shaped bacterial cells enclosed in a sheath and showing occasional false branching are the typical growth habit of the modern iron bacterium *Sphaerotilus natans* (*11*). A possible relation between the fossil bacteria and this extant form is questionable, however, because of the considerably smaller size of the Gunflint organism.

Coccoid bacteria-like objects occur in samples 2 and 6. These nearly spherical, rough-surfaced bodies are approximately 0.35 μ in diameter (Figs. 5 and 6). The cell walls are sometimes broken and may show surficial folding (Fig. 6). The thickness of the cell wall, up to 0.15 μ in some instances, may result from concentration of various minerals, such as iron compounds, either by metabolic activity or by diagenetic alteration. These fossils resemble in size and morphology certain iron bacteria of the genera *Siderocapsa* and *Siderococcus* (*12*), members of which metabolically concentrate iron compounds; this similarity suggests that the pronounced thickness of the cell walls is metabolic rather than diagenetic. Thimann (*13*) has brought to our attention the additional similarity in size, morphology, and general organization of these fossil coccoids to Winogradsky's "microcolonies in soil" (*14*).

That these minute fossils are both organically preserved and relatively undistorted is not surprising when one considers that many other members of the Gunflint assemblage are preserved in this manner and that complex organic molecules are present within the rock (*1, 15*). That these bacteria are indigenous to the rock rather than being laboratory contaminants is supported by the following three considerations: (i) the forms occur in the replicas both as organically preserved structures, and as imprints in the rock surface (Fig. 1); (ii) they are oriented in various positions not only parallel with but passing into the prepared rock surface; and (iii) the forms are consistently present in several samples prepared by different methods.

There seems little doubt that the forms we describe and portray are bacteria; their morphology, size, complexity of structure, and association with more-complex organisms are consistent with this interpretation. Rod-shaped and coccoid forms are widely distributed throughout the bacteria and occur in anaerobic and aerobic and heterotrophic and autotrophic types. Morphology offers, therefore, limited aid in the assignment of taxonomic position to fossil bacteria. A more satisfactory assignment should be based upon physiological processes in addition to morphology. In the absence of sufficient biochemical information on these bacteria, the conferring of taxonomic status by giving them generic and specific names seems unwarranted.

The electron microscope in conjunction with optical microscopy and other traditional methods of micropaleontology provides a powerful tool for morphological investigation of ancient life. Organic and inorganic geochemistry offer means for the investigation of ancient physiological processes. The occurrence of porphyrin derivatives of chlorophyll in Precambrian sediments, as demonstrated by organic geochemical analysis (*16*), may permit determination of the time of origin of the photosynthetic mechanism. Metabolic concentration of sulfur, iron, and other elements in bacterial and other fossils may be detectable by electron probe–x-ray microanalysis. Coordinated application of these and other techniques to the investigation of ancient sediments promises elucidation of diverse aspects of the morphology and physiology of Precambrian life.

J. William Schopf
Elso S. Barghoorn
Department of Biology and *Botanical Museum, Harvard University, Cambridge, Massachusetts 01238*
Morton D. Maser
Robert O. Gordon
Department of Biology, Harvard University

References and Notes

1. S. A. Tyler and E. S. Barghoorn, *Science* **119**, 606 (1954); E. S. Barghoorn and S. A. Tyler, *Ann. N.Y. Acad. Sci.* **108**, 451 (1963); *Science* **147**, 563 (1965); P. E. Cloud, Jr., *ibid.* **148**, 27 (1965).
2. A. M. Macgregor, *Geol. Soc. So. Africa Trans.* **43**, 9 (1941); T. Belsky *et al., Nature* **206**, 446 (1965); P. E. Cloud, Jr., J. W. Gruner, H. Hagen, *Science* **148**, 1713 (1965); W. G. Meinschein, *Science*, in press.
3. E. I. Rabinowitch, *Photosynthesis and Related Processes. Vol. I, Chemistry of Photosynthesis, Chemosynthesis and Related Processes in vitro and in vivo* (Interscience, New York, 1945), chap. 5, pp. 99–107, 445–46.
4. C. E. ZoBell, in "Treatise on marine ecology and paleoecology, 2," *Geol. Soc. Amer. Mem. 67*, p. 693 (1957); S. I. Kuznetsov, M. V. Ivanov, N. N. Lyalikova, *Introduction to Geological Microbiology*, C. H. Oppenheimer, Ed., transl. by P. T. Broneer (McGraw-Hill, New York, 1963), pp. 40–50.
5. J. W. Gruner, *Econ. Geol.* **17**, 415 (1922).
6. H. M. Barton and D. J. Jones, *Science* **108**, 745 (1948); see articles and references in *Handbook of Paleontological Techniques*, B. Kummel and D. Raup, Eds. (Freeman, San Francisco, 1965).
7. J. M. Schopf, E. G. Ehlers, D. V. Stiles, J. D. Birle, *Proc. Amer. Phil. Soc.*, in press; E. G. Ehlers, D. V. Stiles, J. D. Birle, *Science* **148**, 1719 (1965).
8. We thank J. M. Schopf, USGS, for his interest and suggestions.
9. See (*1*) for description of Schreiber locality.
10. Similar results are reported by P. E. Cloud, Jr., and H. Hagen, *Proc. Nat. Acad. Sci. U.S.* **54**, 1 (1965).
11. E. G. Pringsheim, *Trans. Roy. Soc. London B* **233**, 453 (1949); K. V. Thimann, *The Life of Bacteria* (Macmillan, New York, ed. 2, 1963), pp. 709–11.
12. P. Dorff, "Die eisenorganismen, systematik und morphologie," in *Pflanzenforschung 16*, R. Kolkwitz, Ed. (1934), pp. 6–12.
13. K. V. Thimann, private communication, 14 July 1965.
14. S. Winogradsky, *Ann. Inst. Pasteur* **39**, 299 (1925).
15. J. Oro, D. W. Nooner, A. Zlatkis, S. A. Wikstrom, E. S. Barghoorn, *Science* **148**, 77 (1965).
16. W. G. Meinschein, E. S. Barghoorn, J. W. Schopf, *ibid.* **145**, 262 (1964); E. S. Barghoorn, W. G. Meinschein, J. W. Schopf, *ibid.* **148**, 461 (1965).
17. We thank Roger Branson, Harvard University, for assistance. Work supported by NSF grants GP-2794 and G-19727 and by PHS grants CA-06018 and GM-06637; one of us (J.W.S.) is a NSF graduate fellow.

14 July 1965

Sands of the Mid-Atlantic Ridge

Abstract. *Sands collected at 24 locations along the crest of the Mid-Atlantic Ridge between 57°S and 38°N consist predominantly of olivine, diopsidic augite, hypersthene, enstatite, amphibole, quartz, plagioclase, and volcanic glass, suggesting an olivine tholeiitic source. Eight cores contain relatively pure mineral sands; three of these cores reflect local volcanic activity. In 16 cores the manganese-coated mineral grains are mixed in a current-winnowed foraminiferal sand or ooze.*

The petrology of the Mid-Atlantic Ridge has been inferred from the petrology of the nine groups of islands and from about 20 dredge hauls (*1–5*). The rocks of the islands, predominantly composed of alkali basalt or its derivatives, are generally olivine-bearing but sometimes olivine-free (*6*). St. Paul's Rocks, the only exception, are composed of serpentinized dunite (*7*). Shand (*1*) and Quon and Ehlers (*2*) described the petrography of ten dredge hauls from the Mid-Atlantic Ridge near 30°N. The main rock types were serpentine, gabbro, and fine-grained basalt with, and occasionally without, olivine. Engel and Engel (*3*) concluded that the submerged part of the Mid-Atlantic Ridge between 22°S and 5°N is composed predominantly of a low-potassium tholeiite and that only the highest parts of the ridge are composed of alkali basalt; this composition, they believed, derived by differentiation from a parent tholeiitic magma. Nicholls, Nalwalk, and Hays (*4*) concluded from study of samples from three dredge hauls at 22°, 28°, and 50°N that the predominant rock type is a high-alumina olivine tholeiite. Muir, Tilley, and Scoon (*5*) analyzed two dredge hauls from 45°N and found basalts ranging from olivine-bearing tholeiites to transitional or slightly alkalic basaltic rocks.

Deep-sea photographs from the Mid-Atlantic Ridge often reveal ripple marks, scour marks, rock outcrops, and winnowed concentrations of sand (Fig. 1) (*8, 9*). Mineral sands disseminated or concentrated as lenses occur in 24 of the more than 110 sediment cores obtained by Lamont Geological Observatory expeditions from the Mid-Atlantic Ridge (Table 1). When disintegrated, the rocks of the ridge produce a unique assemblage of residual minerals from which the petrology of the ridge can be broadly inferred.

In eight cores the sands occur as nearly pure beds of mineral sand; three cores are entirely of mineral sand. In seven cores the mineral grains occur as a more or less minor constituent of a foraminiferal sand interbedded in foraminiferal lutite. In four cores mineral grains occur in beds of grey foraminiferal ooze interbedded in brown, foraminiferal lutite. These grey oozes are more friable and apparently contain less lutite than the brown, interbedded lutites. In five cores, sand grains are disseminated in ooze (both foraminiferal and of diatomite).

In five cores the sand beds are graded and in one core there is cross-

Table 1. Nature of sands and of their bedding in samples from cores taken from the Mid-Atlantic Ridge. Three hundred heavy-mineral grains and 300 light-mineral grains were counted for each sample except for samples from cores V-9-31, V-9-30, V-16-23, V-16-25, V-16-203, V-16-207, V-15-172, V-14-2, and V-16-206, which contained less than 300 heavy-mineral grains; counts from less than 300 grains are rendered in parentheses. All mineral grains were coated with manganese, except those from cores V-12-82, V-12-83, V-14-151, V-18-170, and V-9-31. Abbreviations: Bsl, depth below sea level; L, length; Smp, depth of sample; Olv, olivine; Cpy, clinopyroxene; Opy, orthopyroxene; Am, amphibole; Ap, alteration products; Qz, quartz; Fs, feldspar; Srp, serpentine; Vg, volcanic glass; Tn, thickness of bed; Ps, primary structure (M, massive bedding; G, graded bedding; X, cross-bedding).

Core					Nature of grains (No.)										Bed	
No.	Source	Bsl (m)	L (cm)	Smp (cm)	Olv	Cpy	Opy	Am	Ap	Qz	Fs	Srp	Vg	Ap	Tn (cm)	Ps
					Mineral sands interbedded with foraminiferal lutite											
A-152-88	39°05′N,26°25′W	2375	364	90	86*	158*	16	31	9	33	39	12	207	9	4	M
V-9-20	09°37′S ,13°18′W	1425	35	10	49	207	8	9	27	5	9	10	35	241	35	M
V-16-24	08°18′N,38°03′W	3702	65	20	9	4	10	6	201	7	10	93	15	175	64	G
					Mineral sands interbedded with red clay in Romanche Trench											
V-12-82	00°19′S ,18°24′W	6079	78	55	52	83	66	46	53	17	37	176	11	59	78	M
V-12-83	00°18′S ,18°35′W	6646	74	40	69*	96	34	43*	58	19	25	78		178	74	M
					Volcanic mineral sands											
V-14-151	38°36′N,28°50′W	200	348	5	243*	57*				18	54	12	210	6	348	G
V-18-170	30°29′S ,14°19′W	3200	254	100	286*	14				6	48	3	150	93	5	M
V-9-31	08°14′N,37°52′W	4656	1118	995	49	4		1	3	40	50	38	136	36	10	M
					Mineral grains in foraminiferal sand interbedded in foraminiferal lutite											
A-153-148	32°34′N,43°28′W	3300	170	80	64	157	10	22	47	39	35	48	138	40	15	M
V-9-28	02°54′N,33°09′W	4305	1189	837	8	10	12	23*	247	15	27	204		54	3	G
V-12-54	41°14′S ,06°07′W	4082	896	800	96*	124	14	18	48	27	69	72	105	27	70	G
V-16-35	17°39′S ,15°06′W	3892	996	60	61	131	9	72	27	23	72	74	80	51	90	G
V-16-204	10°44′N,40°24′W	5273	1147	550	48	86	95	47*	24	22	98	104	13	63	718	X
V-14-61	54°28′S ,02°36′W	1834	610	10	64	146	58	6	26	24	78	12	168	18	610	M
V-9-30	06°01′N,36°39′W	4890	1320	30	18	15	4	4	11	(8)	(15)	(68)	(18)	(29)	2	M
					Mineral grains in grey foraminiferal ooze interbedded in brown foraminiferal lutite											
V-16-23	13°15′N,40°40′W	4887	1270	600	6	9	1			18	66	48	141	27	20	M
V-16-25	05°04′N,36°48′W	4255	1236	100	9	15	4	23	13	12	129	117	6	36	15	M
V-16-203	09°21′N,39°52′W	4159	1283	10	6	4		5	14	48	105	36	51	60	20	M
V-16-207	25°51′N,48°23′W	4828	1236	470	16	18	1	9	29	63	167	20	8	52	10	M
					Disseminated mineral sand in brown foraminiferal lutite											
V-15-172	10°45′N,41°21′W	4460	715	25	26	13	3	10	8	24	93	50	103	30	10	M
					Disseminated mineral sand in brown foraminiferal lutite											
V-14-2	20°43′N,49°26′W	4173	203	30	52	50	11	8	59		24	21	21	234		M
V-16-206	23°20′N,46°29′W	3733	550	70	11	10	2	28	95	42	51	147	12	48	80	M
					Disseminated mineral sand in diatomite											
V-14-59	56°53′S ,09°18′W	4078	39	15	51*	129*	96	14	10	27	57	6	207	3	10	M
V-14-62	54°27′S ,00°08′E	2382	490	75	54	120	112	8	6	15	45	12	219	9	70	M

* Identification confirmed by x-ray analysis.

bedding, but, because of the low content of lutite and the consequent lack of cohesion in most of the dry cores, primary structures could not have been observed even if they had originally been present. Cores V-12-82 and V-12-83 come from the red-clay environment of the Romanche Trench. Core V-12-82 is composed of layers of reddish-brown, red, and green clay, with subangular to subrounded basalt pebbles dispersed through the clay. It appears that the assemblage is primarily a product of weathering *in situ*. Core V-12-83 is composed of subrounded to subangular sand and gravel-sized fragments of basalt which are cemented by a matrix of reddish-brown clay; at the base of the core there are pebbles of brecciated basalt.

Three samples, V-14-151, V-18-170, and V-9-31, were derived from local volcanic eruptions. V-14-151, composed entirely of vesicular glassy sand and gravel, was taken from the submarine slope of Capelenhos Volcano near the western end of Faial Island while the 1957–58 eruption was still in progress. The mineral grains in these cores lack the manganese coating characteristic of all the other cores. In core V-18-170 from the west side of the narrow, rugged, crest zone of the Mid-Atlantic Ridge at 30°S, volcanic gravel is dispersed through a zone of foraminiferal lutite. Photographs made while the core was being taken showed pillow lavas in 9 frames and soft sediment in 15 frames (*9*). Core V-9-31, from the west side of the crest zone at 8°N, is composed of vesicular fragments of volcanic glass.

The grain size of the > 38-micron portion examined lay between 82 and 125 microns. After removal of the manganese coating with H_2O_2, the samples were fractionated into heavy and light portions with bromoform (specific gravity, 2.85); the light-mineral fraction was generally two to three times heavier than the heavy-mineral fraction. Each fractionated sample was mounted and a 300-grain line-count was made of the nonopaque minerals in each slide. To supplement microscopic analysis, identification of olivine, pryoxene, and amphiboles in eight selected cores was checked by x-ray-diffraction methods.

Microscopic analysis of the heavy-mineral fractions revealed that 22 of the cores contain olivine, clinopyroxene, and amphibole (Fig. 2). The three volcanic sands contain an exceptionally high percentage (> 80 percent) of euhedral olivine, with minor amounts of clinopyroxene; these grains occur partially or wholly within volcanic glass. As a result of subaqueous weathering and alteration, five cores (V-16-24, V-9-28, V-16-207, V-14-2, V-16-206) contain an abnormally high percentage of alteration products. In contrast with the fresh appearance of the other samples, mineral grains in these cores are all greatly altered. In all other samples, olivine grains ranged in frequency from 15 to 30 percent; judged from the optic angle (2*V*) of 75 to 85 degrees and the index of refraction of 1.64 to 1.69, the composition of the olivine is forsterite$_{85\text{-}90}$fayalite$_{15\text{-}10}$. The value of the *d*-spacing of (130), determined by x-ray analysis, indicates an olivine composition of $Fo_{88}Fa_{12}$ (*10*). The most abundant clinopyroxene species, diopsidic augite, varies in abundance from 20 to 50 percent. Titaniferous augite was found in eight samples but only in amounts less than 5 percent. The orthopyroxene species, predominantly hypersthene, with lesser amounts of a variety richer in magnesium are identified in 20 cores and range in abundance from 2 to 45 percent.

The amphibole suite is composed predominantly of lamprobolite and green hornblende and varies in frequency from 3 to 25 percent, while in samples from the equatorial Atlantic (0° to 10°N) the predominant amphibole species is uralite. The identification of uralite was confirmed by x-ray analysis; it is generally considered to be actinolitic in composition and to be produced by alteration of earlier-crystallized pyroxene as a result of enrichment of late-stage magmatic fluids with water (*11*). The alteration products consist of unidentifiable, altered mineral grains, with lesser amounts of partially serpentinized fragments of olivine. A few grains of apatite, chlorite, clinozoisite, epidote, garnet, iron ore, rock fragments, sphene, and zircon are occasionally found.

Analysis of the light minerals revealed that feldspar and serpentine occur in all 24 samples; quartz, in 23. The percentage of quartz varies from 2 to 18 percent, the average being around 7 percent. The feldspar constituent is predominantly plagioclase with an anorthite content of about 50 percent; frequency of the plagioclase ranges from 6 to 55 percent, with the abundance notably depressed when the percentage of alteration products is high. Alteration products are predominantly palagonite mixed with unidentifiable, altered mineral grains. The serpentine is predominantly antigorite and ranges

Fig. 1. Coarse debris and residual sand scattered around large rocks in the Vema fracture zone, North Atlantic. Core site, V-16-70 (16); location, 10°45′N, 40°30′W; depth, 5116 m; field, 6 m^2.

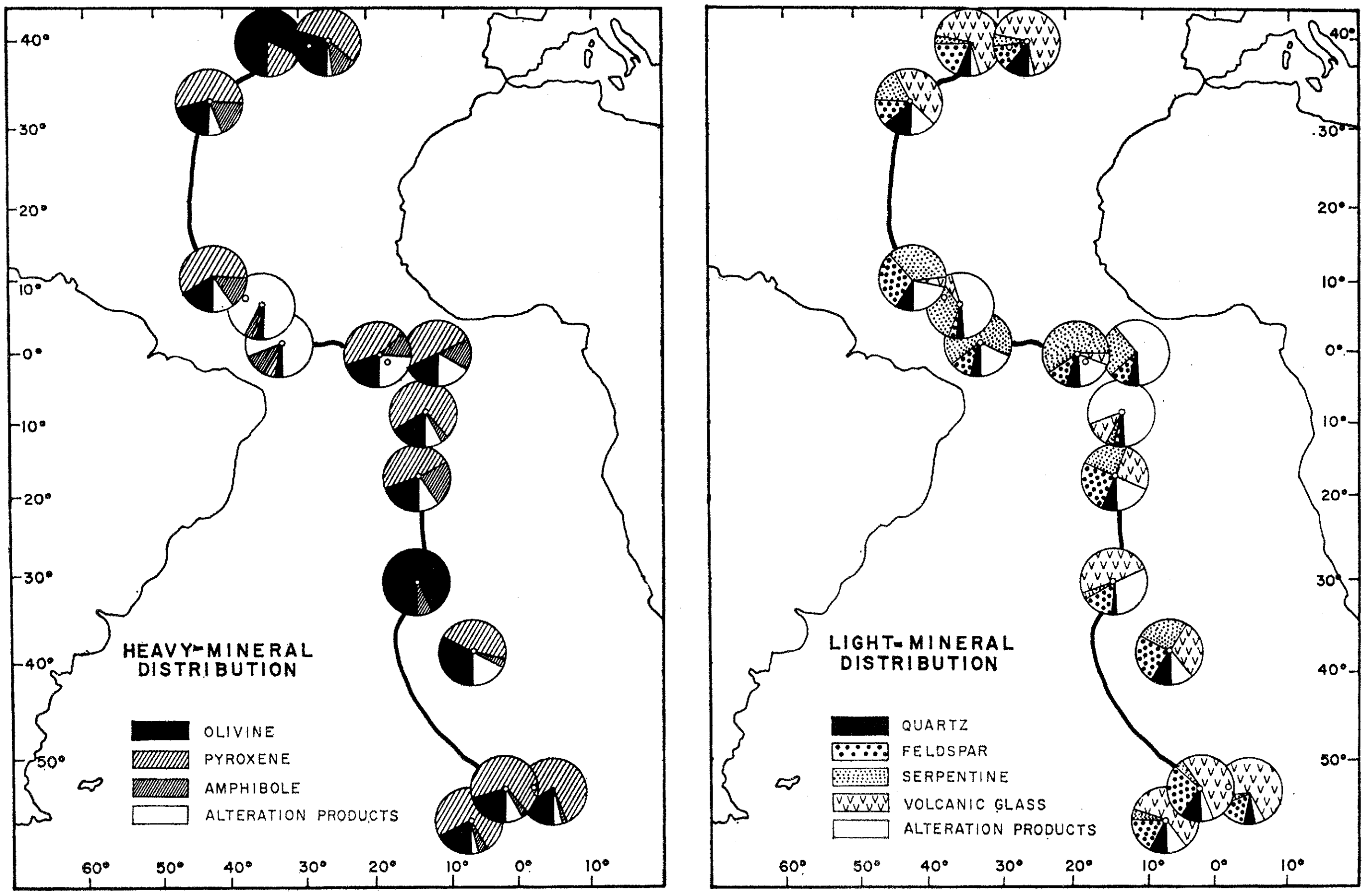

Fig. 2. Mineral composition of deep-sea sands: (left) heavy minerals; (right) light minerals. Samples containing less than 300 heavy-mineral grains are omitted; small circles indicate sources of cores.

in frequency from 4 to 50 percent, the highest percentages occurring in the equatorial Atlantic. The refractive indexes of the volcanic glass range from 1.56 to 1.60, indicating a silica content ranging from 49 to 53 percent.

In two cores (V-16-24 at 60 cm and V-9-20 at 39 cm), basalt pebbles large enough to be thin-sectioned were found. Both fragments must have been chilled quickly because of the variolitic arrangement of the zoned acicular plagioclase phenocrysts (anorthite$_{50}$). Olivine was identified, although phenocrysts of olivine were subhedral because of partial resorbtion of the olivine by the melt before the complete crystallization of the rock. The only other mineral present was scattered clinopyroxene microphenocrysts, which are studded with fine, opaque granules. The glassy groundmass has been partially altered by palagonitization.

The mineral suite of the sands agrees with an olivine tholeiitic composition for the axis of the Mid-Atlantic Ridge. The high magnesium content of unzoned olivine is characteristic of olivines associated with oceanic tholeiites; a lower magnesium content of the olivine is charactistic of the alkali basalts of the islands of the Mid-Atlantic Ridge (*5*). Quartz or hypersthene, or both, are typically associated with tholeiitic basalts. The basaltic glass contains 49 to 53 percent silica, a range characteristic of tholeiitic-type basalts, while alkaline basalts usually contain less than 49 percent. Therefore the rock type that produced the mineral assemblages analyzed probably lies between the planes of silica undersaturation (diopside-albite-forsterite) and silica saturation (diopside-albite-enstatite) in the Yoder-Tilley diopside-forsterite-nepheline-quartz tetrahedron (*12*).

In the equatorial region two mineral species, uralite and serpentine, occur together; both are alteration products associated with the hydration of basaltic melts. There may be a genetic relation between the fracture zones of the region and the occurrence of these minerals.

The occurrence of these locally derived mineral sands on the Mid-Atlantic Ridge clearly requires a slight revision of Goldberg's (*13*) conclusion (based mainly on study of the lutite fraction) that the ridge sediments are "composed primarily of continentally derived materials, and there is no indication of solid phases being derived from the weathering of the ridge itself or from volcanic activity."

PAUL JEFFREY FOX
BRUCE C. HEEZEN

Department of Geology and *Lamont Geological Observatory, Columbia University, Palisades, New York*

References and Notes

1. S. J. Shand, *J. Geol.* **57**, 89 (1949).
2. S. H. Quon and E. G. Ehlers, *ibid.* **74**, 1 (1959).
3. A. E. J. Engel and C. G. Engel, *Science* **144**, 1330 (1964).
4. G. D. Nicholls, A. J. Nalwalk, E. E. Hays, *Marine Geol.* **1**, 333 (1964).
5. I. D. Muir, C. E. Tilley, J. H. Scoon, *J. Petrol.* **5**, 409 (1964).
6. R. H. Daly, *Proc. Amer. Acad. Arts Sci.* **62**, 31 (1927).
7. C. E. Tilley, *Amer. J. Sci.* **245**, 453 (1947).
8. B. C. Heezen, M. Tharp, M. Ewing, *The Floors of the Oceans I: The North Atlantic* (Geological Soc. of America, New York, 1959); B. C. Heezen and C. D. Hollister, *Marine Geol.* **1**, 141 (1964).
9. M. Ewing, J. I. Ewing, M. Talwani, *Geol. Soc. Amer. Bull.* **75**, 17 (1964).
10. H. S. Yoder and Th. G. Sahama, *Amer. Mineralogist* **42**, 475 (1959).
11. W. A. Deer *et al.*, *Rock-Forming Minerals* (Wiley, New York, 1962), vol. 2.
12. H. S. Yoder and C. E. Tilley, *J. Petrol.* **3**, 3 (1962).
13. E. D. Goldberg and J. J. Griffin, *J. Geophys. Res.* **69**, 4293 (1964).
14. Discussions with Vince Manson and Charles D. Hollister were extremely helpful. P. F. Kerr generously made x-ray equipment available. ONR and NSF assisted financially in obtaining the cores. Contribution No. 842 from Lamont Geological Observatory.

17 June 1965