistocene, M/G. **9a–d.** *Globigerina bulloides* d’Orbigny, Sample 152-918A-6H-4, 2–5 cm, *N. pachyderma* sinistral Zone, Pleistocene, G. (a, spiral view; b, side view; c, umbilical view; d, detail of the wall texture except when differently specified). Figures 1 through 3 at the same magnification.

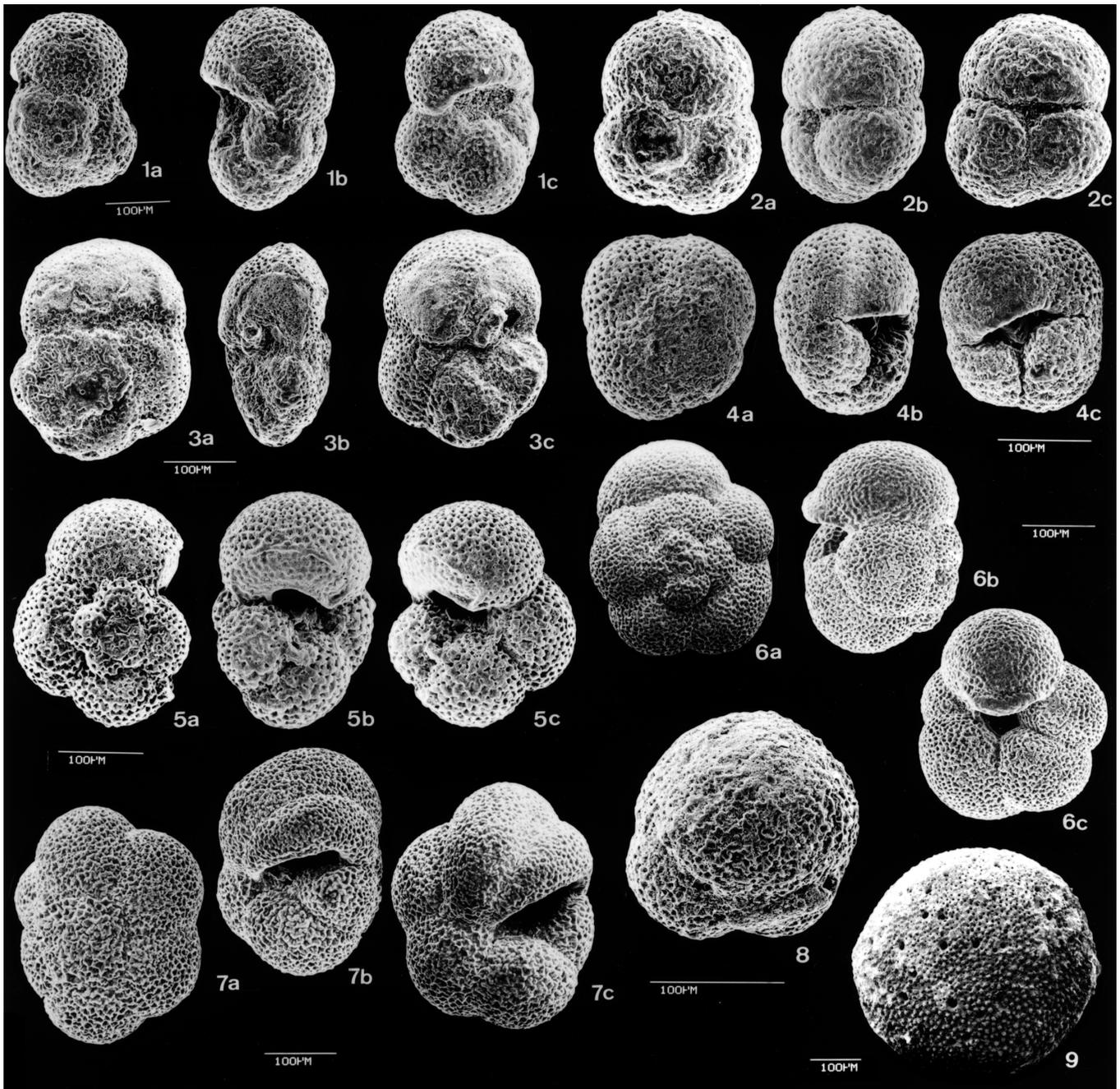


Plate 2. Preservation degree decreases from the more recent to older faunas. **1a–c.** *Zeaglobigerina woodi* (Jenkins), Sample 152-918D-55R-3, 66–68 cm, P, Zone N5–N6, lower Miocene. **2a–c.** *Zeaglobigerina connecta* (Jenkins), Sample 152-918D-55R-3, 66–68 cm, Zone N5–N6, lower Miocene, P. **3a–c.** *Globorotalia zealandica* Hornibrook, Sample 152-918D-52R-4, 124–126 cm, P, Zone N8, lower Miocene. **4a–c.** *Neogloboquadrina pachyderma* (Ehrenberg) dextral coiling, Sample 152-918A-7H-4, 106–108 cm, *N. pachyderma* sinistral Zone, Pleistocene, P/M with inclusion in the aperture. **5a–c.** *Neogloboquadrina atlantica* (Berggren) dextral coiling, Sample 152-918D-32R-1, 95–97 cm, *N. atlantica* dextral Zone, upper Miocene, M/G. **6a–c.** *Neogloboquadrina dutertrei* (d'Orbigny), 152-918A-7H-2, 113–115 cm, *N. pachyderma* sinistral Zone, Pleistocene, G. **7a–c.** *Neogloboquadrina humerosa* (Takayanagi and Saito), Sample 152-918A-4H-6, 141–143 cm, *N. pachyderma* sinistral Zone, Pleistocene, G. **8.** *Globigerinoides bisphericus* Todd, Sample 152-918D-52R-4, 124–126 cm, Zone N8, lower Miocene, P. **9.** *Orbulina universa* d'Orbigny, Sample 152-918D-22R-2, 8–10 cm, *N. atlantica* sinistral Zone, Pliocene, G. (a, spiral view; b, side view; c, umbilical view, except when differently specified). Figures 2 and 4 at the same magnification.