Drilling Operations on Eniwetok Atoll

GEOLOGICAL SURVEY PROFESSIONAL PAPER 260-Y

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By HARRY S. LADD *and* SEYMOUR O. SCHLANGER

BIKINI AND NEARBY ATOLLS, MARSHALL ISLANDS

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A summary report covering equipment, procedures, and logs of 21 shallow holes and 3 deep holes

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ABSTRACT

Shallow holes drilled on islands of Eniwetok Atoll showed that most of the near-surface sediments are unconsolidated except for beach rock at intertidal levels. Texture varies with organic composition, and depth to zones of leaching and recrystallization is variable. One hole, mostly in solid rock to a depth of 130 feet, may have been drilled through the irregular but rigid reef framework that is thought to encircle the atoll; all other holes appear to be in lagoon deposits. Shallow holes on the reef flat entered a solid plate thicker than anything found under the islands.

Deep drilling revealed the presence of olivine basalt beneath shallow water limestone of Eocene age at a depth of more than 4,000 feet. The drilling of the first of three deep holes (K–1B) on the northeast side of the atoll was carried to a depth of 1,280 feet, ending in lower Miocene rocks; the other deep holes were put down on opposite sides of the atoll: F–1 on the northwest where a guyot adjoins the atoll at 700 fathoms, E–1 on the southeast where no guyot projects from the atoll. In F–1, hard basement rock was struck at 4,610 feet, but no sample was recovered. In E–1 ,unweathered basalt cuttings were obtained at 4,158 feet and solid basalt core from 4,208 to 4,222 feet. Most of the sedimentary section was soft or weakly consolidated. The holes showed similar sections to depths of 1,400 feet, below which there were striking differences in lithologic character, organic constitution, and the distribution of hard rock and cavities. Starting at 2,900 feet, F–1 entered 1,000 feet of *Globigerina*-rich limestone, apparently deposited in deeper waters than those in which the lagoonal sediments of E–1 were deposited.

The drilling revealed the occurrence of leached zones in which the aragonite of corals and most mollusks has been largely removed or recrystallized to calcite. These zones are thought to record periods when the top of the atoll stood above sea level and was subjected to atmospheric erosion. No aragonite was recognized below a depth of 2,020 feet in F–1, nor below 2,808 feet in E–1; in K–1B aragonite was found at a maximum depth of 1,230 feet.

In F–1, dolomite was found in the following depth intervals: 1,232–1,248; 2,662–2,687; 3,052–3,055; 4,197–4,222; 4,316–4,341; 4,406–4,431; 4,500–4,525; 4,528–4,553 feet. In E–1 dolomite was identified only from the 4,078–4,100-foot interval; no dolomite was identified from K–1B.

INTRODUCTION

In connection with tests carried out in the Marshall Islands by the Atomic Energy Commission and the Los Alamos Scientific Laboratory, considerable drilling was done on Eniwetok Atoll. In 1950 four shallow holes were drilled on the seaward reef off Engebi island; the following year samples and logs for 17 shallow holes drilled on 6 different islands by the Atomic Energy Commission were made available for study. Three deep holes were drilled on the atoll: K–1B was put down in 1951 on Engebi to a depth of 1,280 feet; in 1952 hole F–1 was drilled to 4,630 feet on Elugelab and hole E–1 to 4,222 feet on Parry Island.

The present report contains descriptions of equipment and procedures together with generalized logs of all the holes drilled. The junior author is primarily responsible for the petrographic descriptions of the sediments.

LOCATION OF DRILL HOLES

Approximate location of the shallow holes drilled on half a dozen islands are shown in figure 260. Sites of shallow holes drilled on reef off Engebi are shown on figure 267.

The 3 deep holes drilled on Eniwetok were located close to the lagoon shore (fig. 261) in the belief that caverns might be less extensive there than beneath sites located closer to the seaward edge of the reef. The exact site of F–1 on Elugelab is now of little more than academic interest as the entire island was destroyed in a test of a thermonuclear device shortly after drilling was completed. The site of K–1B on Engebi was also obliterated by an atomic test but E–1 on Parry Island remains open. For comparative purposes the locations of the deep holes relative to lagoon and reef are given below:

	Distances, in feet, from—		
	Lagoon	Seaward edge of island	Seaward edge of reef
F–1	118	78	3, 700
E–1	95	495	1, 320
K–1B	450	3, 750	4, 600

ACKNOWLEDGMENTS

The records of the shallow drilling, done by the Atomic Energy Commission under the supervision of

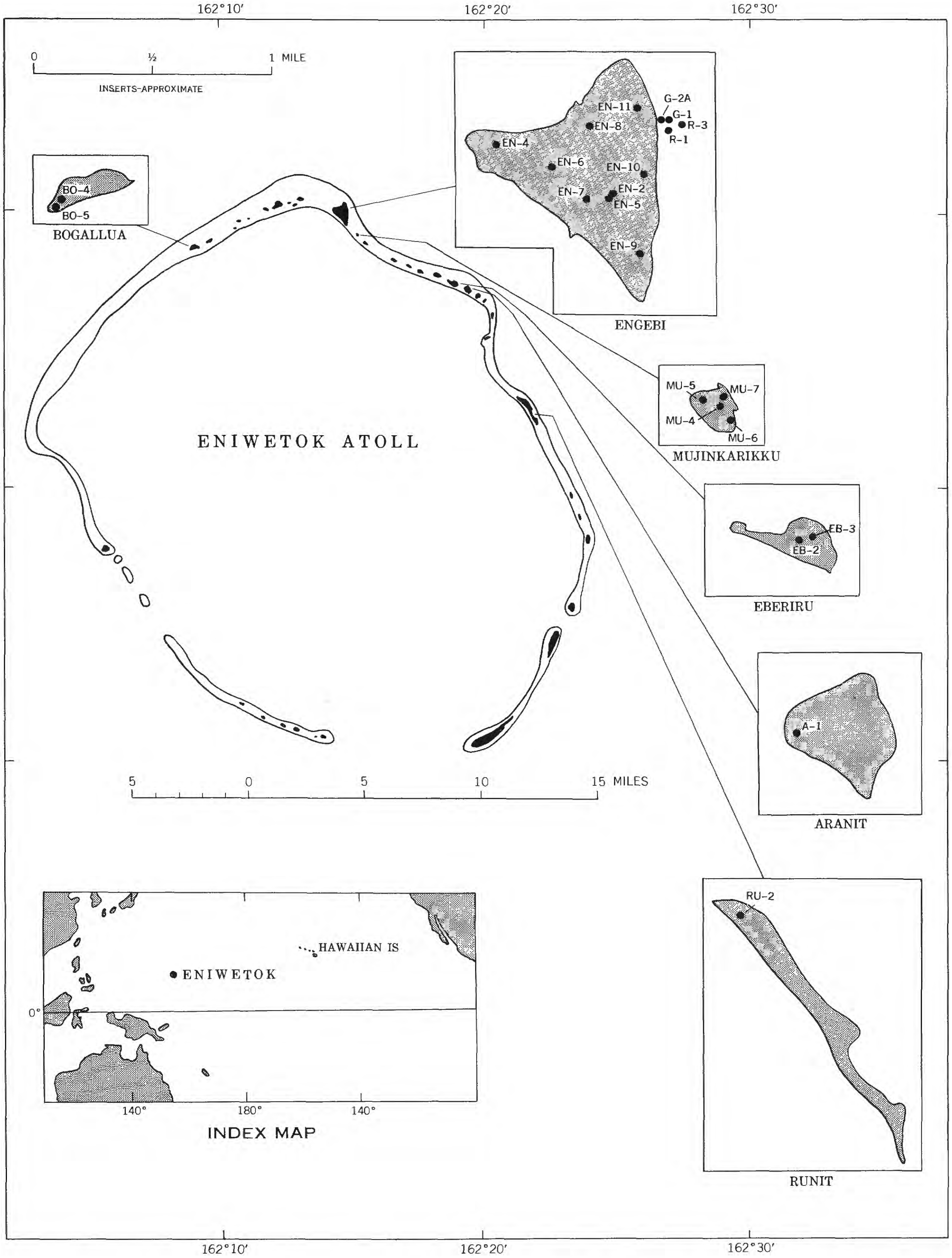

FIGURE 260.—Location of shallow holes drilled on islands and on reef flat.

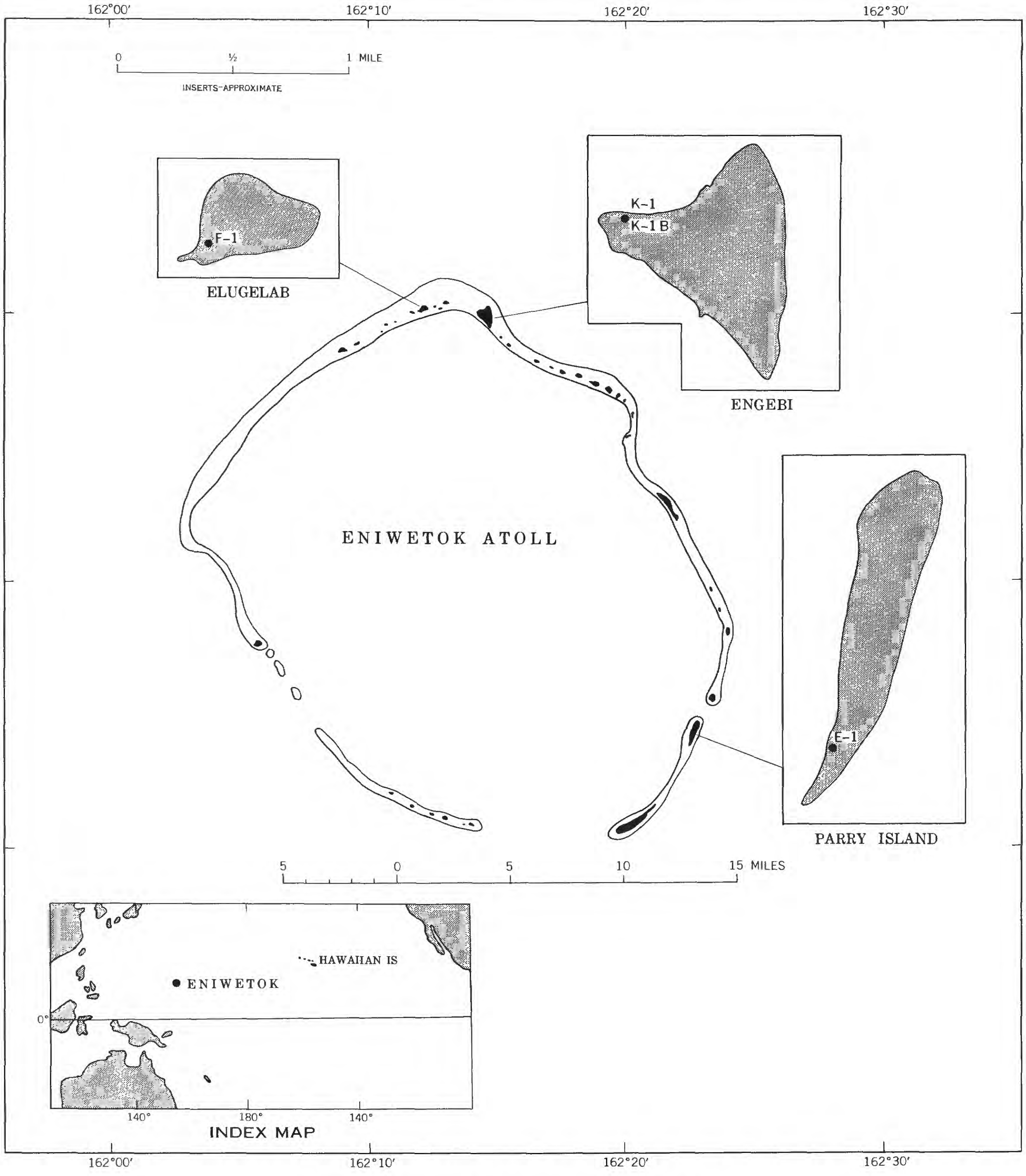

FIGURE 261.—Location of deep holes drilled on Eniwetok Atoll.

Vernon Kenney, were made available by C. T. Cooper and J. Rantilla. Mr. Kenney also assisted in drilling holes on the reef flat of Engebi. Several shallow holes on Bogallua, Aranit and Eberiru were drilled by AEC personnel under the supervision of Martin Russell of the U.S. Geological Survey.

The deep drilling described in the present report was supported by the Armed Forces special weapons project and carried out for the Atomic Energy Commission and the Los Alamos Scientific Laboratory in cooperation with the Office of Naval Research. In planning the work Ladd was assisted by Beauregard Perkins of the Armed Forces special weapons project, Gordon Lill of the Office of Naval Research, the late H. Kirk Stephenson of the Los Alamos Scientific Laboratory, and V. C. Mickle of the Geo. E. Failing Supply Company. The

FIGURE 262.—Truck-mounted rotary core drill set up over deep hole K–1B, close to lagoon shore (background) on Engebi in 1951. This rig was also used to drill shallow holes on various islands and the deep holes on Bikini. Photograph by Atomic Energy Commission.

work done in 1952 could not have been completed successfully without the active support of Maj. Gen. P. W. Clarkson of the Atomic Energy Commission. Personnel stationed on Eniwetok helped in carrying out the drilling projects in many ways and in this connection special thanks are expressed to C. T. Cooper, C. L. Coray, Vernon Kenney, and Paul W. Spain.

A preliminary report of the deep drilling was published in 1953 (Ladd, Ingerson, Townsend, Russell, and Stephenson). Much of the material in the preliminary report is included in the present paper. Fred A. Hildebrand of the Geological Survey analyzed samples by means of X-rays for clay materials and Paul D. Blackmon made the X-ray analyses for aragonite, calcite, and dolomite cited in table 3.

EQUIPMENT MATERIALS AND PERSONNEL

The shallow holes on the reef were drilled at times of low tide with an air drill mounted on a truck. A few of the shallow holes on the islands were drilled with cable tools but most of them with a truck-mounted rotary core drill, the rig previously used for deep drilling on Bikini Atoll (Ladd, Tracey and Lill, 1948, p. 51). This same rotary rig was used in drilling K–1B on Engebi in 1951 (fig. 262). For the deep holes drilled in 1952 (F–1 on Elugelab and E–1 on Parry Island), a heavier, trailer-mounted rotary rig was utilized (fig. 263).

In drilling the two deepest holes, rock bits were used for straight drilling and diamond bits for coring. Size and amounts of casing used in each of these holes is

FIGURE 263.—Trailer-mounted drill set up over hole F–1 near the lagoon shore (background) on Elugelab in 1952. Photograph by Atomic Energy Commission.

shown in plate 265. Salt water was used with salt-water mud and a variety of lost-circulation materials as required.

In the drilling of K–1B in 1951, V. C. Mickle was in charge of 2 drilling crews of 3 men each, the drill being operated continuously in 12-hour shifts. In the drilling of F–1 and E–1 in 1952 Willie Springer had charge of three crews of four men each. A geologist was on duty at all times during each operation. In 1951 Ladd was assisted by Martin Russell of the Geological Survey and Carl Alexis of the Office of Naval Research. In 1952 similar assistance was furnished by Earl Ingerson, Martin Russell, W. L. Smith and R. C. Townsend of the Geological Survey, the late H. Kirk Stephenson of the Los Alamos Scientific Laboratory and R. C. Fitzpatrick of the Office of Naval Research.

OPERATIONS

STRAIGHT DRILLING

In the shallow holes drilled with a rotary rig on the land and in the deep holes, three-cone rock bits were used exclusively for straight drilling.

COLLECTION OF CUTTINGS

In order to reduce contamination, cuttings were collected close to the top of the casing. In drilling the shallow holes they were picked up in a ditch leading from the casing to the mud pit. In drilling deep hole K–1B they were taken in a sieve from the overflow at the casing head. With the big rig used to drill F–1 and E–1, a more elaborate setup was utilized. An 8⅝-inch pipe was welded to the casing below the drill table and inclined in the direction of the mud pits. At a point 7 feet 8 inches from the casing, a 2-inch sleeve was welded into the bottom of the sludge pipe as an outlet for cuttings (fig. 264).

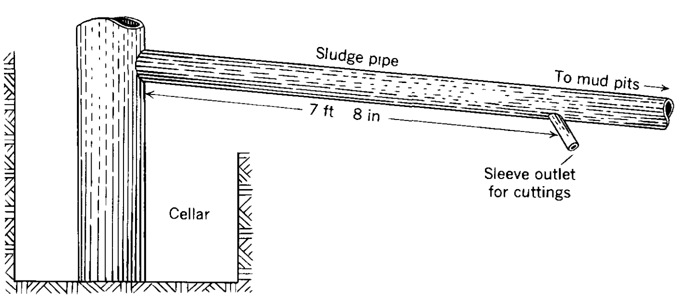

FIGURE 264.—Arrangement for collecting cuttings from holes F–1 and E–1.

Certain particles freed during rock-bit drilling (such as the light porous segments of *Halimeda* and minute thin-shelled mollusks) may remain suspended in the viscous drilling fluid for a considerable time, making one or more complete trips through the drill rods and the mud pits. Sparse or solitary occurrences of such elements in any given sample of cuttings are, therefore, to be viewed with suspicion. The same is true, of course, for small but identifiable fragments of larger forms. In examining a series of cuttings from progressively deeper horizons the first appearance of a given form is the significant one. Significant also is the presence of any form in great abundance in a given sample especially when this abundance is greater than in samples from immediately above or below.

ESTIMATES OF LAG

In soft sections such as that found beneath Eniwetok, drilling speeds are rapid, and cuttings from the bit arrive at the surface only after the bit has gone considerably deeper than the horizon at which the samples were cut. In order to obtain some idea of the amount of this lag in the arrival of the cuttings at the surface, the speed of movement of the drilling fluid from the bottom of the hole to the sampling outlet was determined by dye tests. These tests and calculations based on them were made by R. C. Townsend and Martin Russell, as described below, and their suggested correction figures are included in tables 1 and 2. The corrected figures have not been attached to any of the samples nor have they been used in the present series of reports because they are, admittedly, interpretations based on somewhat inadequate data. Alternate interpretations can be made from the data presented by anyone interested. The decision to use uncorrected depth figures for the cuttings is in accordance with standard practice.

Inasmuch as viscous fluid was used in drilling for cuttings, and the specific gravity of the cuttings was not great, the speed of movement of the cuttings was assumed to be essentially that of the drilling mud. Dye tests were made by two methods: containers of powdered dye were attached to the bit in such a manner that they would be broken when the bit hit bottom; and dye was placed in the cavity above the seated cone of the float valve where it would be released when the pressure was applied to circulate drilling fluid. In both cases, after a signal from the driller that the dye was released, the time for the dye to appear at the surface was determined with stop watches. Before the tests were made the holes were flushed clean, and during the tests pumps were run at average pressures for the depth and the bit was rotated at average speed but with light bit pressure so as not to deepen the hole greatly. Because of loss of circulation in much of the porous rock, and because of convenience in drilling operation, tests were made immediately after casing had been set to the bottom of the hole.

Several different water-soluble dyes were used in the tests. Sodium fluorescein, green and fluorescent when diluted, proved strong enough to color the thick mud. The other dyes used were all concentrated basic dye stuffs (phthalic anhydrides) made primarily for use with textiles.

Data from four tests at different depths were sufficiently reliable to be graphed and converted to figures for a depth of 2,000 feet. Time was not available for making two or more tests at a single depth under different pressures to determine accurately the influence of pump pressures. However, after converting to average pump pressure, the range in circulation time was found to be from 14.42 minutes to 19.69 minutes. The weighted average for 2,000 feet is 17.77 minutes. By using 17.77 minutes at 2,000 feet and zero minutes at zero depth, a straight-line function was graphed to determine circulation time of all depths. Accurate drillers' logs show the time required for the bit to penetrate each 10-foot interval. Samples were labled in the field with the depth of the bit at the time the samples were taken. In calculating corrections that might be made for the labeled depths, the columns of figures shown in tables 1 and 2 were set up. In determining the correct depth for any 10-foot sample, the circulating time (column 2) for that depth was first noted. Then the drilling rate (column 3) in minutes per 10-foot interval was examined. To the number of minutes required to drill the 10-foot interval being corrected was added the number of minutes of drilling time for the 10-foot units above until the total equaled the circulating time given in column 2. The corrected depth was then seen to be the depth figure in column 1 opposite the last or highest figure of the drilling rates (column 3) that was added to make the total drilling time equal to the circulating time. Interpolations to ±1 foot were made when necessary.

This method of correction is known to be imperfect. Time and the condition of the hole prevented sufficient tests for complete control of all factors; the speed of movement of the fluid may be a curved function instead of a straight-line function as graphed. Although the correction figures obtained are believed to approximate closely the true correction, they are less than, rather than in excess of, the true correction. In uncased sections of the hole the return of cuttings would be slower and the correction factor greater because of loss of fluid in the porous rock; complete return of the mud was seldom attained in an uncased hole.

TABLE 1.—*Lag correction data for hole F-1*

Recorded depth, in feet below drill table	Circulating time, in min., determined from graph	Drilling rate, in min. per 10 ft	Corrected depth, in feet below drill table	Calculated lag
10	0.1	----------	10	----------
20	.2	4	20	----------
30	.3	2	29	1
40	.4	2	39	1
50	.4	3	49	1
60	.5	9	60	----------
70	.6	13	70	----------
80	.7	13	80	----------
90	.8	15	90	----------
100	.9	13	100	----------
110	1.0	15	110	----------
120	1.1	15	119	1
130	1.2	20	130	----------
140	1.2	7	139	1
150	1.3	8	149	1
160	1.4	15	159	1
170	1.5	14	169	1
180	1.6	(1)	(1)	----------
190	1.7	(1)	(1)	----------
200	1.8	----------	200	----------
210	1.9	7	209	1
220	2.0	7	218	2
230	2.0	5	226	4
240	2.1	5	236	4
250	2.2	4	245	5
260	2.3	4	255	5
270	2.4	4	264	6
280	2.6	3	273	7
290	2.6	5	285	5
300	2.7	2	289	11
310	2.8	8	307	3
320	2.8	6	316	4
330	2.9	3	321	9
340	3.0	2	327	13
350	3.1	3	339	11
360	3.2	3	349	11
370	3.3	4	361	9
380	3.4	2	372	8
390	3.5	4	377	13
400	3.6	3	392	8
410	3.6	2	396	14
420	3.7	2	405	15
430	3.8	2	412	18
440	3.9	3	426	14
450	4.0	4	440	10
460	4.1	2	445	15
470	4.2	3	456	14
480	4.3	2	464	16
490	4.4	2	469	21
500	4.4	3	484	16
510	4.5	2	493	17
520	4.6	4	508	12
530	4.7	2	514	16
540	4.8	4	526	14
550	4.9	5	541	9
560	5.0	2	544	16
570	5.1	2	548	22
580	5.2	2	555	25
590	5.2	3	569	21
600	5.3	2	579	21
610	5.4	(1)	(1)	----------
620	5.5	(1)	(1)	----------
630	5.6	10	630	----------
640	5.7	5	632	8
650	5.8	4	638	12
660	5.9	6	650	10
670	6.0	3	655	15
680	6.0	3	660	20
690	6.1	4	673	17
700	6.2	4	684	16
710	6.3	5	697	13
720	6.4	6	709	11
730	6.5	5	718	12
740	6.6	3	723	17
750	6.7	3	729	21
760	6.8	4	741	19
770	6.8	5	756	14
780	6.9	4	766	14
790	7.0	5	775	15
800	7.1	5	786	14
810	7.2	6	797	13
820	7.3	7	809	11
830	7.4	6	818	12
840	7.5	7	829	11
850	7.6	4	835	15
860	7.6	4	841	19
870	7.7	5	856	14
880	7.8	5	866	14
890	7.9	4	872	18
900	8.0	5	883	17
910	8.1	6	894	16
920	8.2	7	906	14

See footnotes at end of table.

TABLE 1.—*Lag correction data for hole F–1*—Continued

Recorded depth, in feet below drill table	Circulating time, in min., determined from graph	Drilling rate. in min. per 10 ft	Corrected depth, in feet below drill table	Calculated lag
930	8.3	7	916	14
940	8.4	5	925	15
950	8.4	6	935	15
960	8.5	6	946	14
970	8.6	3	951	19
980	8.7	8	968	12
990	8.7	8	979	11
1,000	8.9	6	986	14
1,010	9.0	3	990	20
1,020	9.1	9	1,010	10
1,030	9.2	3	1,023	7
1,040	9.2	3	1,028	12
1,050	9.3	6	1,039	15
1,060	9.4	7	1,046	14
1,070	9.5	5	1,053	17
1,080	9.6	4	1,059	21
1,090	9.7	11	1,081	9
1,100	9.8	3	1,084	16
1,110	9.9	4	1,088	22
1,120	10.0	4	1,093	27
1,130	10.0	4	1,105	25
1,140	10.1	9	1,127	13
1,150	10.2	8	1,138	15
1,160	10.3	19	1,155	5
1,170	10.4	6	1,158	12
1,180	10.5	7	1,165	15
1,190	10.6	4	1,171	19
1,200	10.7	7	1,181	19
1,210	10.8	25	1,206	4
1,220	10.8	16	1,213	7
1,230	10.9	4	1,217	13
1,240	11.0	(1)	(1)	----
1.950	17.3	6	----	----
1,960	17.4	2	----	----
1.970	17.5	11	1,949	21
1.975	17.5	5	1,953	22
1,978–1,979	17.6	(1)	(1)	----
1,980	17.6	(1)	1,980	----
2,000	17.7	(1)	(1)	----
2,005	17.8	----	----	----
2,010	17.9	[2] 12	2,003	7
2,020	17.9	57	2,017	3
2,030	18.0	96	2,028	2
2,040	18.1	65	2,036	4
2,050	18.2	65	2,046	4
2,060	18.3	33	2,055	5
2,070	18.4	24	2,063	7
2,080	18.5	11	2,069	11
2,090	18.6	30	2,084	6
2,100	18.7	27	2,093	7
2,110	18.7	31	2,103	7
2,120	18.8	30	2,113	7
2,130	18.9	20	2,121	9

[1] Core taken.
[2] Minutes required to drill 5 feet.

TABLE 2.—*Lag correction data for Hole E–1*

Recorded depth, in feet below drill table	Circulating time, in min. (based on 33.75 at 2,000 ft)	Drilling rate in min. per 10 ft	Circulating time, in min. (based on 17.77 at 2,000 ft)	Corrected depth, in feet	Calculated lag
10	0.2	----	.1	10	----
20	.3	----	.2	20	----
30	.5	----	.3	30	----
40	.7	----	.4−	40	----
50	.8	----	.4+	50	----
60	1.0	----	.5	60	----
70	1.2	----	.6	70	----
80	1.4	30	.7	80	----
90	1.5	25	.8	90	----
100	1.7	12	.9	100	----
110	1.9	15	1.0	110	----
120	2.0	7	1.1	119	1
130	2.2	5	1.2−	128	2
140	2.4	10	1.2+	139	1
150	2.5	5	1.3	147	3
160	2.7	5	1.4	157	3
170	2.9	3	1.5	165	5
180	3.0	4	1.6	176	4
190	3.2	3	1.7	184	6
200	3.4	2	1.8	191	9
210	3.5	4	1.9	205	5
220	3.7	3	2.0−	213	7
230	3.9	4	2.0+	225	5
240	4.1	3	2.1	233	7
250	4.2	2	2.2	239	11

TABLE 2.—*Lag correction data for Hole E–1*—Continued

Recorded depth, in feet below drill table	Circulating time, in min. (based on 33.75 at 2,000 ft)	Drilling rate in min. per 10 ft	Circulating time, in min. (based on 17.77 at 2,000 ft)	Corrected depth, in feet	Calculated lag
260	4.4	2	2.3	248	12
270	4.6	2	2.4	258	12
280	4.7	2	2.5	267	13
290	4.9	2	2.6	277	13
300	5.0	2	2.7	286	14
310	5.2	2	2.8−	296	14
320	5.4	1	2.8+	302	18
330	5.6	1	2.9	306	24
340	5.7	2	3.0	320	20
350	5.9	2	3.1	335	15
360	6.0	2	3.2	344	16
370	6.2	3	3.3	358	12
380	6.4	3	3.4	369	11
390	6.6	2	3.5	375	15
400	6.8	3	3.6−	387	13
410	6.9	3	3.6+	398	12
420	7.1	3	3.7	408	12
430	7.3	4	3.8	420	10
440	7.4	2	3.9	425	15
450	7.6	4	4.0	440	10
460	7.8	2	4.1	445	15
470	7.9	2	4.2	450	20
480	8.1	2	4.3	458	22
490	8.3	3	4.4−	473	17
500	8.4	3	4.4+	486	14
510	8.6	3	4.5	496	14
520	8.8	3	4.6	506	14
530	8.9	3	4.7	516	14
540	9.1	3	4.8	526	14
550	9.3	3	4.9	535	15
560	9.5	3	5.0	545	15
570	9.6	2	5.1	550	20
580	9.8	2	5.2−	557	23
590	10.0	2	5.2+	564	26
600	10.1	2	5.3	574	26
610	10.3	1	5.4	578	32
620	10.5	1	5.5	583	37
630	10.6	2	5.6	592	38
640	10.8	3	5.7	613	27
650	11.0	2	5.8	626	24
660	11.1	2	5.9	637	23
670	11.3	2	6.0−	640	30
680	11.5	3	6.0+	655	25
690	11.6	3	6.1	669	21
700	11.8	4	6.2	683	17
710	12.0	3	6.3	692	18
720	12.2	3	6.4	699	21
730	12.3	2	6.5	707	23
740	12.5	3	6.6	718	22
750	12.7	2	6.7	722	28
760	12.8	2	6.8−	732	28
770	13.0	3	6.8+	741	29
780	13.2	2	6.9	751	29
790	13.3	2	7.0	760	30
800	13.5	2	7.1	767	33
810	13.7	2	7.2	774	36
820	13.8	2	7.3	784	36
830	14.0	2	7.4	793	37
840	14.2	2	7.5	803	37
850	14.3	2	7.6−	812	38
860	14.5	2	7.6+	822	38
870	14.7	2	7.7	832	38
880	14.9	2	7.8	841	39
890	15.0	2	7.9	851	39
900	15.2	3	8.0	865	35
910	15.4	3	8.1	880	30
920	15.5	3	8.2	895	25
930	15.7	3	8.3	904	26
940	15.9	2	8.4−	909	31
950	16.0	2	8.4+	916	34
960	16.2	3	8.5	926	34
970	16.4	3	8.6	937	33
980	16.5	3	8.7	952	28
990	16.7	4	8.8	967	23
1,000	16.9	3	8.9	971	29
1,010	17.0	4	9.0	985	25
1,020	17.2	4	9.1	997	23
1,030	17.4	2	9.2−	1,002	28
1,040	17.6	2	9.2+	1,007	33
1,050	17.7	2	9.3	1,012	38
1,060	17.9	1	9.4	1,015	45
1,070	18.0	2	9.5	1,023	47
1,080	18.2	2	9.6	1,027	53
1,090	18.4	4	9.7	1,047	43
1,100	18.6	2	9.8	1,061	39
1,110	18.7	2	9.9	1,071	39
1,120	19.0	3	10.0−	1,082	38
1,130	19.1	4	10.0−	1,095	35
1,140	19.2	3	10.1	1,110	30
1,150	19.4	3	10.2	1,120	30
1,160	19.6	20	10.3	1,155	5
1,,170	19.7	80	10.4	1,169	1
1, 180	19.9	19	10.5	1,174	6
1,190	20.0	43	10.6	1,187	3
1 200	20.2	5	10.7	1,189	11

TABLE 2.—*Lag correction data for Hole E-1*—Continued

Recorded depth, in feet below drill table	Circulating time, in min. (based on 33.75 at 2,000 ft)	Drilling rate in min. per 10 ft	Circulating time, in min. (based on 17.77 at 2,000 ft)	Corrected depth, in feet	Calculated lag
1,210	20.4	44	10.8−	1,207	3
1,220	20.6	30	10.8+	1,212	8
1,230	20.8	15	10 9	1,219	11
1,240	20.9	24	11.0	1,236	4
1,250	21.1	15	11.1	1,239	11
1,260	21.3	20	11.2	1,254	6
1,270	21.4	6	11.3	1,257	13
1,280	21.6	5	11.4	1,260	20
1,290	21.8	6	11.5	1,269	21
1,300	21.9	8	11.6−	1,284	16
1,310	22.1	12	11.6+	1,301	9
1,320	22.3	16	11.7	1,313	7
1,330	22.4	7	11.8	1,317	13
1,340	22.6	4	11.9	1,320	20
1,350	22.8	3	12.0	1,323	27
1,360	23.0	5	12.1	1,330	30
1,370	23.1	44	12.2	1,367	3
1,380	23.3	6	12.3	1,369	11
1,390	23.5	5	12.4	1,370	20
1,400	23.6	3	12.4	1,374	26
1,410	23.8	3	12.5	1,378	32
1,420	24.0	5	12.6	1,388	32
1,430	24.1	3	12.7	1,396	34
1,440	24.3	2	12.8	1,404	36
1,450	24.5	3	12.9	1,410	40
1,460	24.6	3	13.0	1,416	44
1,470	24.8	3	13.1	1,424	46
1,480	25.0	3	13.1	1,434	46
1,490	25.1	2	13.2	1,442	48
1,500	25.3	3	13.3	1,452	48
1,510	25.5	3	13.4	1,464	46
1,520	25.7	2	13.5	1,468	52
1,530	25.8	2	13.6	1,476	54
1,540	26.0	2	13.7	1,484	56
1,550	26.2	2	13.8	1,494	56
1,560	26.3	2	13.9	1,498	62
1,570	26.5	2	13.9	1,505	65
1,580	26.7	9	14.0	1,545	35
1,590	26.8	6	14.1	1,571	19
1,600	27.0	3	14.2	1,575	25
1,610	27.2	2	14.3	1,578	32
1,620	27.3	2	14.4	1,580	40
1,630	27.5	2	14.5	1,582	48
1,640	27.7	2	14.6	1,586	54
1,650	27.8	4	14.7	1,594	56
1,660	28.0	3	14.7	1,602	58
1,670	28.2	3	14.8	1,616	54
1,680	28.4	3	14.9	1,630	50
1,690	28.5	2	15.0	1,640	50
1,700	28.7	3	15.1	1,648	52
1,710	28.9	3	15.2	1,658	52
1,720	29.0	3	15.3	1,666	54
1,730	29.2	3	15.4	1,676	54
1,740	29.4	2	15.5	1,683	53
1,750	29.5	3	15.5	1,696	54
1,760	29.7	3	15.6	1,706	54
1,770	29.9	2	15.7	1,714	56
1,780	30.0	2	15.8	1,718	62
1,790	30.2	4	15.9	1,730	60
1,800	30.4	3	16.0	1,743	57
1,810	30.5	4	16.1	1,757	53
1,820	30.7	3	16.2	1,769	51
1,830	30.9	4	16.3	1,784	46
1,840	31.1	4	16.3	1,796	44
1,850	31.2	3	16.4	1,804	46
1,860	31.4	2	16.5	1,809	51
1,870	31.6	2	16.6	1,817	53
1,880	31.7	2	16.7	1,822	58
1,890	31.9	2	16.8	1,826	64
1,900	32.1	3	16.9	1,834	66
1,910	32.2	3	17.0	1,840	70
1,920	32.4	4	17.1	1,855	65
1,930	32.6	2	17.1	1,865	65
1,940	32.7	2	17.2	1,874	64
1,950	32.9	3	17.3	1,889	61
1,960	33.1	2	17.4	1,896	64
1,970	33.2	1	17.5	1,899	71
1,980	33.4	1	17.6	1,903	77
1,990	33.6	2	17.7	1,908	82
2,000	33.7	2	17.7	[1] 1,913	87
2,010	33.9	(2)	17.9	(2)	--
2,020	34.1	(2)	17.9	(2)	--
2,030	34.3	(2)	18.0	[3] 2,030	--
2,040	34.4	4	18.1	[3] 2,035	5
2,050	34.6	4	18.2	[3] 2,039	11
2,060	34.8	3	18.3	[3] 2,042	18
2,070	34.9	3	18.4	[3] 2,044	26
2,080	35.1	4	18.5	[3] 2,045	35
2,090	35.3	5	18.6	[3] 2,046	44
2,100	35.4	5	18.7	2,055	45
2,110	35.6	7	18.7	2,076	34
2,120	35.8	8	18.8	2,093	27
2,130	35.9	6	18.9	2,103	27
2,140	36.1	6	19.0	2,112	28
2,150	36.3	5	19.1	2,118	32

See footnotes at end of table.

TABLE 2.—*Lag correction data for Hole E-1*—Continued

Recorded depth, in feet below drill table	Circulating time, in min. (based on 33.75 at 2,000 ft)	Drilling rate in min. per 10 ft	Circulating time, in min. (based on 17.77 at 2,000 ft)	Corrected depth, in feet	Calculated lag
2,160	36.5	5	19.2	2,125	25
2,170	36.6	5	19.3	2,133	37
2,180	36.8	6	19.4	2,142	38
2,190	37.0	6	19.5	2,154	36
2,200	37.1	7	19.5	2,169	31
2,210	37.3	6	19.6	2,179	31
2,220	37.5	6	19.7	2,188	32
2,230	37.6	6	19.8	2,197	33
2,240	37.8	8	19.9	2,211	29
2,250	38.0	6	20.0	2,220	30
2,260	38.2	4	20.1	2,227	33
2,270	38.3	4	20.2	2,233	37
2,280	38.5	4	20.3	2,238	42
2,290	38.6	4	20.3	2,243	47
2,300	38.8	4	20.4	2,249	51
2,310	39.0	4	20.5	2,259	51
2,320	39.2	4	20.6	2,269	51
2,330	39.3	3	20.7	2,276	54
2,340	39.5	7	20.8	2,294	46
2,350	39.7	7	20.9	2,310	40
2,360	39.8	7	21.0	2,330	30
2,370	40.0	7	21.1	2,340	30
2,380	40.2	8	21.1	2,352	28
2,390	40.3	6	21.2	2,360	30
2,400	40.5	4	21.3	2,367	33
2,410	40.7	4	21.4	2,374	36
2,420	40.8	6	21.5	2,378	42
2,430	41.0	10	21.6	2,397	33
2,440	41.2	5	21.7	2,409	31
2,450	41.3	5	21.8	2,417	33
2,460	41.5	7	21.9	2,425	35
2,470	41.7	8	21.9	2,436	34
2,480	41.9	7	22.0	2,450	30
2,490	42.0	8	22.1	2,461	29
2,500	42.2	14	22.2	2,480	20
2,510	42.4	17	22.3	2,496	14
2,520	42.5	9	22.4	2,503	17
2,530	42.7	10	22.5	2,509	21
2,540	42.9	12	22.6	2,519	21
2,550	43.0	9	22.7	2,528	22
2,560	43.2	5	22.7	2,534	26
2,570	43.4	5	22.8	2,537	33
2,580	43.5	5	22.9	2,542	38
2,590	43.7	5	23.0	2,547	43
2,600	43.9	5	23.1	2,554	46
2,610	44.0	3	23.2	2,559	51
2,620	44.2	6	23.3	2,573	47
2,630	44.4	4	23.4	2,576	54
2,640	44.6	5	23.5	2,591	49
2,650	44.7	5	23.5	2,599	51
2,660	44.9	5	23.6	2,612	48
2,670	45.1	5	23.7	2,621	49
2,680	45.2	5	23.8	2,632	48
2,690	45.4	7	23.9	2,645	45
2,700	45.6	5	24.0	2,656	44
2,710	45.7	3	24.1	2,662	48
2,720	45.9	3	24.2	2,668	52
2,730	46.1	4	24.3	2,675	55
2,740	46.2	6	24.3	2,685	55
2,750	46.4	5	24.4	2,695	55
2,760	46.6	4	24.5	2,704	56
2,770	46.7	4	24.6	2,717	53
2,780	46.9	5	24.7	2,729	51
2,790	47.1	5	24.8	2,738	52
2,800	47.3	8	24.9	[4] 2,753	47
2,810	47.4	(5)	25.0	--	--
2,820	47.6	10	25.1	[6] 2,815	5
2,830	47.8	10	25.1	[6] 2,819	11
2,840	47.9	18	25.2	[6] 2,823	17
2,850	48.1	25	25.3	2,839	11
2,860	48.3	13	25.4	2,845	15
2,870	48.4	10	25.5	2,849	21
2,880	48.6	17	25.6	2,861	19
2,890	48.8	28	25.7	2,881	9
2,900	48.9	27	25.8	2,891	9
2,910	49.1	11	25.9	2,895	15
2,920	49.3	14	26.0	2,900	20
2,930	49.4	16	26.0	2,912	18
2,940	49.6	18	26.1	2,925	15
2,950	49.8	33	26.2	2,942	8
2,960	50.0	30	26.3	2,951	9
2,970	50.1	20	26.4	2,958	12
2,980	50.3	15	26.5	2,965	15
2,990	50.5	10	26.6	2,969	21
3,000	50.6	9	26.7	2,974	26
3,010	50.8	15	26.7	2,988	22
3,020	51.0	16	26.8	3,004	16
3,030	51.1	12	26.9	3,011	19
3,040	51.3	14	27.0	3,020	20
3,050	51.5	15	27.1	3,031	19
3,060	51.6	12	27.2	3,040	20
3,070	51.8	15	27.3	3,050	20
3,080	52.0	18	27.4	3,063	17
3,090	52.1	16	27.5	3,072	18
3,100	52.3	15	27.5	3,082	18

See footnotes at end of table.

TABLE 2.—*Lag correction data for Hole E-1*—Continued

Recorded depth, in feet below drill table	Circulating time, in min. (based on 33.75 at 2,000 ft)	Drilling rate in min. per 10 ft	Circulating time, in min. (based on 17.77 at 2,000 ft)	Corrected depth, in feet	Calculated lag
3,110	52.5	10	27.6	3,089	21
3,120	52.7	8	27.7	3,094	26
3,130	52.8	9	27.8	3,099	31
(7)					
4,130		5			
4,140		5			
4,150		21			
4,160		26			
4,170	70.4	21	37.0	4,154	16
4,180	70.5	10	37.1	[8] 4,158	22
4,190	70.7	9	37.2	4,161	29

1 Approaches 2,000 ft for samples collected during cleanout before coring.
2 Core taken 2,003–2,028 ft; drilling time 6 min. after cleaning hole.
3 Arbitrarily adjusted. Driller had to circulate mud without drilling at end of several of these intervals to permit filling sample bags. Normal lag resumes at 2,100 ft (column 6).
4 Approaches 2,800 ft for samples collected during cleanout before coring.
5 Core taken 2,802–2,808 ft; drilling time 31 min.
6 Arbitrarily adjusted. Normal lag resumes at 2,850 ft.
7 Lost circulation at 3,127 ft; returned at 4,170 ft.
8 Probable depth at which hard basalt cuttings were drilled.

CORING

Cable tools were used to drill four of the shallow holes on the islands; the others were drilled with a rotary core drill. A standard core barrel with diamond or hard metal inserts was used in hard formations; in the softer parts of the section cores were obtained with an open barrel driven (usually to refusal) with a hammer. The holes on the reef were cored continuously with diamond bits.

In drilling K–1 and K–1B an open core barrel was used successfully in three out of four attempts; the others were taken with a standard barrel and diamond bit. A thickness of 52 feet was cored with a recovery of 32 percent.

Diamond bits were used for all core runs in holes F–1 and E–1. A total of about 350 feet was cored with a recovery of 35 percent in hole F–1 and 56 percent in hole E–1. In drilling these two holes the drill rods were measured with a steel tape each time the core barrel was placed in the hole. The depths of coring intervals, therefore, are completely trustworthy. In those rare instances when 100-percent recovery was obtained, the exact depth of each core piece is known. When less than 100-percent recovery was obtained, only the approximate position of any given core piece in the cored interval can be determined.

Because available time and facilities would permit only a limited amount of coring and because much of the section appeared soft or unconsolidated, the core barrel was usually put in the hole only when the drilling record indicated that a hard or firm layer had been reached.

Deviation of holes F–1 and E–1 from the vertical was determined periodically by dropping a recording instrument into the drill pipe. Results of the readings are given below:

Record of deviation from the vertical in drill holes F–1 and E–1

F-1			E-1		
Depth (feet)	Deviation (degrees)	Deviation (minutes)	Depth (feet)	Deviation (degrees)	Deviation (minutes)
160	0	15	146	0	30
1,232	0	45			
1,650	0	15			
1,968	1	05			
1,975	0	55	2,000	0	30
2,470	4	30			
2,900	5	30	2,802	0	30
3,350	3	30			
3,650	2	45			
3,963	4	0			
4,182	4	0	4,078	1	0
4,197	3	30			
4,406	3	0			
4,500	3	15			

SUMMARY OF OPERATIONS

All the deeper holes on Eniwetok entered cavities, which increased mud consumption or led to complete loss of circulation. An example of the radical changes in section that may be expected in atoll drill holes was recorded in the drilling of the second of the "K" holes on the island of Engebi in 1951. K–1 was drilled to a depth of 433 feet, at which point difficulties in attempting to run casing caused the hole to be abandoned, and the rig was skidded 6 feet, N. 65° W. to the site of K–1A. At a depth of 329 feet this hole reached a 2-foot cavity and all circulation was lost. Attempts to restore circulation were not successful and K–1B was started at a new site, located 24 feet S. 65° E. of K–1.

Perhaps the most conspicuous feature of the sedimentary sections found in the two deepest holes is the large proportion of soft or unconsolidated beds compared with layers that may be called firm or hard rock. In the first hole (F–1), on Elugelab, soft beds and cavities totaled 70 percent of the section. The cavities alone totaled 122 feet (pl. 265) and were found to depths of more than 2,700 feet. These cavities were primarily responsible for the high consumption of mud materials and for the complete loss of circulation at five different levels. In the first hole (F–1) circulation was never regained after it was lost at 2,135 feet, and 70 percent of the hole was drilled with untreated sea water. During the drilling of the deeper parts of the hole, four pumps were operated continuously to keep the pits supplied with sufficient water for uninterrupted operation. The largest of the cavities in hole F–1 was 55 feet deep. In this and other intervals called cavities, the bit would drop with all the appearance of a free fall. Many of the cavities are believed to be actual voids filled only with sea water, but some may have been filled or partly filled with sediment so loose that the pump pressure readily cleared a way for the bit. One observation favoring the sediment-fill conception is that in some instances after drilling was halted at a cavity in order to refill the pits with water, there would be considerable caved material to remove when drilling was resumed.

Drilling characteristics, sample collection data, and age of beds are given for all three of the deep holes in plate 265. The depths of cuttings are not corrected for lag.

In hole F–1 a section of soft chalky limestone totaling approximately 1,000 feet was drilled, starting at 2,900 feet (pl. 265). With nearly 1,000 feet of open hole, partly cavernous, above the zone, and with no circulation, it was difficult to obtain samples. The material was much softer than anything drilled at higher levels, yet cuttings did not pack around the bit and drill collar as each succeeding joint of drill pipe was added. The chances of obtaining any recovery with the diamond-core barrel seemed remote so the "junk basket" (a short section of pipe with an annular opening at the top, used to clean steel fragments from hole prior to coring) was run to bottom at a depth of about 3,045 feet. This produced a small but recognizable sample consisting mainly of fine white chalky limestone, composed of grains of several sizes to a maximum of 1 millimeter—rods, spheres, discs, and arcuate and platy fragments. Most of these when pressed beneath the needle broke into a powder. A few grains contained clear, crystalline calcite that did not powder under the needle. When small lumps of the material were placed in fresh water they disintegrated, making the water milky.

In an attempt to obtain a larger and less contaminated sample the core barrel was put in at 3,052 feet and drilled dry (no pump pressure) for a distance of 3 feet. This hazardous procedure yielded 3 feet (100-percent recovery) of soft chalky limestone containing globigerinids and a few molds of minute gastropods. A second dry run was made from 3,350 to 3,353 feet, but core totaling only 3 inches was recovered; this was in a single piece, apparently from an indurated layer at the end of the run. Three other core runs were made in the soft section: a 5-foot run starting at 3,650 feet yielded no recovery; a 10-foot run starting at 3,655 feet brought in a 33-percent recovery of hard to friable coral and shell limestone—the material being considerably firmer than the drilling-time record would suggest, a 25-foot run starting at 3,963 feet recovered 12 percent of friable algal limestone. This soft section in F–1 had no counterpart at similar depths in hole E–1 (pl. 265).

Most of F–1 was drilled without circulation and the drilling time record was the only continuous guide to the nature of the formation drilled. Checks of this record with driller's remarks and with cores and cuttings where available usually substantiated the relative hardness as indicated by the drilling-time record. Complete reliance cannot be placed on it, however, because rocks of equal hardness in different parts of the column may take different lengths of time to drill, depending upon such factors as the individual driller's preferred drilling rate, the type of rock bit in use, or the type of drilling fluid being pumped.

At a depth of 3,980 feet the section in F–1 was appreciably harder and five successful core runs were made between 4,000 and 4,600 feet (pl. 266). Much of the core below 4,300 feet consisted of dolomite or dolomitic limestone. None of these cores contained any volcanic material though some of the core pieces were stained gray or green. Somewhat harder rock was found at 4,610 feet, and at 4,619 the core barrel was put in the hole. There was no difficulty in getting to bottom, and it was believed that a core could be obtained without making further inroads on the limited supply of drilling mud that was then available. The core barrel was drilled down to 4,630 feet, at which point sections of the uncased part of the hole collapsed, locking the core barrel and drill pipe in the hole. Prolonged efforts to free the core barrel were not successful, though at one stage it was possible to rotate the string. A shot line was rigged and the drill pipe finally freed at a depth of 3,750 feet. Equipment needed for time-consuming whip-stocking operations was not available, and with reluctance the drill was moved to Parry Island, where the site for a second hole had been prepared.

The collapse of the uncored section of hole F–1 may have been caused by the presence of a highly cavernous zone in the limestone above the impervious basement rock. When coring of the basement rock was started all of the drilling fluid may have escaped in this porous zone without lifting new and old cuttings to higher levels as it had done up to that time.

In hole E–1 only 55 percent of the section was soft or cavernous. Only two small cavities—totaling about 8 feet—were found, but both caused complete loss of circulation. The lower cavity was at 3,127 feet, and circulation was regained only once beyond this point though batches of mud were used at intervals to clean out the hole. Twenty-five percent of hole E–1 was drilled with untreated sea water and without circulation.

LITHOLOGIC CHARACTER OF SECTIONS DRILLED

SHALLOW HOLES

HOLES ON ISLANDS

Many shallow holes were drilled on the islands by the Atomic Energy Commission in connection with their test programs. The locations of a representative series are shown in figure 260 and graphic logs are given in plate 266. In the more detailed descriptions given below, drillers' logs have been supplemented by an examination of the cores and cuttings in the laboratory. Generalized interpretations are given in the summary section that follows.

Drill hole 4 on Bogallua

[Elevation 8.9 feet]

Interval (feet)	*Lithologic character*
0–6	Coral sand and gravel, light tan to white, coarse; contains some layers of medium-grained to coarse sand.
6–6. 5	Coral conglomerate, badly fractured.
6. 5–12. 5	Coral sand, coarse with gravel of coral and shells to a maximum diameter of 1 in.
12. 5–13. 5	Coral gravel, as large as 2 in. in diameter with little sand.
13. 5–23	Coral sand, fine, white; with large pieces of broken coral.
23–25. 5	Sand, containing large shell (*Tridacna*).
25. 5–26. 5	Sand and silt, largely fine; with abundant unaltered segments of *Halimeda* to a maximum of 5 mm across and fragments of branching coral, mollusks and nodular coralline algae. Sand of matrix is mostly unidentifiable fragments of shells, well-preserved miliolids and other small benthonic foraminifers, a few tests of *Calcarina*.
26. 5–30. 5	Sand and silt; similar to preceding unit, partly cemented.
30. 5–36	Coral sand, fine, white; with scattered gravel.
36–39	Sand, coarse and granule-size *Halimeda*, coral, and coralline algae; few small fragments of mollusks and echinoid spines, all unaltered; small amount of silt and fine sand.
39–40	Coral, broken pieces as large as 3.5 in. in matrix of sand.
40–43	Coral sand, fine, white: with pieces of broken coral.

Drill hole 5 on Bogallua

[Elevation 7.0 feet]

Interval (feet)	*Lithologic character*
0–5. 5	Sand, coarse to fine; some gravel to maximum diameter of three-fourths inch. Loose to depth of 2.0 ft, compact to 5.5 ft. Many Calcarinas, Marginoporas.
5. 5–7	Beach rock.
7–9	Sand, medium and fine gravel. Many algal nodulesand well-graded assortment of *Calcarina*, *Halimeda*, broken mollusk shells. Few *Tubipora* fragments and encrusting Foraminifera. Some compact hard pieces of algae as large as 1½ in.
9–11	Algal rock, hard, white, chunks as large as 2 in. in diameter; pieces of hard fine-pored coral rock in matrix of fine sand (*Calcarina*, *Marginopora*, and *Homotrema*); white silt.
11–13	Sand, medium, to fine gravel. Topmost part contained *Heliopora* fragments, rather thin, but 2 in long. Bottom part a fine, silty sand. Some Foraminifera.
13–15	No sample.

Drill hole 5 on Bogallua—Continued

Interval (feet)	*Lithologic character*
15–17	Sand, fine with gravel as large as one-half inch in diameter. Fragments of coral, some encrusted with white algae. Matrix containing *Halimeda*, *Marginopora*, and few small Calcarinas.
17–19	No sample.
19–23. 5	Sand, fine and silt with fragments of coral and dense white algae (some cemented pieces) as large as 1 in. Few echinoid spines. Drilling action suggests evidence of much larger boulders.
23. 5–29. 5	No sample.
29. 5–31	Solid rock and broken core. One rock fractured by sampler in pieces as large as 1½ in.
31–34. 5	No sample.
34. 5–36. 5	Sand, fine, white; soft mixture with many *Halimeda* fragments. Few large chunks of coral as large as 2 in.
36. 5–40	No sample.
40–42	Sand, fine, cream white; *Halimeda* in matrix.
42–44	No sample.
44–46	Sand of tan *Halimeda* with corals in position of growth.
46–48	No sample.
48–50	Sand, light-tan, compact, fine, contains many *Halimeda* segments. Rare coral encrusted with algae. Many *Homotrema*.
50–53	No sample.
53–54	Sand, light-tan, fine; many *Halimeda* segments, pieces of worn and broken coral as large as 2½ in.
54–58	No sample; hard drilling at 56.5 ft.
58–59	Gravel, cream-white, chalky; maximum size, 1 in. Minor amounts of silt and fine sand, rough broken coral pieces, some *Halimeda*. Rare streaks of light-brown material.
59–63	No sample.
63–70	Sand to fine gravel, poorly cemented, cream-white, coarse; fragments of coral, some *Halimeda*.
70–74	No sample.
74–75. 5	Sand, fine and silt matrix containing cream-white, rough pieces of limestone as large as 1 in. in diameter.
75. 5–84. 5	No sample.
84. 5–85. 5	Coral, hard, in large chunks and some fine sand and silt; unaltered; not cemented; poor recovery.
85. 5–95	No sample.
95–96	Conglomerate, irregular pieces of white, well-lithified; unaltered, poorly sorted; containing molluscan debris (*Trochus*), coral and algae in a sandy matrix.
96–106	No sample.
106–107	Conglomerate. Similar to preceding layer but less well cemented; some algal and foraminiferal encrustations. Many *Halimeda* segments.
107–116. 5	No sample.
116. 5–121. 5	Coral and algal debris, well-cemented. Coral pieces as large as 2 in. in diameter.
121. 5–127	No sample.
127–128. 5	Conglomerate, same as 95–96 ft.
128. 5–137. 5	No sample.

Drill hole 5 on Bogallua—Continued

Interval (feet)	*Lithologic character*
137. 5–139	Conglomerate; same as 95–96 ft.
139–148	No sample.
148–149. 5	Coral pieces, white, slightly recrystallized; and pieces of sandy limestone with algal fragments; some fine sand and silt.
149. 5–158. 5	No sample.
158. 5–159. 5	Coral pieces, same as 148–149.5 ft.

Drill hole 4 on Engebi

[Elevation: 7.06 feet]

Interval (feet)	*Lithologic character*
0–5. 3	Sand and black top (fill)
5. 3–13. 5	Sand, coarse, foraminiferal; contains some fine sand and some rounded and polished coral fragments as large as three-fourths inch in diameter; rich in worn and rounded *Calcarina* and *Marginopora*. Small, mollusks (*Cardium*, *Tellina*, limpet, trochids *Diala* and other cerithids) and *Halimeda* fragments are common.
13. 5–21	Sand white, fine- to medium-grained; contains some pieces of coral as large as 3½ in. in diameter.
21–32	Unconsolidated debris, poorly sorted; largely fine sand and silt with some coarse sand and coral and algal debris as much as 1½ in. in diameter. The bulk of the fine material isuni dentifiable calcite and aragonite fossil fragments. Small, well-preserved miliolid and coiled Foraminifera are common; some large reef types. Granule-size fraction includes a few mollusks (arcids, tellinids, cerithids, *Vanikoro*) and unaltered *Halimeda* segments.
32–36	Unconsolidated debris; similar to preceding sample but lacks the pebble-size coral debris; granule-size *Halimeda* and molluscan debris abundant.
36–40	Unaltered material, loose. Largely foraminiferal sand with abundant granule-size *Halimeda* debris and some fine sand and silt; coral and algal fragments common and less than one-half inch in diameter. Mollusks include tellinids and many well preserved shells of *Diala*.
40–48	Sand, white, fine; contains broken mollusk shells.

Drill hole 6 on Engebi

[Elevation: 10.2 feet]

Interval (feet)	*Lithologic character*
0–5	Sand, tan, silty; contains some fine gravel; unconsolidated.
5–9	Poorly cemented light-tan sand and gravel mostly less than one-half inch in diameter; contains numerous voids.
9–11	Beach rock, tightly cemented, medium- to fine-grained; grades downward into loose and caving material of same composition.
11–14. 5	Gravel, unconsolidated and coarse sand.

Drill hole 6 on Engebi—Continued

Interval (feet)	*Lithologic character*
14. 5–20	Sand, silty; contains imbedded fragments of branching coral, mainly blue *Heliopora*, unidentifiable mollusk shell fragments, and some medium gravel; coral fragments as much as 1½ in. in diameter. Fine debris includes *Halimeda* and small Foraminifera.
20–22	Sand, silty.
22–34	Sand, silty; contains imbedded gravel fragments.
34–40	No sample.
40–46	Sand, silty; increase in gravel content.
46–50	Sand; as above, with increasing rock content. The section from 14.5 to 50 ft evidently was all loose material composed largely of silty sand with coral fragments and gravel.
50–55	Breccia, porous, moderately lithified; made up of branching coral fragments as much as 1 in. long, algal debris—both *Halimeda* and coralline types, and Foraminifera set in a silty sand matrix; material poorly sorted. No evidence of recrystallization or solution.
55–58	No sample.
58–59	Coral-algal debris, porous, lithified; in irregular pieces.
59–60	No sample.
60–62	Coral, unaltered, massive; contains clumps of smaller coral debris and foraminiferal sand cemented to it.
62–65	No sample.
65–74	Limestone, dense, vuggy, light-tan; pocked with numerous platelike voids obviously the result of solution of former *Halimeda* segments. The original fine-grained matrix has been recrystallized into hard rock. A few *Halimeda* segments remain recognizable; coral debris also present.
74–75	No sample.
75–76. 5	Limestone, white, friable, *Halimeda*-bearing, silty, and sandy; irregular pieces with coral fragments. No recrystallization.
76. 5–86	No sample.
86–91	Coral, unaltered, massive; imbedded in a well-lithified breccia of algal debris and foraminiferal sand; shows patchy recrystallization and some solution voids; much material unaltered.
91–96	Coral; largely massive; several types in random position; a coral-rich boulder conglomerate. Coral is packed in *Halimeda*-bearing, foraminiferal sand matrix. Matrix well-lithified but retains original porosity. Rock essentially unaltered.
96–101	Coral, unaltered, massive; solid pieces, some separated and coated by irregular layers of sandy, weakly lithified limestone.

Drill hole 7 on Engebi

[Elevation 7.7 feet]

Interval (feet)	*Lithologic character*
0–2. 5	Sand, dark-gray, dense, dry; with some fine to medium sized gravel.
2. 5–9	Beach rock; firmly cemented sand and gravel in 6-in zones, separated by beds of loose, coarse sand and medium-sized gravel.

Drill hole 7 on Engebi—Continued

Interval (feet)	*Lithologic character*
9–21. 5	Sand, tan, compact, medium- to coarse-grained; with some fine gravel.
21. 5–29	Sand; as above; increase in fine fraction.
29–32	No sample.
32–34	Sand; similar to interval at 9–21.5 ft.; gravel with maximum diameter of three-fourths in. in sand.
34–38	No sample.
38–40	Sand; similar to interval at 9–21.5 ft.; gravel with maximum diameter of 1½ in. in sand.
40–52. 5	Sand; similar to interval at 9–21.5 ft.; increase in gravel fraction.
52. 5–54. 5	Predominantly rock fragments.
54. 5–60	No sample.
60–61	Rock fragments in alternating weakly and firmly cemented beds with silty sand matrix.
61–70	No sample.
70–71	Rock fragments ¾–1 in. in diameter.
71–80	No sample.
80–82	Rock fragments; similar to interval at 70–71 ft, some fine sand and gravel.
82–90	Coral and rock fragments, irregular, partly recrystallized. Alternating sections of weakly and firmly cemented conglomerate 3–5 in thick.
90–91	One solid core, 3 in long, of partly altered, massive coral imbedded in coarse porous well-cemented unaltered *Halimeda* debris; irregular fragments of coral and *Halimeda* limestone also.
91–106	Coral, massive solid cores show patchy recrystallization to calcite; also includes cores of porous well-cemented sandy limestone and some chalky limestone.

Drill hole 8 on Engebi

[Elevation· 10.9 feet]

Interval (feet)	*Lithologic character*
0–2	Sand and gravel, silty, gray; contains a few roots·
2–5	Sand and gravel, tan; maximum 1½ in. in diameter·
5–12	Conglomeratic zones, weakly cemented; as large as 6 in thick in section from 5 to 11.5 ft.
12–14	Sand, coarse and fine to medium-sized gravel.
14–15	No sample.
15–20	Sand, similar to interval at 12–14 ft; increase in finer sizes.
20–22	Pieces of gravel; 4–6 in. in diameter in sand matrix.
22–25	No sample.
25–27	Gravel, similar to interval at 20–22 ft; increase in finer sizes.
27–30	No sample.
30–32	Sand and gravel, gray, silty.
32–35	No sample.
35–37	Sand, similar to interval at 30–32 ft; softer drilling.
37–41	No sample
41–47. 5	Sand, similar to interval at 30–32 ft with noticeable increase downward in pebble and boulder content.
47. 5–50	Limestone, well-lithified, vuggy, partly recrystallized, coraliferous; irregular pieces. Fossil molds common. Coral, however, retains some original aragonite. Algae and Foraminifera coat some pieces.
50–55	No sample.

Drill hole 8 on Engebi—Continued

Interval (feet)	*Lithologic dharacter*
55–57	Sand and gravel with some silt; few gravel pieces as large as 2 in. in diameter.
57–60	No sample.
60–62	Sand and gravel; silty; few boulders.
62–70	No sample; harder drilling.
70–72	Conglomerate, fine- to medium-grained; in thin, weak, and well-cemented beds. Porous, *Halimeda*-rich limestone with sandy matrix. *Halimeda* are unaltered; segments are locally packed in open framework without matrix. Coral fragment 1 in long.
72–75	No sample.
75–76	Largely cemented *Halimeda* fragments.
76–80	No sample.
80–85. 5	Drilling action indicates alternating hard and soft zones, 6 to 8 in thick. Recovered core is well cemented, vuggy, *Halimeda*-rich limestone containing some rounded coral fragments. Rock matrix contains numerous Foraminifera and some small gastropods. Matrix shows some recrystallization to calcite, but many *Halimeda* are unaltered.
85. 5–87. 5	Breccia, well-cemented algal and coral; little alteration. One core, 10 in long, shows irregular masses of partly recrystallized and calcite-filled coral in coarse, porous breccia made up of algal, molluscan (fragments of heavy-shelled pelecypods and gastropods); and coral debris in a chalky, sandy matrix. Void fillings in the rock show flat floors toward the top of the core indicating infiltration of fine material after incorporation of the coral in the rock.
87. 5–90	No sample; apparently similar to last.
90–95	Conglomerate and coral breccia. Upper core 4 in. long; well-cemented but porous, poorly sorted conglomerate; contains *Halimeda*, fragments of encrusting algae, and coral debris in sandy matrix; *Halimeda* partly altered; rock shows some recrystallization. Middle cores, totaling 2 ft, coarse coral breccia; some partly altered pelecypod shells; rock shows irregular veins and areas of dense, light-tan, fine-grained calcite, parallel to the core axis. Lower core, 8 in. long, a solid piece of unaltered massive coral with pockets of coarse breccia. Piece from bottom of run shows brown calcite areas.
95–96	No sample.
96–98	Conglomerate and breccia; similar to interval at 90–95 ft; much of the rock, where not recrystallized and filled with calcite, disintegrated to chalk.
98–101	No sample.
101–103	Coral, massive, in upper 6 in of 2-ft core recrystallized to calcite and also filled by calcite; alteration stops along irregular line; below, the core is of porous unaltered massive coral; coral shows patchy recrystallization and reduction to white powder in the lower part of the core.
103–105	No sample.
105–106. 5	Coral, massive, patchily recrystallized and calcite-filled similar to interval at 101–103 ft.

Drill hole 9 on Engebi

[Elevation: 11.0 feet]

Interval (feet)	*Lithologic character*
0–2	Sand dark-gray, dense, with gravel as large as three-fourths inch in diameter.
2–4	Sand, porous, loose, tan, foraminiferal-algal with thin gravel lenses as much as 2 in thick. Worn mollusk shells abundant: small *Tridacna* and many gastropods—limpet, trochids, cerithids.
4–5	Sand and gravel, light-tan, medium- to coarse-grained contains worn mollusks (rissoids, cerithids).
5–5. 5	Beach rock, firmly cemented.
5. 5–8. 5	Sand, slightly cemented, with gravel as large as one-half inch in diameter.
8. 5–11	No sample.
11–21	Beach rock, firmly cemented beds 2 to 6 in thick, alternating with unconsolidated beds.
21–22. 5	Sand, medium and coarse-grained with a little gravel as much as three-fourths inch in diameter.
22. 5–25	No sample.
25–27. 5	Sand, medium- and coarse-grained; increase in gravel fraction with some silt; gravel as much as 2½ in. in diameter.
27. 5–30	Sand and gravel, compact; contains some silt; cemented sections in this interval.
30–49	Increase in gravel content; material as large as 2 in. in diameter; *Halimeda* and few mollusks—tellinid, cerithids.
49–50	Coral; solid core of slightly-recrystallized, massive material; pierced by borings of organisms.
50–56	Coral, solid, unaltered, massive; slightly less dense than coral from above interval; encrusting algae, Foraminifera, and worm tubes noted; Pierced by circular holes, as large as three-fourths inch in diameter made by *Lithophaga;* smaller curved bore holes are lined with calcium carbonate.
56–58	No sample.
58–70	Coral, single piece, unaltered, massive; alternating hard and soft layers.
70–71. 5	Limestone, lithified; contains poorly sorted coral and algal debris with some well-preserved mollusks in sandy matrix; locally rich in unaltered *Halimeda.*
71. 5–75	No sample.
75–78	Limestone, moderately lithified, *Halimeda;* 1.2-ft core recovered; segments show tendency to parallel bedding; much of the space between the segments is open and cores show irregularly distributed matrix of fine sand and silt. One fragment of unaltered coral is 1½ in long.
78–85	No sample.
85–87	Coral, massive, unaltered; 1.8 ft of irregular core recovered; contains films of encrusting algae and Foraminifera and pockets of *Halimeda* limestone like that described above.
87–90	Breccia, porous, friable; 1.5 ft of irregular pieces of core recovered; contains *Halimeda*, coralline algae, and coral debris in a sand matrix; some mollusks preserved as internal calcite molds.
90–95	No sample.

Drill hole 9 on Engebi—Continued

Interval (feet)	*Lithologic character*
95–100	Coral, unaltered, massive; 4-ft core recovered, upper 3½ ft in a single massive coral in position of growth; remainder of section of irregular pieces of breccia with silty matrix.
100–105	No sample.
105–110	Coral; top of core, 6 in long, a single piece of coral; rest of section irregular massive coral packed in sand matrix; coral shows encrustations of algae and Foraminifera.

Drill hole 10 on Engebi

[Elevation: 10.4 feet]

Interval (feet)	*Lithologic character*
0–3	Sand and gravel, gray to white; as much as 1½ in. in diameter.
3–6	Sand and gravel, clean, white; contains pieces as much as 4 in. in diameter.
6–9. 5	Conglomerate, dense, tightly cemented.
9. 5–11. 5	Sand, silty and gravel with fragments as much as 2 in. in diameter.
11. 5–15	No sample.
15–17	No recovery; alternating hard and soft layers.
17–18	Coral gravel and small boulders.
18–23. 5	Drilling action indicated some hard rock in this interval; no samples recovered.
23. 5–25. 5	Coral, patchily recrystallized, massive, irregular cores many pieces show algal-foraminiferal encrustations.
25. 5–32	Circulation lost at 26.5 ft; no sample.
32–34	Gravel, clean, loose, as much as three-fourths inch in diameter; no fine material recovered.
34–42	Mud loss at 36.0 ft. Lithology as above.
42–44. 5	Gravel, loose; as much as 1½ in; some coarse sand.
44. 5–47	No sample.
47–49	Gravel, similar to interval at 42–44.5 ft with increase in sand size.
49–50	No sample.
50–51	Gravel, fine; with some sand.
51–54. 5	No sample.
54. 5–55. 5	Sand, gravel, and cobbles with traces of silt; gravel as much as 6 in. in diameter.
55. 5–60	Similar to above; alternating hard and soft beds 4–6 in thick.
60–80	Similar to above; increase in fine sand in upper part; firmer at bottom of interval.
80–82. 5	Solid cores of unaltered massive coral.
82. 5–86	Breccia, upper pieces of cores are friable, porous, and made up of unaltered *Halimeda* and pelecypod shells randomly scattered in a silty sand matrix; lower two pieces recovered are well-lithified coarse, coral breccia with thin partings filled by *Halimeda* debris and foraminiferal sand; solid massive coral which shows irregular but intense recrystallization and pore filling bv calcite in lowest core. Drilling indicated alternating zones of hard and soft rock.
86–95	No sample; drilled like the interval at 82.5–86 ft above.
95–97. 5	Material identical to that recovered from interval at 82.5–86 ft. Breccia and irregularly altered coral; massive.

Drill hole 10 on Engebi—Continued

Interval (feet)	*Lithologic character*
97. 5–106	No change in drilling character; no samples.
106–107. 5	Breccia, white, friable, porous, *Halimeda*-bearing, poorly sorted.

Drill hole 11 on Engebi

[Elevation 8.6 feet]

Interval (feet)	*Lithologic character*
0–2	Fill.
2–4. 5	Sand, clean and gravel with few coral boulders as much as 6 in. in diameter.
4. 5–8	Conglomerate, dense, well-cemented, hard.
8–12	Rock less firm below 9.5 ft; separated into beds by layers of white silty sand and fine gravel as much as 6 in. thick; core of well-cemented coarse coral breccia; laminae of encrusting Foraminifera and algae are common; partings occupied by unaltered, friable, coarse sand made up of *Halimeda*, *Calcarina*, and shell debris; clumps of encrusting algae and *Homotrema* are common. Coral shows spotty recrystallization.
12–21	Sand, medium- to coarse-grained; with gravel as much as 2½ in. in diameter; drilling action indicated alternating hard and soft layers with general decrease in amount of cemented strata with depth.
21–22	Sand, fine and silt rock fragments as much as 2 in. in diameter.
22–33	Sand and rock fragments as much as 2 in. in diameter
33–38	Sand and rock fragments as above with increase in hard rock content; coral cobbles 4–6 in. in diameter in a silty sand matrix.
38–43	Coral-algal rock, cavernous; massive coral thickly coated by encrusting algae and Foraminifera; pockets filled by porous *Halimeda* debris; coral shows spotty recrystallization; *Halimeda* unaltered but firmly cemented together; some voids show fillings of fine material.
43–46	No samples; no change in drilling characteristics.
46–51	Large fragments of massive coral in a porous matrix of unsorted *Halimeda* debris mixed with other fragmental algae and Foraminifera; spotty recrystallization, irregular in some of the coral fragments; some irregular filling of the coral by calcite.
51–60	No sample; penetration irregular in sections 2–4 in thick; uniform and hard drilling at 58.0 ft.
60–62. 5	Limestone, irregularly cemented; composed of *Halimeda* segments, Foraminifera, sand, and granule size fossil debris; porous lenses that lack a fine matrix; unaltered fossils cemented together; a silty sand matrix occupies much of the interfossil space; the *Halimeda* as well as small gastropods are still aragonite.
62. 5–70	No sample; no change in drilling action.
70–73	Limestone, patchily recrystallized, coral-algal solid cores with pockets and lenses of *Halimeda*-rich debris; much initial porosity retained; the *Halimeda* segments unaltered.

Drill hole 11 on Engebi—Continued

Interval (feet)	*Lithologic character*
73–76	No sample.
76–77	Limestone porous, friable, many irregular *Halimeda* pieces; fossils unaltered and very lightly cemented.
77–80	No sample; drilling action indicated harder rock.
80–82. 5	Coral, solid, patchily recrystallized, calcite-filled, massive; one core, 4 in long, shows a completely recrystallized and calcite-filled central band slightly inclined to the core axis; ends of the core show numerous *Halimeda*-shaped voids in recrystallized matrix.

Drill hole 4 on Mujinkārikku

[Elevation: 9.10 feet]

Interval (feet)	*Lithologic character*
0–5. 5	Sand, largely coarse; dominated by well-worn, spineless tests of *Calcarina*, with subordinate *Amphistegina* and *Marginopora;* contains miliolids and other small Foraminifera in the fine sand fraction; Alcyonarian spicules, worn mollusk shells, foraminiferal debris, pink fragments of *Homotrema*(?) make up part of the finer fraction; granule- to pebble-size debris of coralline algae, mollusks (*Cardium*, limpets, *Turbo*, *Vanikoro*, *Diala* and other cerithids), coral, and echinoids abundant but subordinate to sand; several pieces of well-indurated, porous, foraminiferal-algal limestone as much as 1½ in across; each test and fragment in the limestone is coated with carbonate cement.
5. 5–8. 0	Beach rock.
8. 0–14. 5	Sand, poorly cemented, coarse with a high proportion (30–50 percent) of granule- and pebble-size coral and nodular algal debris, fragments of massive coral as much as 1½ in long, including blue *Heliopora;* mollusks include tellinids, trochids, cerithids, rissoids, *Cheilea*, *Vermetus*.
14. 5–19	Sand, largely medium- to fine-grained; and silt; *Calcarina* less abundant than above; granules and pebble-size fragments include mollusks (*Cardium*, tellinids, *Diala* and large cerithids, mitrid, *Triphora*) delicate branching coral, crustacean fragments, and nodular coralline algae; angular fragments of blue *Heliopora* as much as 2 in across; irregular masses of lithified sediment bound by encrusting Foraminifera.
19–26. 5	Sand, abundant, fine and silt mixed with granule- to pebble-size nodular algal and coral debris; same coarse sand; coral includes delicate *Seriatopora;* mollusks include *Arca*, *Cardium*, lucinids, *Turbo*, *Trivia*, *Columbella;* cobble-size, rounded fragments of massive coral, echinoid spines, and a fragment of *Tridacna* shell, 2 in across; fine fraction contains well-preserved small gastropods, including *Diala*, and some miliolids but consists mostly of unidentifiable silt; a few rounded, worn *Calcarina* and well-preserved *Marginopora* and *Heterostegina*.

Drill hole 4 on Mujinkārikku—Continued

Interval (feet)	*Lithologic character*
26. 5–31	Sand, poorly sorted; containing fossil debris as much as three-fourths inch in diameter; sand fraction contains numerous delicate miliolids and other small Foraminifera; *Calcarina* still retain their spines; small, well-preserved *Marginopora*, Alcyonarian spicules, and coral-algal debris common; granule to pebble fraction contains numerous whole and fragmental *Halimeda*, fragments of nodular algae, twigs of delicate branching coral, tests of *Marginopora*, echinoid spines, and a molluscan assemblage similar to that in interval at 19–26.5 ft.
31–40	Sand; similar to preceding sample; rich fauna of mollusks includes arcids, lucinids, tellinids, limpets, *Triphora*, *Diala* and other cerithids, fragmentary crustaceans, echinoid spines, and angular chips of massive coral as much as 2 in across.
40–48	Sand, poorly sorted; fine sand and silt to coral fragments 2 in across; rich in smaller Foraminifera and mollusks, especially tellinids, cerithids and *Strombus;* medium- and coarse-grained sand largely *Halimeda* debris, worn tests of *Calcarina* and *Marginopora*, small mollusks and debris of coral.

Drill hole 5 on Mujinkārikku

[Elevation: 0.0 feet]

Interval (feet)	*Lithologic character*
0–3. 5	Sand, compact, grayish-black, some fine gravel.
3. 5–7. 0	Sand, white, clean; some fine gravel.
7. 0–11. 0	Sand; as above; gradual increase in gravel content in this interval with lessening of sand content.
11–12	Sand, white, cohesive, silty; interbedded angular to round coral debris; numerous shells.
12–13	No sample.
13–18	Alternating hard and soft layers; no samples.
18–21. 6	Limestone, well-lithified but porous, consisting of fragments of branching coral as large as 2 in long, blue *Heliopora*, branches of coralline algae as much as 1 in long, and irregular masses of encrusting algae and Foraminifera, few fragments of thick shelled mollusks—*Tridacna*, *Turbo*, *Conus*. No alteration; encrusting Foraminifera coat much debris.
21. 6–26	No sample.
26–29	Sand and gravel, white, compact, silty; fragments as long as 2 in.
29–33	No sample.
33–35. 5	Sand and gravel; similar to interval at 26–29 ft; increase in gravel content.
35. 5–40	No sample.
40–41. 5	Sand, compact, white, silty; abundant imbedded coral fragments; silt-sand lenses as much as 1 in thick.
41. 5–45	Bit action indicates firm rock at 44.5 ft.

Drill hole 5 on Mujinkārikku—Continued

Interval (feet)	*Lithologic character*
45–50	Breccia, white, friable, moderately lithified; abundant angular to round fragments of nodular coralline algae, *Halimeda* segments, Foraminifera, coral debris, and some echinoid spines randomly oriented in a soft, silty sand matrix; no recrystallization seen; cementation varies within the core run; rock lacks stratification and is poorly sorted.
50–52	No sample.
52–54	Breccia; similar to interval at 45–50 ft with few pelecypod molds as much as 1 in across; irregular lithification and recrystallization to hard, porous limestone; spotty porosity in recrystallized areas produced by a solution and fossils altered in friable areas to soft, chalky carbonate.
54–58	No sample.
58–60	Algal limestone; angular rock chips (ditch sample) contains unaltered *Halimeda* segments, granule- and sand-size coralline algal debris, foraminiferal sand, a few small gastropods (cerithids, *Triphora*) and fragments of branching coral and only a few percent of fine sand and silt-size material.
60–62	No sample.
62–68	Limestone conglomerate; degree of cementation variable; patchy recrystallization with slight development of solution voids and fossil molds; abundant unaltered *Halimeda* segments set in a porous silty sand matrix in the lowest core segment.
68–73	Ditch sample similar to 58–60 ft interval.
73–80	Limestone conglomerate made up largely of silt-sand-size material with minor amount of coarse organic debris; minor recrystallization and solution pitting.

Drill hole 6 on Mujinkārikku

[Elevation: 8.0 feet]

Interval (feet)	*Lithologic character*
0–1. 5	Sand and gravel, gray-tan loose, dry fill.
1. 5–5	Sand, medium- and coarse-grained; some gravel.
5–5. 5	Beach rock, well-cemented, porous sandstone made up of foraminiferal and algal debris approximately 1 mm in diameter; high gloss and a dense cement that extends down into the rock for about one-fourth inch on bedding plane surface at top of recovered bed; bottom of the bed irregular and contains coarse unsorted algal, coral, and mollusk debris as much as 1 in long.
5. 5–16	Sand and gravel well-cemented in layers 6–8 in thick separated by 2- to 3-in beds of loose sand and gravel containing few mollusks (*Dlaia*, *Triphora*); an increase in thickness and frequency of unconsolidated beds with depth accompanied by a gradual reduction in the amount of cemented beds.
16–21	Sand, compact, medium- to coarse-grained; some fine gravel.
21–23	Coarse sand, some fine gravel

Drill hole 6 on Mujinkārikku—Continued

Interval (feet)	*Lithologic character*
23–24	Sand, fine- to medium-grained and gravel.
24–27	No sample.
27–29	Sand and gravel, coarse.
29–31	No sample.
31–33	Sand, fine, and some silt; numerous thin shell fragments.
33–41	No sample.
41–43	Sand, fine- to medium-grained; trace of silt; few small well-preserved shells as much as one-eighth inch in diameter.
43–47	Conglomerate, fractured.
47–48	Conglomerate, weakly cemented; numerous silt-filled seams between solid pieces 6 in or less in length; recovered sample consists of a few pieces of limestone containing abundant unaltered *Halimeda* segments, fragments of encrusting algae, and pelecypod shells in a silty sand matrix; no solution or recrystallization; loose debris contains *Halimeda*, small gastropods (*Turbo*, *Triphora*, *Caecum*, *Cheilea*), coral, and Foraminifera.
48–52. 5	No sample.
52. 5–62. 5	Coral pieces, unaltered, massive; in position of growth; packed in a well-cemented unsorted breccia made up of *Halimeda* and coralline algae, shell debris, echinoid spine and Foraminifera in a silt and sand matrix; coral makes up about 80 percent of the 3 ft of core recovered.
62. 5–65	Conglomerate; alternating hard and soft beds 4–6 in thick.
65–68	Conglomerate; similar to last; ditch sample of coarse sand and gravel; rounded coral debris shows high polish like beach rock particles; contains worn and corroded *Cypraea;* gravel-size fraction contains abundant polished fragments of coralline algae and coral; sand fraction contains abundant tests of *Marginopora*, *Calcarina*, and *Amphistegina*.
68–70	No sample.
70–71	Coral; similar to material from core run in the interval at 52.5–62.5 ft.
71–75	No sample.
75–76	Sand and gravel; coarse, made up of worn *Marginopora*, *Amphistegina*, unaltered *Halimeda*, coralline algal debris, echinoid spines and fragments of mollusk shells; contains abundant fine rock chips (ditch sample) as large as one-fourth inch across.
76–82	No sample.
82–83. 5	Sand and gravel; similar to interval at 75–76 ft.
83. 5–90	Limestone, well-lithified; made up of poorly sorted, algal, molluscan, echinoid and foraminiferal debris in a sand matrix; coral rare; entire core honey-combed by solution and recrystallization; *Halimeda* show solution effects; mollusk molds common; thin coatings of drusy calcite.
90–95	No sample.
95–100	Coral, abundant, unaltered, massive; and rare mollusks (*Cypraea*); associated with poorly sorted unaltered molluscan, *Halimeda*, and foraminiferal debris in a moderately lithified silty sand matrix; little or no solution or recrystallization; *Halimeda* retain original aragonite; marked difference from section, at 83–90 ft.

Drill hole 7 on Mujinkārikku

[Elevation: 8.5 feet]

Interval (feet)	*Lithologic character*
0–3	Sand, coarse; some fine gravel.
3–7	Sand, clean, white.
7–13	Sand, highly cemented, and gravel; alternating layers as much as 6 in thick separated by beds of loose sand and gravel as much as 1 in thick.
13–24	Coral, unaltered, massive; most pieces are solid cores as much as 6 in long, which still retain their original high porosity except where they have been locally filled with lithified fine white mud; encrustations of algae and Foraminifera abundant; pockets in the coral filled with foraminiferal sand in places; some cores largely composed of moderately cemented coarse algal debris packed between coral; small amount of patchy recrystallization of the coral; cores were imbedded in medium- to fine-grained sand which washed out during operations, according to the drilling record.
24–26	Coral, unaltered, massive; irregular pieces, subangular to rounded, as much as 3 in across; algal and foraminiferal encrustations; some angular fragments of blue *Heliopora* also imbedded in loose sand according to the drilling record.
26–34	Coral, as above; fragments in a sand matrix.
34–36	Coral, unaltered, massive; irregular pieces encrustations of algae and Foraminifera in matrix fine grayish sand.
36–48	Coral, green and gray, pieces as large as 2 in. in diameter; few pieces fine-grained limestone.
48–51	Coral unaltered, massive; in one piece, 7 in long, in growth position; shows algal encrustation; *Halimeda* segments and sand packed between some other coral fragments show no recrystallization or solution effects; seams between coral fragments filled with silty sand.
51–58	No sample.
58–61	Limestone, moderately lithified, white, porous; contains abundant randomly oriented *Halimeda* and some films of encrusting algae in a chalky silty sand matrix containing numerous Foraminifera.
61–62	No sample.
62–63	Conglomerate; composed of fine-sand- to gravel-size coral and algal debris including unaltered *Halimeda* and coralline algae, the latter having a high polish; coarse sand fraction includes common worn and broken tests of *Marginopora*, *Amphistegina*, and *Calcarina* as well as *Halimeda* debris; finer fraction contains gastropods, miliolids and other small Foraminifera, echinoid spines and alcyonarian spicules; common fragments of drusy calcite crystals indicate some solution and recrystallization.
63–64. 5	No sample.

Drill hole 7 on Mujinkārikku—Continued

Interval (feet)	*Lithologic character*
64. 5–69. 5	Coral, irregular cores massive; as long as 5 in; coral surfaces show encrustations of algae and Foraminifera; well-lithified coarse debris of algae and Foraminifera in a chalky silty sand matrix packed between the coral; parts of the coral show irregular and patchy recrystallization to medium-grained calcite crystals; surface of the core slightly vuggy; below the first two pieces of coral core (total about 12 in) the remainder of the run is limestone composed of packed *Halimeda* segments in a chalky sandy matrix; segments generally unaltered but a few show minor effects of solution.
69. 5–80	Coral similar to last; shows recrystalization to calcite; numerous clusters of light-tan to white calcite crystals; *Halimeda* segments and some coral fragments show partial alteration to calcite but much debris, including echinoid spires, *Heliopora,* and worn fragments of mollusk shells, unaltered; sand fraction contains numerous worn tests of *Marginopora, Amphistegina,* and *Calcarina.*
80–85	Limestone, algal; upper 4 inches of core of a lacey framework with intersecting voids partially packed by foraminiferal sand; lower part of cored section made up of unaltered, massive coral totaling about 10 in; no recrystallization or calcite deposition.
85–90	No sample.
90–97. 5	Coral, unaltered, massive, as much as 7 in. in diameter; alternate with *Halimeda*-rich limestone; coral shows some void filling by fine material but no recrystallization; *Halimeda* segments set in a sandy foraminiferal matrix, show no alteration but are well cemented.
97. 5–100	No sample.

Drill hole 2 on Eberiru

[Elevation: 9.5 feet]

Interval (feet)	*Lithologic character*
0–4. 5	Sand, coarse; some gravel.
4. 5–8	Sand, cemented, coarse, and gravel.
8–15. 5	Sand, uncemented, tan, coarse; contains pieces of coral as large as 3 in. in diameter.
15. 5–19	Sand, tan, coarse; made up largely (75 percent) of worn tests of *Calcarina;* worn tests of *Marginopora* and unaltered segments of *Halimeda* also common; contains small mollusk shells—*Cardium*, tellinid, cerithids—some fine sand and gravel.
19–21	Sand, poorly sorted, fine, and silt mixed with coarse sand and granule-size debris; fine fraction contains abundant, well-preserved miliolid and other small Foraminifera; coarse-sand fraction largely well-preserved to worn tests of *Calcarina* and *Marginopora;* granule fraction of *Halimeda* segments and coralline algal debris; many mollusks: (*Tellina*, *Cardium* cerithids, trochids) and fragments of red *Homotrema.*
21–29	Sand, as above but with silt and fine sand making up the bulk of the material; mollusks include tellinids, lucinids, trochids.

Drill hole 2 Eberiru—Continued

Interval (feet)	*Lithologic character*
29–31	Sand, fine; contains pieces of coral.
31–36	Coral, massive; irregular pieces as large as 2 in across; some blue *Heliopora*, red *Tubipora*, and coralline algal debris make up the bulk of the material; remainder is fine sand.
36–40	Sand and silt, fine; well preserved and abundant tests of miliolids and other small Foraminifera; coarse sand and granule-size debris make up approximately 10 percent of the sample and include tests of *Calcarina, Marginopora,* and *Heterostegina; Halimeda* debris; well-preserved gastropods and pelecypods; some coral and nodular coralline algae.
40–53. 5	Sand, fine, white; some fragments of unaltered coral and algae as long as 2 in; poorly sorted.

Drill hole 3 on Eberiru

[Elevation: 10.32 feet]

Interval (feet)	*Lithologic character*
0–1	Fill.
1–4	Sand and gravel, dark-brown, sandy, well-graded; few boulders as large as 1.5 ft across; many roots; few streaks of clean light sand and fine gravel.
4–4. 5	Sand, clean, light; loose fine gravel, poorly graded; almost pure *Calcarina* sand with few pieces of coral as long as one half inch.
4. 5–6	Beach rock, poorly cemented.
6–7. 5	No sample.
7. 5–9. 5	Sand, well-graded, coarse and fine gravel. Many Calcarinas, Marginoporas, corals, fresh mollusks, and algal fragments with maximum diameter of 1 in.
9. 5–10. 5	No sample.
10. 5–12. 5	Sand, coarse, and medium-grained gravel with a maximum diameter of 1 in; well-graded, unconsolidated; no silt or other binder; many Calcarinas; some Marginoporas, coral fragments, algal nodules, mollusks.
12. 5–14. 5	*Calcarina* sand and coral gravel; compact but not cemented; mollusks, algae.
14. 5–15	No sample.
15–17	Gravel, fine mixed with sand; well-graded, compact; many Foraminifera.
17–19	No sample.
19–21	Sand, clean, uniform-sized; fragments of mollusks as large as one half inch across, about 80 percent Calcarinas.
21–25	No sample.
25–27	Sand and coral fragments, including *Heliopora* and *Tubipora*; smooth algal nodules, few Foraminifera and mollusks; not cemented.
27–30	No sample.
30–32	Sand and silt, fine, many *Halimeda, Tubipora,* small coral, and echinoid spines.
32–35	No sample.
35–37	Silt, light-tan, sandy; coral pieces as much as 1½ in. in diameter.
37–40	No sample.
40–42	Silt, light-tan, sandy; *Heliopora* as large as three-fourths inch.
42–44. 5	No sample.

Drill hole 3 on Eberiru—Continued

Interval (feet)	*Lithologic character*
44. 5–46. 5	Sand, light-tan, fine; corals and mollusks.
46. 5–51	No sample; much harder drilling at 49 ft.
51–53	Sand, light-tan silty; scattered small mollusks shells and branched coral; hard pieces of well-cemented mollusk and coral debris as large as 2½ in. in diameter; remainder weakly cemented.
53–56	No sample.
56–57	Coral debris, coarse, angular; *Halimeda* and mollusks mixed with fine sand and silt.
57–64	No samples.
64–66	Coral, white to tan gravel-size fragments with minor amount sand and silt; compact; *Halimeda* and mollusks abundant.
66–74	No samples.
74–76	Limestone, weakly cemented; made up of unaltered *Halimeda* (75 percent) with fragmentary mollusks, Calcarinas and echinoid spines.
76–84	Started drilling hard and uniform at 77 ft.
84–86	Coral pieces as large as 2 in. in diameter; friable, poorly sorted limestone made up of Foraminifera, *Halimeda* mollusks (*Spondylus, Trifora,* cerithids) and echinoid spines in fine matrix, no recrystallization or solution noted.
86–98	No samples.
98–100	Coral heads, large, massive; apparently in position of growth; cemented *Halimeda* debris abundant with minor amounts of silt.
100–105	No sample.
105–107	Rock debris, compact, weakly cemented; consists principally of coral fragments and secondarily of *Halimeda*; minor amounts of silt and fine white, silty sand.
107–116	No sample.
116–117	*Halimeda* debris; white, weakly cemented; hard pieces of coral as much as 1 in. in diameter; some sand and silt.
117–126	No sample.
126–128	Coral and *Halimeda* debris, white, weakly cemented, coral appears recrystallized; few molds of mollusk shells.
128–138. 5	No sample.
138. 5–148. 5	Coral as much as 1 in or more with irregular pieces of tan well-cemented limestone; spotty recrystallization into solid calcite, some fragments of encrusting algae; rare recrystallized mollusk shells.
148. 5–154	No sample.
154–155. 5	Limestone, white, gritty, cemented; contains many *Calcarina*, with few spines; few pieces coral 1 in. in diameter.

Drill hole 1 on Aranit

[Elevation: 6.51 feet]

Interval (feet)	*Lithologic character*
0–6	Sand, silty; contains fine- to medium-grained gravel, and fragments of *Homotrema* and *Calcarina*.
6–10	Sand, medium- to coarse-grained foraminiferal; many cream-colored Calcarinas; rounded fragments of algae and coral as much as 1 in. in diameter; some fragments with encrusting *Homotrema*.
10–12	Sand, coarse, foraminiferal; large rounded pieces coral and algae; subangular, but water worn; some encrusting Foraminifera; material well graded; thin (1–2 in) zones are weakly cemented.
12–14	Gravel, well-graded, one-half inch in diameter; many Calcarinas, few shell fragments; coral and algae fragments, some with encrusting Foraminifera; unconsolidated.
14–16	Sand, well-graded, medium-grained; to gravel, some silt; coral and algal fragments subangular to three-fourths inch in diameter including *Tubipora, Calcarina* and *Marginopora* and fragmentary mollusks.
16–18	Sand, similar to last; many fragments *Tubipora* and *Heliopora, Halimeda* and nodular algae, echinoid spines, many Calcarinas, few mollusks.
18–20	Sand, coarse, and pebbles of *Heliopora* to 1½ ins. in diameter. Many Calcarinas and *Halimeda*. Many scattered *Tubipora*.
20–25	Sand and gravel.
25–27	Sand, cream-colored, coarse, and medium-sized gravel held together by pasty silt; pieces of *Heliopora* as much as 2 ins. in diameter; many Calcarinas, some Marginoporas, few *Tubipora* particles; no consolidation.
27–30	No samples. Drilled easily.
30–37	Sand, light-tan, fine; few pieces *Heliopora, Marginopora*, few trochoid gastropods; material compact and holds together well though not consolidated.
37–40	No samples. Drilled easily.
40–42	Sand, light-tan; coral fragments; weakly cemented.
42–45	No sample.
45–47	Sand, light-tan, and gravel as much as ¾ in. in diameter; few gastropods.
47–48	No sample; drilled easily.
49–51	No sample; increasingly hard to drill. Hard rock at 51 ft.
51–56	Coral, irregular pieces, unaltered, massive; heavily encrusted with algae and Foraminifera; some *Halimeda* cemented to coral; echinoid spines; numerous cavities.
56–58	No sample, drilled hard.
58–63	Coral; similar to interval at 51–56 ft.
63–70	No sample.
70–75	Coral, some encrusted or weakly cemented algal debris.
75–80	No sample.
80–81. 5	Coral debris compact, partly consolidated; maximum diameter 1½ in.; *Halimeda* and few smaller Foraminifera in white sand and silt; small mollusks numerous—arcids, *Mitra, Triphora*, rissoids, cerethids.
81. 5–90	No sample; drilled easily.
90–91	Gravel, cream-colored, well-graded; some light-brown streaks of fine material; hard algal and coral limestone pieces as much as 2 in across; molds of small gastropods.
91–100	No sample; drilled easily.

Drill hole 1 on Aranit—Continued

Interval (feet)	*Lithologic character*
100–101. 5	Coral and algal debris, white to cream-colored, coarse, angular; 1/8 to 1½ in. in maximum diameter; partly consolidated; few Foraminifera, rare molds of small gastropods.
101. 5–110	No sample.
110–112	Gravel, well-graded, in pasty, white silt binder; pieces 1 in. in diameter; white to cream colored; fragments show minute crystal faces when dry.
112–120	No sample.
120–121	Sand, medium-light-tan, underlain by gravel in silty matrix.
121–136. 5	No sample.
136. 5–138	Coral, partly recrystallized, as large as 2 in. in diameter with streaks and irregular areas of fine- to medium-grained, compact sand containing rich assemblage of well-preserved mollusks: *Lithophaga*, *Mytilus*, *Cardium*, tellinids, *Diala*, *Strombus*, *Columbella*, *Triphora*, *Vermetus*, mitrids, cerithids, rissoids; *Halimeda*, echinoid spines and crustaceans rare.
138–147	No sample.
147–152	Coral and fine sand; weakly cemented.
152–161	No sample; alternating hard and soft.
161–169	No sample; uniformly medium hard.
169–175. 5	Coral, mostly gravel-size fragments of branching *Acropora*; many well-preserved mollusks packed in light-tan cemented fine sand; small thin-shelled venerids and tellinids, heavy-shelled *Nassarius*, strombids, and cerithids.
175. 5–189	No sample.
189–191	Limestone, white, sandy abundant silt; unaltered *Halimeda* abundant; mollusks (small bivalves and cerithids) and Foraminifera rare.
191–200	No apparent change; not sampled.

Drill hole 2 on Runit

[Elevation: 9.2 feet]

Interval (feet)	*Lithologic character*
0–1. 5	Fill.
1. 5–4. 5	Sand and gravel, loose; fragments as much as ¾ in. in diameter.
4. 5–5. 5	Beach rock, cemented; sand and fine gravel.
5. 5–11	Sand, coarse, with fine to medium gravel; definite lack of fine material.
11–30	Sand and gravel, unconsolidated; (hard drilling 23.5–24.5), includes one piece coral 3 in. in diameter.
30–31. 5	Abrupt change to hard rock at 30 ft.
31. 5–42	Limestone, *Halimeda*-foramineral; *Halimeda* segments up to 4 mm across and tests of Foraminifera 1 mm in diameter are tightly packed and well-cemented by calcite; porous and only locally shows a fine-grained matrix; *Halimeda* segments generally unaltered.
42–43	No sample.
43–52	Coral and algal conglomerate, porous, friable, *Halimeda*-bearing; poorly sorted coralline algal debris, coral fragments, and *Halimeda* segments are in a fine-grained, powdery matrix; where matrix is lacking the rock is porous; encrustations of Foraminifera and algae common; massive coral at base; no solution effects noted.

Drill hole 2 on Runit—Continued

Interval (feet)	*Lithologic character*
52–53. 5	No sample.
53. 5–61. 5	Limestone, porous, friable, *Halimeda*-foraminiferal in upper part; localized fine-grained matrix; lower part vuggy, recrystallized, massive coral; patchy alteration to calcite.
61. 5–70. 5	Limestone; dense, recrystallized coral-algal. Locally coral is altered.
70. 5–84	No apparent change; no sample.
84–94	Limestone, porous, well-cemented, recrystallized; irregular laminae of encrusting algae and Foraminifera binding coral fragments and other fossil debris. Numerous solution voids, many shaped like *Halimeda* segments, are present.
94–104. 5	No apparent change; no sample.
104. 5–108	Limestone partly recrystallized coral-algal and massive coral, also partly altered to calcite; corals thickly coated by laminae of encrusting algae and Foraminifera; some well-cemented *Halimeda*-foraminiferal limestone in which many of the algal segments are aragonite; the lowest cores include irregular pieces of dense, fine-grained limestone pocked by many *Halimeda*-shaped solution voids.
108–118. 5	Limestone similar to last; ditch samples of angular rock chips; unaltered *Halimeda*, small worn mollusks and Foraminifora may represent contamination.
118. 5–121. 5	Coral-algal rock with lenses and pockets of porous, friable to well-cemented *Halimeda*-foraminiferal debris; massive coral shows patchy recrystallization to calcite and filling by calcite; some *Halimeda* segments unaltered.
121. 5–130	Drilling action indicates hard rock.
130–135	Slightly less drilling resistance.

SUMMARY OF SECTIONS IN SHALLOW HOLES ON ISLANDS

The lateral variation in lithologic character and hardness of the deposits immediately beneath the islands of Eniwetok is obviously a matter of considerable practical importance. The engineers, in planning construction, tried by drilling to locate the "top of the rock," an almost continuous stratum which, it was hoped, would be discovered beneath the unconsolidated surface sands and gravels. As shown in plate 266, however, the drilling revealed no solid foundation of this kind. The hard layers of beach rock,[1] present at intertidal levels and immediately above intertidal levels in many holes, proved to be the nearest approach to a hard persistent stratum beneath the islands.

BEACH ROCK

Layers of beach rock, either hard sandstone or conglomerate or a combination of the two, were found in most of the 17 holes shown in plate 26b. The zone, however, varied in thickness from 1 foot or less (B–4 and Ru–2) to 6 feet or more (EN–7, EN–8, EN–9,

[1] Beach rock is used in the logs as a descriptive term. Most intervals so labeled were probably cemented at intertidal levels.

EN–11, M–6). In hole EN–9 the zone measured 25 feet, but, in much of the section, the cementation was weak or uncemented beds alternated with hard layers. The lithologic character of the beach rock is shown in figures 265 and 266. These 5-inch cores were taken from holes drilled close together near the center of the large island of Engebi (fig. 260). At the site of these holes the beach rock was later uncovered by excavation. This revealed large and irregular areas of soft material and actual voids in the rock. EN–4 on the lagoon side of Engebi showed no beach rock but in the deep hole K–1 located only 200 feet away 2½ feet of well-cemented beach sandstone was found. The beach rock is by no means an ideal foundation rock.

HARD ROCK BELOW BEACH ROCK ZONE

Most of the 17 holes revealed some hard rock below intertidal levels, which were mostly conglomerate and massive coral heads. Many of the conglomerate deposits were well cemented but the massive coral heads in many places were completely unaltered. The most unusual of the holes that showed hard rock was RU–2, where, from a depth of 30 feet to the bottom of the hole at 135 feet, the entire section seemed to be hard, most of it recrystallized and firmly cemented by calcite. The possible significance of this hole is discussed under the section on structure.

The conglomerate is of varied thickness and degree of cementation as well as position relative to the sur-

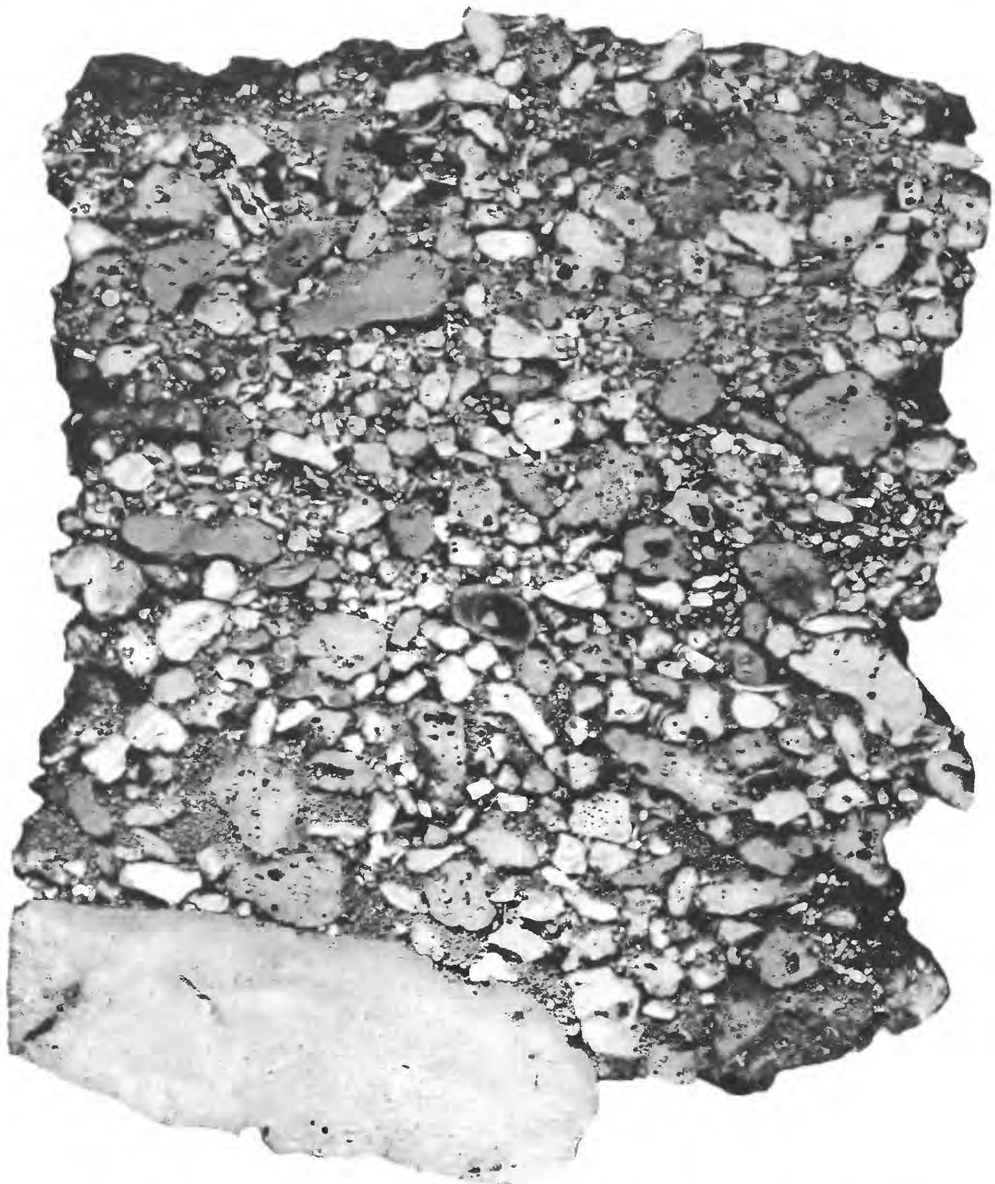

FIGURE 265.—Core of beach conglomerate from a depth of 12 to 14 feet in hole EN–2 on Engebi. Most of the large white pebbles are rounded fragments of coralline algae; the gray pebbles are coral debris. Pebbles are imbedded in a porous matrix of sand and granule-size foraminiferal and algal debris. Minor amounts of worn mollusk shells and echinoid spines are present. ×1.

FIGURE 266.—Core of bedded beach conglomerate and sandstone from a depth of 9.5 to 11.5 feet in hole EN-5 on Engebi. The upper part consists of well-sorted, porous, foraminiferal-algal sand, containing larger fragments of coral oriented parallel to the bedding. The conglomeratic part below contains lenses of sand, and porosity has been reduced locally by intergranular fillings of lithified, fine-grained carbonate.

face. The amounts of conglomerate are shown in plate 266, the degree of cementation is given in the written logs.

LEACHING AND RECRYSTALLIZATION

The depths to zones of leaching and recrystallization appear to be almost as variable as the original lithologic features of the sediments. Thus, fossil molds were found in hole EN-8 at 47.5–50 feet and in MU-5 between 52–55 feet but in hole EB-3 no such molds were found above 126 feet.

The boundaries between the hard and soft lithologic units in plate 266 are not as clear cut in many instances as the sharp lines suggest. Beds labeled as silt and sand almost always contain scattered coral or algal gravel, and *Halimeda* in small quantities is almost ubiquitous. Locally sands are well sorted; most sands contain coarser material of some kind. Most of the *Halimeda*-rich sediments were unconsolidated, but moderately to well-cemented *Halimeda* limestone was found in EN-8 and EN-9.

Most of the sediments penetrated in the shallow holes appear to have been deposited in a lagoon not unlike the one in which sediments are being formed at Eniwetok Atoll today. The existing lagoons of Eniwetok and Bikini Atolls were mapped in detail, dredged, and extensively sampled during Operation Crossroads and the types of sediments and organisms that characterize several fairly distinct facies have been described (Emery and others, 1954, p. 50–68, 95–99, 146–147).

In these lagoons the assemblages of organisms—algae, Foraminifera, corals, and mollusks—differ considerably depending upon depth, distance from the reef, or proximity to one of the hundreds of coral knolls that rise to varying heights from all parts of the lagoon. Dredging and sampling revealed abrupt changes, yet there was an overall pattern—beach type Foraminifera near the reef, other types in the deeper parts of the lagoon, *Halimeda* at intermediate depths, and a rich growth of corals on the knolls. The large massive coral heads are particularly characteristic of the lagoon. The sands yielded characteristic molluscan assemblages—arcids, tellinids, cardids, venerids, cerithids, and strombids—and these seemed most numerous in the shallow water over the terraces. No attempt is made at this time to analyze the assemblage found in any individual core or cutting sample obtained from the shallow holes.

HOLES ON THE REEF

In an attempt to determine the depth of consolidation immediately below the reef flat, a series of shallow holes was drilled on the seaward reef off Engebi Island (fig. 267). Two of these were located on a pennantlike groin extending out on the flat (G-1 and G-2A), two others on the flat itself (R-1 and R-3). The surface of the groin was partly covered by the highest tides and its rock surface was exceedingly rough. A bulldozer was used at low tide to push a carpet of loose sand over the rock surface. A truck with an air-driven diamond drill mounted on the rear was then

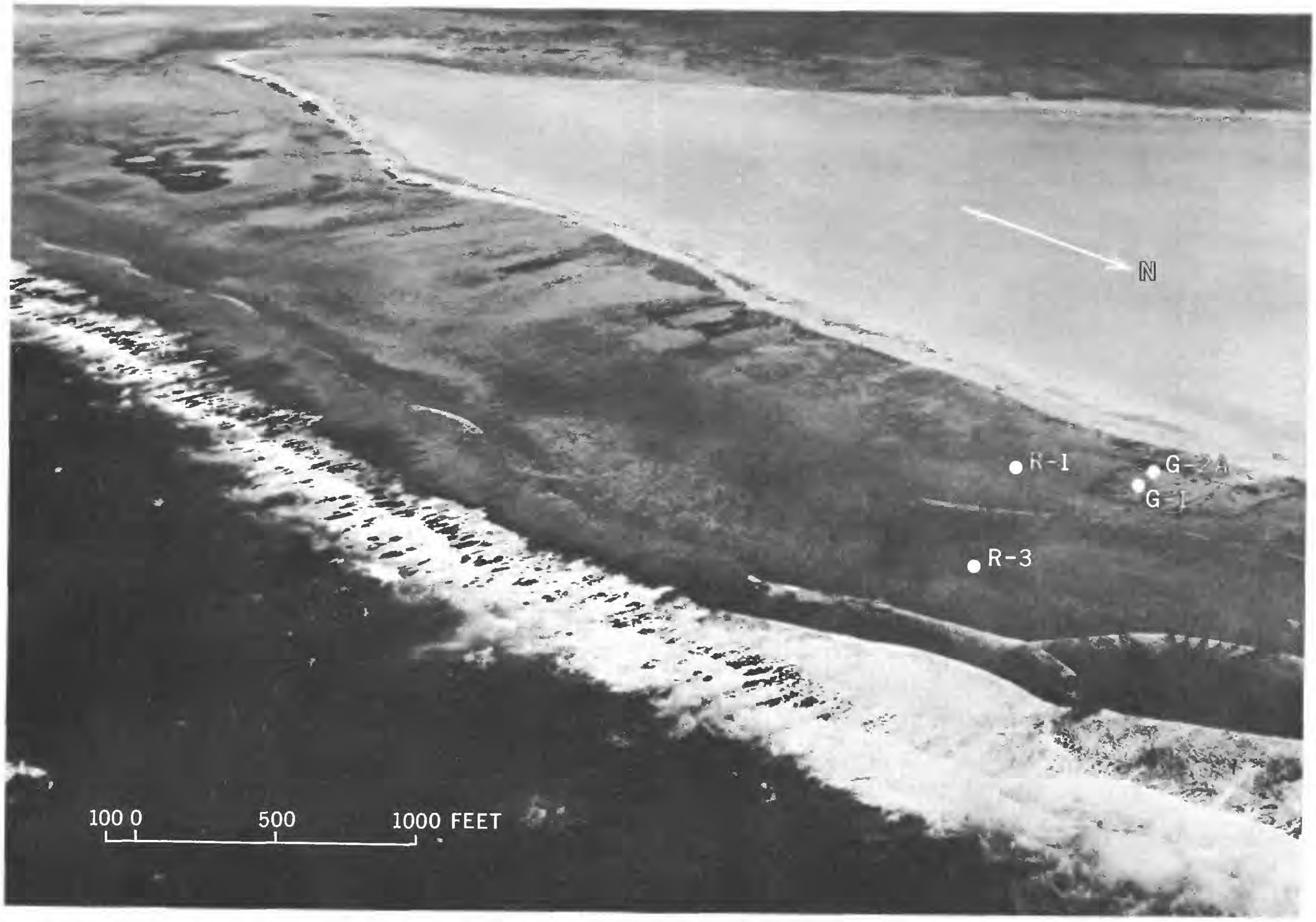

FIGURE 267.—Sites of holes drilled on the reef off the seaward side of Engebi. Features on the island have been painted out. Letter *R* marks holes on the reef flat; letter *G* those on the groin. Photograph by the Atomic Energy Commission.

backed on the groin along with an air compressor. A core barrel taking a 3¾-inch core was available for spudding in but most of the coring was done with a smaller barrel, yielding 1⅝-inch cores.

The same drilling outfit was driven out on the reef flat at a succeeding low tide. The locations of the four holes that were successfully cored are shown on figure 267. Prior to drilling G–2A another site located 11 feet to landward was tested. Sandstone with pieces of coral was found, the material being considerably broken and poorly cemented to a depth of 2½ feet. When the core barrel was withdrawn the hole filled with a foot of sand. At this time the drill was moved to site G–2A. A site, R–2, between R–1 and R–3, was not drilled.

Cores from the four completed holes are briefly described below. They are essentially similar in lithologic characteristics and representative pieces are illustrated on figures 268–273. The dominant fossils are Foraminifera (largely beach and reef types such as *Calcarina* and *Marginopora*) coral, calcareous algae (largely encrusting corallines and *Halimeda*) with subordinate mollusks and echinoid spines. The types illustrated change abruptly and several separate lithologic units may appear in a single core piece: foraminiferal sand, a single coral, an algal head. Pores may be primary intergranular voids or empty chambers in fossils. Lithified "mud" (fine sand to clay-size calcareous material) is abundant in all cores and fills a large percentage of original voids. Thin films of drusy calcite are also widespread and firmly cement much of the debris. Fossils have retained their original color: blue *Heliopora,* brown worm tubes, red encrusting Foraminifera and purple echinoid spines. There appear to be no secondary voids formed by solution.

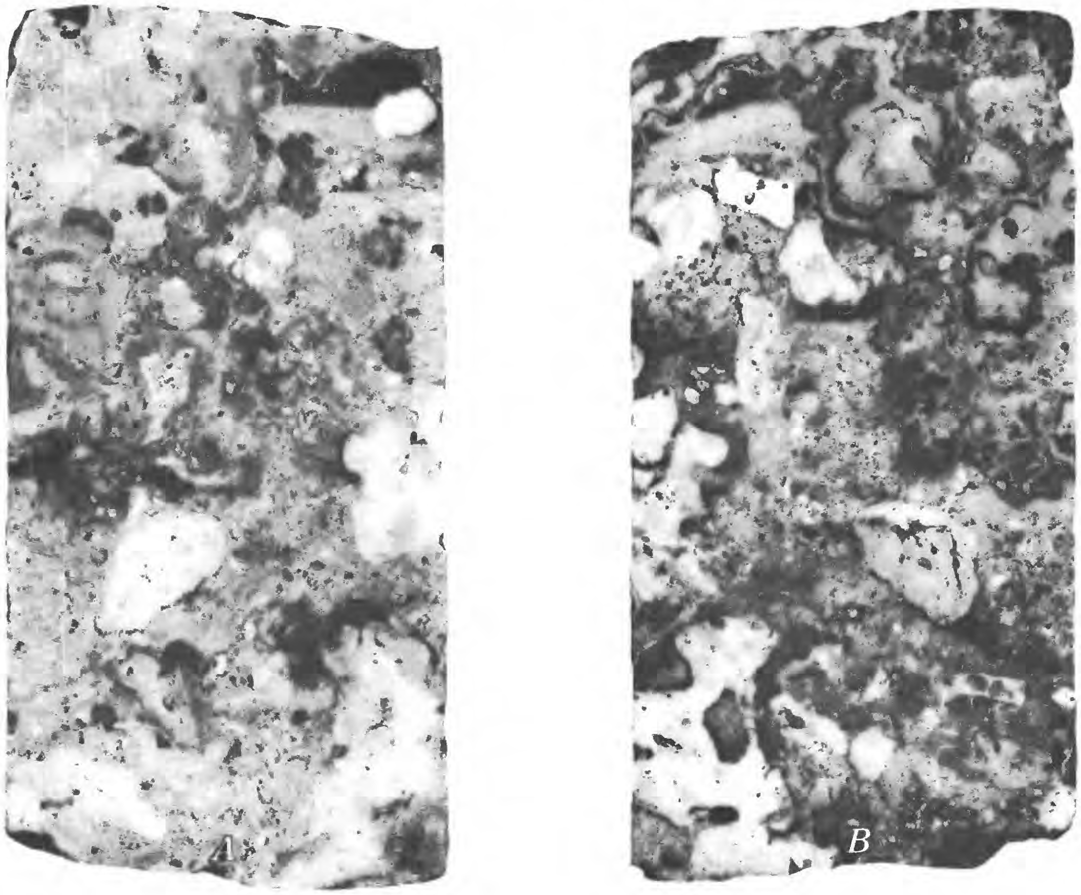

FIGURE 268.—Core (R-3-10) from 2 feet 3 inches to 2 feet 6 inches in the reef hole R-3 off Engebi. This core was split and one half stained with Meigen's solution. *A*, The unstained half, largely encrusting Foraminifera that show as dark patches and encrusting coralline algae. Encrusting forms coat the coral and algal debris. Void in the upper right corner is partly filled with fine carbonate overlain by a film of drusy calcite. *B*, The stained half, showing the generally darker color of widely disseminated aragonite.

Description of cores from drill hole R-1

Drilled to a depth of 14 feet 8 inches. A 50-percent core recovery was obtained in the first 11 feet 2 inches; no recovery from the section below. Top of hole under 3 inches of water at low tide]

Depth of cores (feet and inches)	*Lithologic character*
0–1 ft 4 in	Pieces 1–4, totaling 8 in, composed of randomly oriented fragments of coral as much as 2 in. in length, coated by encrusting algae and red Foraminifera. Angular spaces between corals filled by coarse foraminiferal-algal sand most of which is well cemented by lithified mud matrix. Where matrix is absent, sand is held together by thin film of clear drusy calcite. Soft white mud fills much of the interseptal spaces in the corals. A small percentage of primary porosity remains in the sand areas.
	Piece 5, length 1½ in, consists of well-sorted, coarse, foraminiferal-algal sand irregularly cemented by a lithified mud matrix, locally coated by drusy calcite films (fig. 269).
	Pieces 6–8, totaling 5½ in. One-half inch of sand as above, overlying irregular masses

Description of cores from drill hole R-1—Continued

Depth of cores (feet and inches)	*Lithologic character*
	of encrusting algae laced by red encrusting Foraminifera. Rest of section irregular pieces of coral packed in mud with algal-foraminiferal debris in large interstices. Irregular primary voids total several percent.
1 ft 4 in–6 ft 1 in	Piece 9, length 2½ in. Gravel-size fragments of encrusting algae, *Halimeda*, Formainifera, coral, and a large echinoid spine packed in well lithified mud.
	Pieces 10 and 11, total length 4 in. Irregular stems of branching algae in a lithified mud matrix. *Halimeda*, red encrusting Foraminifera and rare echinoid spines are scattered in matrix. Brown worm tubes cutting through rock are mud filled.
	Pieces 12, 13, 14, total length 6½ in. Large fragments of mud-filled coral packed in porous to mud-filled foraminiferal-algal sand. Worm tubes common. Last part of piece 14 is coarse encrusting algal debris in well-lithified mud and algal detritus.

Description of cores from drill hole R–1—Continued

Depth of cores (feet and inches)	*Lithologic character*
	Pieces 15–24, total length 17 in. Leaflike masses of branching algae (*Porolithon*) and one coral. Spaces between algae are packed to varying degree by foraminiferal-algal sand and mud. Detrital matrix locally lacking and primary porosity is high. Worm tubes common and locally floored by mud, showing orientation of core.
	Pieces 25–32, total length 8½ in. Coarse debris of encrusting algae, red encrusting Foraminifera, and coral in matrix of locally porous foraminiferal-algal sand and mud.
6 ft 1 in–11 ft 2 in	Pieces 33–41, total length, 14 in. Largely massive coral with minor amounts of encrusting algae and red encrusting Foraminifera. Piece 41 is coral, largely packed with lithified mud; locally matrix incompletely fills interseptal spaces, the open pores above indicating top of core.
11 ft 2 in–14 ft 8 in	Soft material; bit removed with difficulty; no recovery.

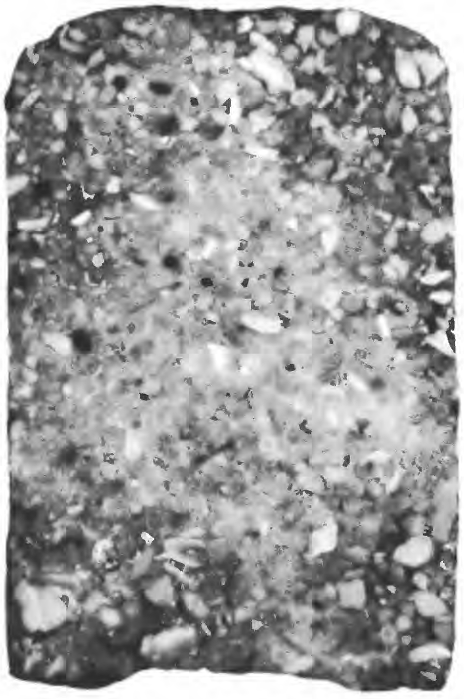

FIGURE 269.—Core (R–1–5) from 10 to 12 inches in reef hole R–1 off Engebi. Sand and granule-size foraminiferal and algal debris tightly packed and well cemented. In some areas the skeletal material is invested in a lithified fine-grained matrix; elsewhere the original intergranular porosity is preserved, but the pores are lined with calcite. × 2.

Description of cores from drill hole, R–3

[Drilled to a depth of 8 feet 11 inches into soft material at bottom of hole, with an overall recovery of 73 percent]

Depth (feet and inches)	*Lithologic character*
0–8 ft 11 in	Forty-one pieces of core recovered. All hard, dense, well-cemented limestone, composed almost entirely of coarse debris of coral, encrusting calcareous algae, red encrusting Foraminifera (fig. 270); few beach type Foraminifera and *Halimeda;* large purple echinoid spines scattered throughout but form a small part of the rock; gastropod shells and fragments of blue *Heliopora* rare; brown worm tubes, partly filled with fine debris common. Most of the space between the larger fossil fragments filled with the fine material; locally, where no filling, fossils are coated with laminated drusy calcite. Fossils not altered or recrystallized in any way; no evidence of subaerial solution (figs. 270 and 271).

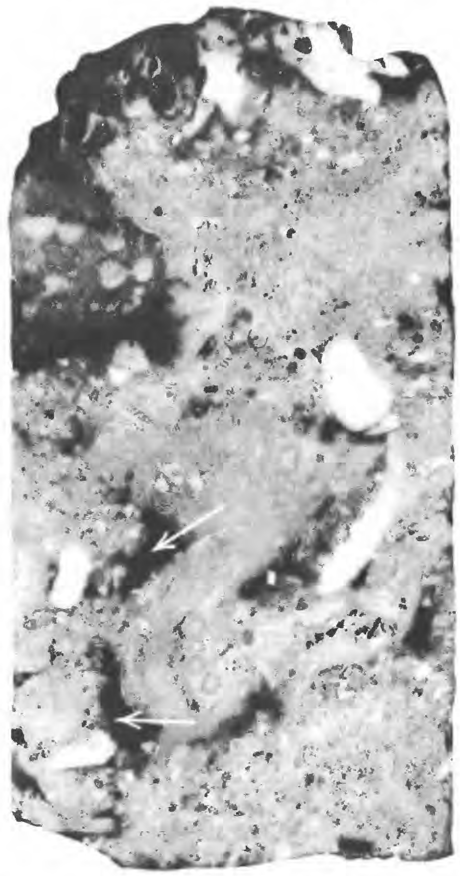

FIGURE 270.—Core (R–3–1) from 0 to 3 inches in reef hole R–3 off Engebi. Coral, coralline algal debris, *Halimeda*, Foraminifera, and mollusks are imbedded in a dense matrix of fine carbonate. The two dark irregular areas to the lower left (arrows) are encrusting red Foraminifera. Present voids are lined with fine drusy calcite; much original pore space has been filled with similar deposits. The top of the core, which was at the reef surface, is deeply pitted, possibly the result of solution by the algal mat that covered it. × 2.

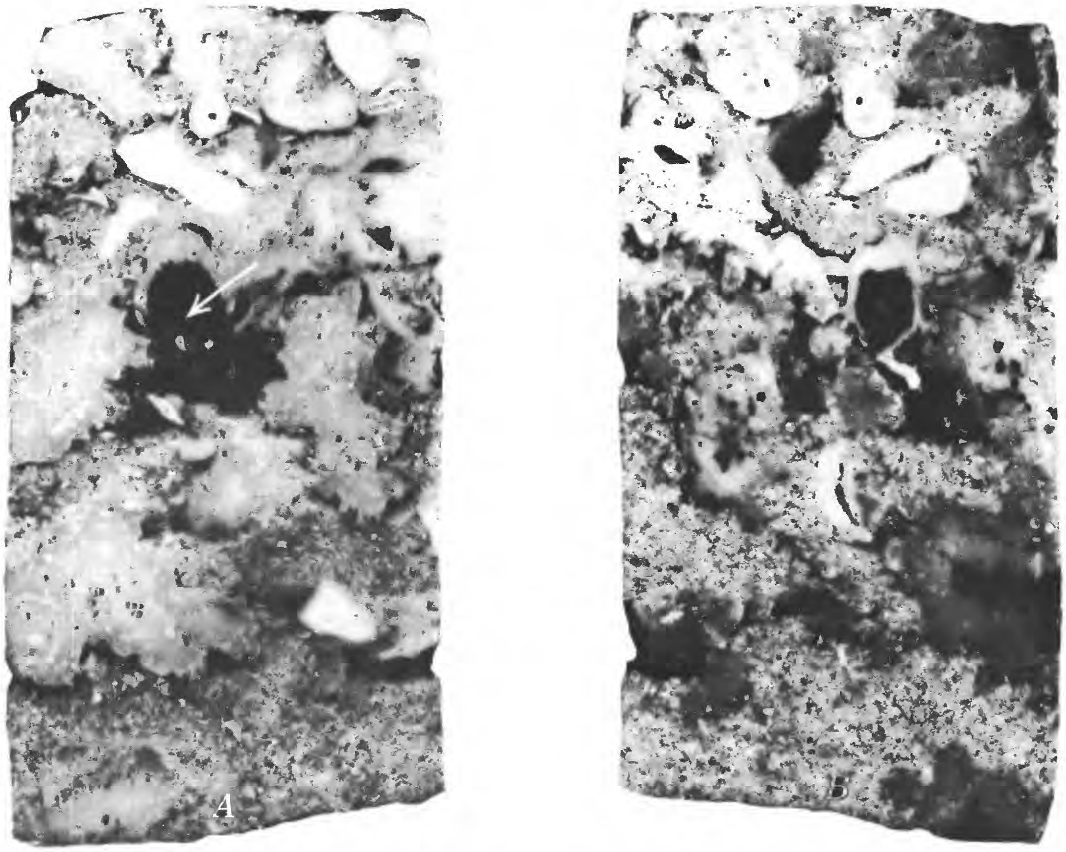

FIGURE 271.—Core (R-3-39) from 8 feet 5 inches to 8 feet 7 inches in reef hole R-3 off Engebi. This core was split and half was stained with Meigen's solution. *A*, The unstained half, coral and corralline algal debris packed in a foraminiferal-algal sand and cemented by intergranular calcite encrustations. The black bullet-shaped area (arrow) is an oblique section of a purple echinoid spine. All pores in the rock are completely lined with calcite. *B*, Stained half. Aragonitic coral areas are dark, algal areas are white. Some fine-grained aragonite fills the voids and is disseminated through the sand areas. × 2.

Description of core from drill hole G–1

[Drilled to a depth of 15 feet 11 inches with an overall recovery of 59 percent]

Depth (feet and inches)	*Lithologic character*
0–1 ft 2 in	Large core barrel used to drill upper surface of groin, recovering 12 in of 3¾-in core out of 14 in drilled. Hard conglomeratic limestone made up largely of corals and Foraminifera.
1 ft 2 in–2 ft 7 in	Pieces 1–6 (these and remainder of cores are 1⅛ in in diameter), length 10 in. Poorly sorted algal-coral gravel with rare mollusk shells and blue *Heliopora* packed in dense matrix of coarse foraminiferal-algal sand. Mud irregularly distributed in matrix; some sand areas porous and cemented by films of drusy calcite.
2 ft 7 in–4 ft 8 in	Pieces 7–19, length 19 in. Pieces 7–14 largely coarse well-cemented foraminiferal sand with scattered gravel-size pieces of calcareous algae; traces of bedding distinguished. Upper pieces have a mud matrix with low porosity, except for local voids; lower pieces show discrete bands of porous rock where mud matrix is lacking and Foraminifera are cemented by calcite films. Pieces 17–19 (fig. 272) vuggy, well-cemented conglomerate, made up of coral, algae, and encrusting Foraminifera; vugs lined with calcite.
4 ft 8 in–7 ft 2 in	Pieces 20–31, length 23 in. Dense, well-cemented limestone made up of large pieces of massive coral separated by vuggy lenses of poorly sorted algal-foraminiferal debris. Sand areas porous locally, due to absence of mud filling.
7 ft 2 in–9 ft 8 in	Pieces 32–44, length 20 in. Pieces 32–39 of unaltered massive coral, locally riddled with worm tubes and containing patches of red encrusting Foraminifera. Pieces 40–44 well-cemented, coarse, poorly sorted, vuggy coral-algal conglomerate with lenses of *Halimeda*-foraminiferal sand.
9 ft 8 in–12 ft 2 in	Pieces 45–51, length 13 in. Pieces 45 and 46, solid cores of massive unaltered coral. Pieces 47 and 48, irregular cores of well-cemented coral-algal conglomerate. Piece 49, a single coral with open interseptal spaces. Piece 50 an irregular core like 47 and 48; piece 51 is a coral like 45 and 46.

Description of core from drill hole G–1—Continued

Depth (feet and inches)	*Lithologic character*
12 ft 2 in–14 ft 8 in	Pieces 52–56, length 6 in. Uppermost piece, well-cemented coral-algal conglomerate; grades downward into coarse, porous, foraminiferal-algal sand, well-cemented by calcite with irregularly distributed mud matrix. Remainder of core, single piece of unaltered massive coral.
14 ft 8 in–15 ft 11 in	Soft material; no recovery.

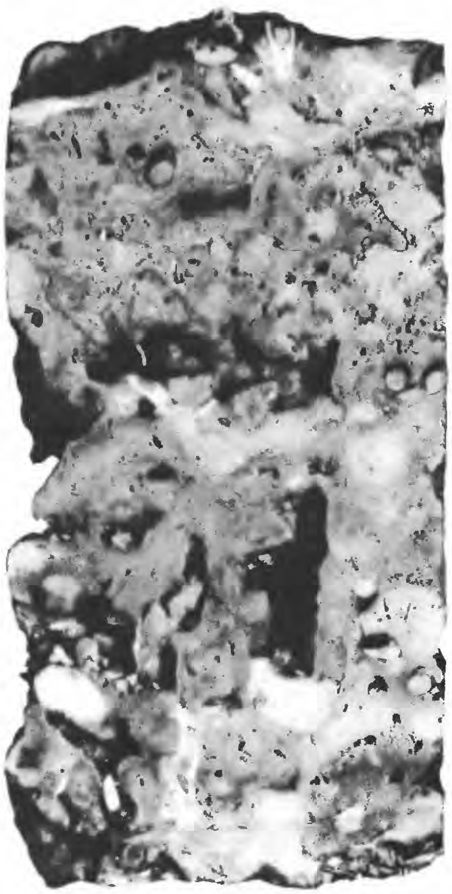

FIGURE 272.—Core (G–I–17) from 4 feet 1 inch to 4 feet 3 inches in the hole drilled through the groin on reef flat off Engebi. Coral-algal limestone with irregular voids, some passing completely through the core. In addition to much lithified fine-grained matrix, the rock is cemented by calcite films that coat all pores. × 2.

Description of cores from drill hole G–2A

[Drilled to a depth of 6 feet into soft material at bottom of hole with a recovery of 39 percent]

Depth (feet and inches)	*Lithologic character*
0–2 ft 6 in	Piece 1, length 2 in. Mass of leafy coralline algae (*Porolithon*) packed with well cemented foraminiferal-algal sand (fig. 273).
	Pieces 2 and 3. Irregular fragments of algae as above and coral encrusted by red Foraminifera.

Description of cores from drill hole G–2A—Continued

Depth (feet and inches)	*Lithologic character*
	Piece 4, length 1½ in. Solid piece of massive coral; interseptal spaces partly open and partly filled by mud.
	Piece 5, length 1 in. Coral and echinoid spine (encrusted by red Foraminifera) in a vuggy mud matrix, the vugs lined with films of drusy calcite. Lower half of piece is dense foraminiferal-algal sand.
2 ft 6 in–3 ft 7 in	Piece 6, length 4 in. Upper half of porous massive coral firmly cemented to lower half, which is a dense mud- and sand-packed coral-algal conglomerate.
	Piece 7, length 1 in. Dense, coral-algal conglomerate.
	Pieces 8 and 9, length 4½ in. Coral fragments including piece of blue *Heliopora* in coarse matrix of unsorted foraminiferal-algal debris; matrix well-cemented by lithified fines.
3 ft 7 in–6 ft	Pieces 10–15, length 13 in. As above including section of massive coral 5 in long. All voids are lined with thin films of drusy calcite.

FIGURE 273.—Core (G2A–1) from 0 to 2 inches in reef hole G–2A off Engebi. The section is through a single head of branching coralline algae. The spaces between the parallel branches are packed with tests of Foraminifera and cemented sand-sized skeletal debris. × 2.

The holes described above seem to be the first that have been drilled on the surface of an atoll reef. Two holes were drilled on the Great Barrier Reef of Australia but the sites were on islands and are not closely comparable to conditions at Eniwetok.

Four holes were drilled through the fringing reef of Pago Pago Harbor in Samoa between 1917–20. In a paper dealing with the structure and ecology of Samoan reef, published posthumously, A. G. Mayor briefly referred to the work. Three holes were on the Utulei reef 200, 575, and 925 feet from shore and ranged in depth from 68 to 120 feet, all ending in hard, unweathered basalt. These holes were cored, but little was said about the degree of consolidation except to note that "even loose sand" was recovered. A fourth hole on the more exposed Aua reef, at a point 512 feet from shore, was drilled through more compact and solid limestone, relatively little sand being met with before basalt was struck at 156 feet (Mayor, 1924, p. 13, pls. 3, 6).

Cary in 1931 gave a more detailed account of the drilling. He reported that the sections drilled were nearly identical in each of the four holes. The outstanding feature was a solid surface crust, some 6 feet in thickness. This rock was hard, composed of madrepore skeletons and cemented *Sclerophytum* spicules, and yielded a nearly continuous core. He stated (p. 88)

> As shown by the cores obtained at each of the drilling stations, the surface layer is essentially homogeneous in composition. All the component elements are bound into a dense mass. All of the small cavities are clean-cut and do not show any indication of regularly occupying former interstices among branches of a coral colony, or even those between adjacent colonies, as appears to be true for the deeper portions of the reef revealed by the drillings, and also for the living reef in the channel beyond the border of the Utulei south reef. In other words some mechanical changes, such as the binding together of all the material by Lithothamnium, *Sclerophytum* spicule rock, or the remains of other organisms, have taken place, supplemented perhaps by chemical changes which altogether have resulted in the formation of the dense crust over the entire reef surface.

In a summary on page 96 after commenting again on the 6-foot surface layer Cary noted that it was underlain by about 8 feet of open coral containing much sand.

> Another dense layer occurs at 14 to 15 feet. From this point to a depth of 46 feet, loose material with freely flowing sand was encountered, then a very hard layer 2 feet in thickness. From approximately 50 feet, down to the substratum, the reef was made up of a relatively open framework with the interstitial material transformed from sand to a dark-brown, rather coarse, sticky "mud." The coral skeletons have also undergone considerable change in color, so that only a narrow central core of white limestone remained. The structural identity of the different species was, however, retained in both madrepores and alcyonarians.

The thick crust of the Samoan fringing reef is similar superficially to the hard plate that was found in the Eniwetok reef holes.

The cores from the reef holes on Eniwetok strongly resemble cores from an interval at the depth of 11–22 feet in drill hole 3 on Bikini, described by Emery, Tracey and Ladd (1954, p. 255) as reef rock.

DEEP HOLES

SEDIMENTARY SECTION

The sediments found in the three deep holes are briefly described in table 3. A more detailed report on the petrography of the limestone and dolomite is being prepared by the junior author and will be submitted later. A short discussion of dolomite formation in the Eocene section has been published elsewhere (Schlanger, 1957, p. 181–186). A report on the molluscan faunas and the paleoecological conditions suggested by them is being prepared by the senior author.

TABLE 3.—*Description of samples from the deep holes*

F-1		E-1		K-1	
Depth (feet)	Lithologic character	Depth (feet)	Lithologic character	Depth (feet)	Lithologic character
0–45	Sand, uncemented; made up largely of beach-type Foraminifera such as *Calcarina* and *Marginopora*, mixed with fragments of larger forms, including corals (*Tubipora*), echinoid spines, crustacean fragments, and segments of *Halimeda;* rich assemblage of small mollusks in interval at 20–45 ft; arcids, lucinids, tellinids, *Mytilus*, trochids, *Diala* and other cerithids, *Vermetus;* hard beach rock from 12.5–14.5 ft depth.	0–30	Sand, uncemented; made up largely of worn tests of beach-type Foraminifera such as *Calcarina* and *Marginopora* mixed with coral pebbles, mollusk shells (limpet, trochids, *Diala* and other cerithids, *Vanikoro*, *Marginella*), echinoid spines, and worn segments of *Halimeda;* hard beach rock at 18–21 ft depth.	0–33	Sand, uncemented; made up largely of beach-type Foraminifera, *Halimeda* segments, mollusk shells, and polished coral and coralline algal debris; no trace of alteration; cored well-cemented porous beach sandstone from 7.5–10 ft made up of worn Foraminifera (*Calcarina Amphistegina*, *Marginopora*) algal, coral, molluscan debris, red encrusting Foraminifera, and purple echinoid spines.
				33–44	Gravel, coarse, unconsolidated; made up of fragments of nodular encrusting algae, branching coral, and fresh mollusk shells with few segments of *Halimeda;* mollusks include *Turbo*, *Columbella*, *Strombus*, *Cypraea* and *Chama;* some pelecypods with both valves.

TABLE 3.—*Description of samples from the deep holes*—Continued

F-1		E-1		K-1	
Depth (feet)	Lithologic character	Depth (feet)	Lithologic character	Depth (feet)	Lithologic character
45–110	Debris, uncemented coarse, platy; poorly sorted mixture of *Halimeda* segments and *Lithothamnium*, worn coral (including *Tubipora*), echinoid spines, foraminifers, and small mollusks (arcids, *Cardium*, *Mytilus*, tellinids, lucinids, venerids, *Emarginula*, *Triphora*, *Atys*, *Columbella*, *Vermetus* tubes, *Diala* and other cerithids; few mollusks preserved as molds in interval 90–110.	30–90	Debris, coarse, platy; with numerous fresh and worn segments of *Halimeda*—some cemented—and many small mollusks and Foraminifera; larger fragments include worn corals and branching *Lithothamnium* and mollusks (arcids, *Cardium*, trochids, *Columbella*, *Cypraea*, *Trivia*, *Triphora*, liotid, cerithids).	44–81	Core and cuttings of unconsolidated mixture of irregular pieces of fine-grained, unaltered limestone, worn coral, beach-type Foraminifera, few fresh mollusk shells (including *Tridacna* and *Cypraea*), and algal debris; some *Halimeda* and fragments of *Heliopora*.
110–191	Worn mollusk shells, massive coral, and delicate, unworn, branching coral; large fragments of yellow calcite; some mollusks preserved as molds. Cores from interval at 170–191 ft are buff white, porous, friable, coral-algal conglomerate (fig. 274). *Acropora* fragments as large as 1 in long, and abundant *Halimeda* segments are mixed with broken mollusk shells and fragments of encrusting Foraminifera; algae coat much of the coral and, in the lower parts of the core, form masses; coral and *Halimeda* are unaltered and rock shows no sign of subaerial solution; *X*-ray analysis of bulk sample shows 60 percent aragonite and 40 percent calcite; matrix is fine sand and silt.	90–145	Coral and sand; some coral worn, some recrystallized to yellow calcite; some mollusks well preserved, others worn and broken; few occur as molds.	81–83.5	Core of limestone, white, well-lithified made up of coral, algal, and molluscan debris in a fine-grained matrix; much of the coral altered to chalky material; contains many molds of mollusks and irregular patches of drusy calcite; voids are partly filled with same material; rock surface pitted by solution.
				83.5–100	Limestone fragments similar to last and others of well-cemented sandy foraminiferal limestone with recrystallized coral showing calcite filling; fragments of unaltered mollusk shells also occur.
				100–103	Coral core; partly recrystallized; original aphanitic aragonite replaced by coarsely crystalline calcite in small isolated patches as much as ¼ in across and also along "fronts"; interseptal openings in the replaced areas choked by euhedral calcite crystals that have grown in from the original septal walls; recrystallized areas separated from the original coral by narrow zones of powdery white aragonite; contact between original coral and secondary calcite is saw-toothed, resembling a styolite (fig. 275).
				103–169.5	Coral, partly recrystallized; *Heliopora* unaltered micromollusks, and fragments of larger forms (*Pecten*, *Strombus*).
191–280	Coral-head limestone; fragments of massive colonies (*Porites*); finer material consists of small mollusks (arcids, *Mytilus*, *Cardium*, rissoids, *Diala*, *Triphora*), Foraminifera and segments of *Halimeda*; some yellow calcite, mollusk molds rare.	145–300	Coral limestone; white friable limestone, recrystallized in places to yellow calcite; mollusks abundant (arcids, *Mytilus*, venerids, trochids, naticids, cerithids, *Triphora*); some preserved as molds; cuttings from depth of 230–240 ft are largely aragonite.	169.5–175	Coral, core, partly recrystallized and calcite-filled; packed in friable porous *Halimeda*-rich sandy limestone; *Halimeda* unaltered. Below, the limestone is sandy and poorly cemented, containing *Halimeda*, gastropod shells and angular fragments of coralline algae.
				175–201	Coral; similar to interval at 103–169.5 ft; molluscan debris, including cerithids and tellinids, abundant below.
				201–253.5	Rich assemblage of small, well-preserved mollusks (arcids, tellinids, *Cardium*, naticids, rissoids, cerithids) with some coral, Foraminifera and *Halimeda*; some mollusk shells partly filled with yellow calcite.
				253.5–264	Cores and cuttings of limestone, chalky and friable: contains unaltered mollusk shells, some fragmentary; some well-lithified and patchily recrystallized pieces of core contain partly dissolved mollusk shells, unaltered *Halimeda* and corals; some fine sand and silt; yellow calcite common.
				264–285	Assemblage of fossils; similar to interval at 201–253.5 ft but with numerous clusters yellow calcite crystals; mollusks have a chalky appearance.
				285–295.5	Unaltered molluscan shells in cuttings mixed with calcite crystals, coral debris and *Halimeda*; one rounded pebble of brown, fine-grained limestone shows molds of small mollusks and voids lined with clear calcite.
280–330	Coral and shell limestone; fine to coarse, uncemented to weakly cemented limestone made up of coral fragments and mollusk shells, many worn and broken (*Cardium*, venerids, *Triphora*, turbids, rissoids, *Diala* and other cerithids).	300–530	Limestone, buff, porous to dense; corals and mollusks preserved as molds; cavities partly filled with yellow calcite. Cuttings from 310–320 ft. are largely calcite; no cuttings at 430–450 ft and at 470–480 ft.	295.5–302.5	Limestone, hard, fine-grained, recrystallized individual corals partly altered to calcite and contain calcite fillings; some unaltered mollusk shells may represent contamination from above.
				302.5–307	Core of coral, solid, massive, completely recrystallized in position of growth overlying hard coralliferous limestone made up largely of encrustations of algae and Foraminifera; original openings in massive coral partly filled with drusy calcite; no aragonite; in hard limestone below, coral is patchily recrystallized and there are pockets of porous, slightly altered *Halimeda* and foraminiferal sand and gravel; limestones resemble the cores obtained below the reef flat.

TABLE 3.—*Description of samples from the deep holes*—Continued

F-1

Depth (feet)	Lithologic character
330–625	Limestone, buff, moderately consolidated; corals and most mollusks preserved as molds; cavities partly filled with yellow calcite. Core from interval at 600–625 ft is buff, vuggy, recrystallized, coralliferous limestone; contains numerous finger-shaped molds of coral, and abundant molds of mollusks and *Halimeda* and coatings of drusy calcite and solution voids; matrix is an *Amphistegina* rich fine sand and silt that appears to be partly replaced with coarse calcite mosaic; X-ray analysis of two pieces show 100 percent calcite.
625–810	Limestone, buff, weakly cemented; made up chiefly of well-preserved corals, shells of mollusks, and smaller Foraminifera in matrix of fine detritus; molluscan assemblage rich and varied; arcids, venerids, cardiids, turbids, strombids, mitrids, neritids, cypraeids, cerithids.
810–850	Corals and many well-preserved mollusk shells similar to preceding sample; contains some carbonaceous, aragonitic, clay-size material, but X-ray examination showed no clay minerals.
850–975	Limestone, buff, coralliferous; contains numerous well-preserved mollusks; some aragonitic clay-size material in interval at 850–860 ft.
975–1,045	No samples.
1,045–1,060	Limestone, hard, gray, porous, recrystallized; fine cuttings.
1,060–1,080	No samples.

E-1

Depth (feet)	Lithologic character
530–840	Limestone, buff, weakly cemented; made up chiefly of corals (slender, branching forms and more massive types, including *Porites* and *Millepora*), well-preserved mollusks and beach-type Foraminifera (brown Marginoporas 760–810 ft); mollusk assemblage rich and varied and mostly small forms, with gastropods (naticids, cerithids, cypraeids, rissoids, vermetids, *Triphora*, *Conus*, *Bulla*) far outnumbering the pelecypods (mostly arcids and venerids).
840–900	Worn coral with rich fauna of well-preserved mollusks. Some carbonaceous, clay-size material, in interval at 870–880 ft but X-ray examination showed no clay minerals—only argonite and trace of calcite.
900–1,070	Limestone, buff to tan, coralliferous; contains varied assemblage of well-preserved mollusks and smaller Foraminifera.

K-1

Depth (feet)	Lithologic character
307–359.5	Coral, recrystallized; coralline algae, and fine-grained hard limestone; corals include delicately branching *Seriatopora;* some *Halimeda* and molluscan debris unaltered; contains calcite crystal rosettes.
359.5–370	Sand, foraminiferal (*Calcarina* and *Marginopora*) with coral, coralline algae, and fine-grained limestone; recrystallization conspicuous, much of the sand-size material being drusy calcite.
370–391	Limestone, recrystallized; contains calcite clusters and molds of corals and mollusks.
391–396	Core of coral, and mollusk-rich limestone, hard, white, porous; molds of pelecypods and randomly oriented fragments of branching coral in matrix of fine, recrystallized, foraminiferal sand; drusy encrustations of calcite abundant.
396–422.5	Similar to interval at 370–391 ft. Small Foraminifera abundant.
422.5–443.5	Limestone, fine-grained, brown, recrystallized; contains abundant miliolids and other small benthonic Foraminifera.
	K-1B
432–436	Core of limestone, hard, solution-pitted coral-molluscan, same as that from the interval at 391–396 ft of K-1.
436–526	Limestone, cream-colored, finely recrystallized, solution-pitted, contains corals and molds of mollusks; drilling indicated zones of variable hardness.
526–531	Core of limestone, dense, white to yellow recrystallized with molds of mollusks and coral debris; some encrusting algae and small mollusk shells in hard, fine-grained matrix.
531–537	Limestone; similar to interval at 432–442 ft. Some fine silt and chalky material.
537–579	Limestone, finely recrystallized, coralliferous; contains mollusk molds and unaltered shells, many are chalky but retain original structure (trochids, turbids); abundant small branches of aragonitic coral and broken pelecypod shells.
579–611	Limestone, chalky, but unrecrystallized coralliferous; some unaltered pelecypods and fine-grained fluffy white carbonate; some mollusk molds and cuttings of recrystallized limestone.
611–621	Debris, chalky, fossil, and recrystallized limestone.
621–623	Core and cuttings of limestone, white, chalky, friable; made up of Foraminifera in a fine sandy matrix; contains molds of gastropods and fragments of unaltered pelecypods.
632–663	Limestone, hard, finely recrystallized and unaltered fossil debris, including corals, small mollusks and abundant larger Foraminifera.
663–716	Limestone, light-tan; with well-preserved branching coral and a rich molluscan fauna.
716–758	Limestone; similar to last. Lower part contains fragments of hard, fine-grained crystalline limestone.
758–768	Limestone, tan; contains many corals and encrusting algae; fragmentary mollusks.
768–779	Limestone, soft, coralliferous; with coralline algae and fragmentary mollusks.
779–790	Silt, light-tan with unaltered corals and mollusks.
790–831	Branching corals, well-preserved *Marginopora*; varied fauna of unaltered mollusks, including one land snail (*Ptychodon*).
831–884	Silt, gray, with unaltered corals and rich assemblage of mollusks.
884–936	Coral cuttings, tan, unaltered mollusk shells.
936–968	Silt, gray, similar to that in interval at 831–842 ft; rich molluscan fauna.
968–1,039	Limestone, tan, contains unaltered corals, algae and mollusks. Same as interval at 663–716 ft.
1,039–1,081	Sand, tan, fine and silt, core and cuttings with numerous unaltered, well-preserved mollusks; contains *Halimeda* and miliolid Foraminifera also.
1,081–1,090	Limestone, light-tan, well-cemented sandy; contains rich molluscan fauna.

TABLE 3.—*Description of samples from the deep holes*—Continued

F-1

Depth (feet)	Lithologic character
1,080–1,248	Limestone, hard, dense recrystallized; contains irregular cavities left by removal of corals and shells. Cores from 1,232- to 1,248-ft interval are buff dense vuggy recrystallized limestone made up of poorly sorted foraminiferal and algal debris in a matrix of fine-grained calcite mosaics; contains abundant *Halimeda* segments, recrystallized to calcite or removed by solution but recognizable as molds; some molds of mollusks; locally abundant coral branches and miliolid Foraminifera; solution vugs lined by as many as 7 laminae of calcite; in one vug lining, rare dolomite crystals were identified by microscopic technique and X-ray analysis confirmed trace of dolomite.
1,248–1,718	No samples
1,718–1,740	Core of limestone, dense fairly porous, white; several rock types grade vertically into one another; porous, well-sorted, coarse-grained foraminiferal limestone most common, with abundant rotalid, miliolid, lepidocyclinid, and heterosteginid Foraminifera, along with some algal debris; primary pore spaces locally open but rock generally cemented by clear, anhedral, granular, calcite; massive, coralliferous conglomerate with well-cemented matrix, is rich in unsorted Foraminifera; molds of coral branches and drusy encrustations of calcite; locally rich in heterosteginid Foraminifera cemented in a recrystallized fine-grained matrix; lower part of core shows Foraminifera cemented by acicular calcite; X-ray analyses of two samples showed 100 percent calcite.
1,740–1,975	No samples
1,975–1,978	Limestone, hard, white to cream-colored; many calcite crystals; some well preserved fragments of coral and mollusk shells; few Foraminifera.
1,978–2,003	Limestone core, dense, cemented, white; includes coarse coralliferous conglomerate with algal debris and *Lepidocyclina* in a matrix of mud; numerous secondary solution voids lined with drusy calcite; mollusk shells completely recrystallized; some parts of core are recrystallized sections of massive coral heads, some, in positions of growth, others not in position; cores of fine-grained, well-sorted foraminiferal-algal limestone dominated by small tests of *Amphistegina*; lower part of core coarse-grained, vuggy, algal-*Lepidocyclina* limestone; X-ray analyses of 3 pieces showed 100 percent calcite.
2,003–2,020	Limestone, tan; with many well preserved coral fragments, Foraminifera, and mollusk shells.
2,020–2,130	Limestone, hard, dense, white, crystalline; shows few traces of organic structure.
2,130–2,662	No samples
2,662–687	Cores of conglomerate, white to buff, vuggy, dense, recrystallized coral-foraminiferal; corals show interseptal mud fillings; larger foraminifera include *Lepidocyclina* and *Operculina;* abundant secondary solution voids show laminated drusy coatings of calcite; X-ray analyses of these coatings showed a trace to 2 percent of dolomite; three other cores showed 100 percent calcite.
2,687–3,052	No samples

E-1

Depth (feet)	Lithologic character
1,070–1,120	Limestone, dense buff coralliferous; contains abundant well-preserved mollusks; some cuttings of hard tan cavernous limestone with mollusks preserved as molds.
1,120–1,190	Limestone, tan porous coralliferous; contains numerous well-preserved small mollusks. Very hard 1,155–1,165 feet.
1,190–1,230	Limestone, buff, cavernous; and white, dense limestone with larger Foraminifera and small mollusks; very hard 1,207–1,211 ft.
1,230–1,482	Limestone, hard, dense, yellowish; contains coral and mollusk molds. No cuttings 1,320–1,330 feet.
1,482–1,569	Limestone, buff, porous, friable; many larger Foraminifera; mollusks as molds.
1,569–1,658	Limestone, hard, porous to dense, yellowish; abundant larger Foraminifera; mollusks as molds.
1,658–1,715	Limestone, gray, porous, friable, foraminiferal; few well preserved corals and mollusks (cerithids, vermitids, neritids, *Triphora*).
1,715–1,835	Limestone, gray to brown; made up of well-preserved corals and shells (similar to last above 1776 ft rich in *Cardium* below); few larger Foraminifera.
1,835–1,993	Limestone, yellowish; contains well-preserved corals, shells, and algae.
1,993–2,440	Limestone, gray, weakly cemented; rich in pelecypod shells, especially complete, and fragmentary shells of a small *Cardium* and a few small gastropods, including *Turritella* and cerithids; some rodlike algae. Cores from the 2,003–2,028-ft interval include unaltered piece of massive *Porites*, apparently in position of growth, and friable gray limestone containing packed shells of *Cardium* and other mollusks in a fine-grained mud and sand matrix; tests of *Austrotrillina* and rodlike algae abundant in this interval; X-ray analysis of a piece of coral showed 98 percent aragonite and 2 percent calcite; analysis of bulk sample of the shelly limestone showed 45 percent aragonite and 55 percent calcite.
2,440–2,510	Siltstone, soft, gray, calcareous, laminated; contains fragmentary plant remains; X-ray examination of siltstone 2,440–2,450 ft showed no trace of clay minerals, only calcite; micromollusca, algal rods, and smaller Foraminifera occur, but not in siltstone; limestone may be interbedded with siltstone.
2,510–2,600	Sandstone, friable, gray; contains many smaller Foraminifera and algal rods; few well-preserved mollusks (*Cardium*, cerithids).

K-1B

Depth (feet)	Lithologic character
1,090–1,196	Tan well-cemented recrystallized limestone with larger Foraminifera and molds of other fossils. Some unaltered mollusk shells.
1,196–1,217	Limestone cuttings; a mixture of recrystallized chips.
1,217–1,230	Limestone, tan; contains abundant unaltered coral and mollusks.
1,230–1,259	Limestone, hard crystalline.
1,259–1,280	(total depth) Softer material; no samples.

TABLE 3.—*Description of samples from the deep holes*—Continued

F-1		E-1		K-1B	
Depth (feet)	Lithologic character	Depth (feet)	Lithologic character	Depth (feet)	Lithologic character
		2, 600–2, 802	Limestone, friable, gray to brown; made up of smaller Foraminifera, algal rods, mollusk shells (*Cardium*, turbids, cerithids, rissoids, *Triphora*, *Turritella*), and corals; few mollusk molds near base of interval.		
3, 052–3, 055	Core of limestone, chalky, white; mostly soft and slightly plastic when wet; contains globigerinids, also some larger Foraminifera and molds of minute gastropods; X-ray analysis showed 100 percent calcite.	2, 802–2, 808	Cores of limestone, white to cream-colored, friable to well-cemented; contains numerous molds of large pelecypods and gastropods (as large as 2 in); spottily recrystallized and shows effects of solution; medium-grained matrix is locally rich in *Triloculina* and *Peneroplis;* X-ray analysis of upper recrystallized core showed 100 percent calcite; analysis of molluscan shell debris from a sandy part of core showed 80 percent calcite and 20 percent aragonite.		
3, 055–3, 350	No samples				
		2, 808–3, 020	Limestone, firm to hard, granular to dense, tan to cream-colored; contains scattered and poorly preserved molds of corals and shells; some smaller Foraminifera.		
		3, 020–3, 050	Limestone, hard, porous, white to cream-colored; contains many smaller Foraminifera and few molds of minute gastropods.		
		3, 050–3, 110	Limestone, cream-colored, sandy; numerous smaller and a few larger Foraminifera; molds of small mollusks rare.		
		3, 110–3, 127	Limestone, hard, dense to porous, gray; containing few coral and small mollusk molds and numerous smaller Foraminifera.		
3, 350–3, 353	Core of limestone, soft to moderately hard, white; contains few molds and coarsely crystalline casts of corals and molds of mollusks; some smaller Foraminifera, chiefly globigerinids, and rodlike algae; X-ray analysis showed a trace of dolomite.	3, 127–4, 078	No samples.		
		4, 078–4, 100	Core of limestone, well-cemented, white, vuggy, recrystallized; rich in corals and encrusting calcareous algae; fossils in a detrital matrix of sand and fine mud; molds of mollusks common; Dolomite as single rhombs or clusters of rhombs in fragments of algae and in fine mud matrix; X-ray analyses of 2 pieces showed 5 percent dolomite and 95 percent calcite, and 14 percent dolomite and 86 percent calcite.		
3, 353–3, 655	No samples				
3, 655–3, 665	Cores of conglomerate, poorly sorted, porous, friable to firm, coral-algal-foraminiferal; locally vuggy and well cemented, showing secondary solution voids; *Halimeda* molds locally abundant and coral molds common; *Pecten* retains original shell but minute gastropods preserved as molds; X-ray analyses of 2 pieces showed 100 percent calcite.				
3, 665–3, 963	No samples.				
3, 963–3, 988	Core of limestone, friable, white; composed mainly of rodlike algae, globigerinid Foraminifera, and fine detritus; few coral and mollusk molds (one *Pecten* unaltered), and echinoid spines; locally cemented by granular calcite; X-ray analysis of one piece showed 100 percent calcite.				
3, 988–4, 197	No samples.	4, 100–4, 170	No samples.		
4, 197–4, 222	Cores of limestone, white, coarse-graind, porous, moderately well cemented foraminiferal algal; Foraminifera mainly large benthonic types such as *Pellatispira;* algae are rodlike; no evidence of solution or extreme recrystallization; dolomite throughout as scattered euhedral rhombs between pieces of algal and foraminiferal debris; X-ray analyses of 5 pieces showed 2 percent dolomite at top and bottom of core and 8 percent near center.	4, 170–4, 190	Olivine basalt; few chips in momentary return of circulation. (Corrected depth of these cuttings is 4,158 ft).		
		4, 190–4, 208	No samples.		
		4, 208–4, 222 (total depth)	Olivine basalt, altered; massive zones as much as 8 in alternating with fractured zones with calcite veinlets.		
4, 222–4, 316	No samples.				
4, 316–4, 341	Limestone, friable to moderately well cemented, porous, white, foraminiferal-algal; upper part of core similar to that from interval at 4,197–4,222 ft; X-ray analysis showed a dolomite content of 11 percent; dolomite as scattered euhedral rhombs; grades downward into hard buff massive dolomite with lenticular solution voids lined with dolomite crystals (fig. 277). X-ray analyses showed dolomite ranging to a maximum of 98 percent (from 65 to 98 percent in a single core piece several inches long); closely packed mosaic of subhedral dolomite crystals; in some pieces "dusty" fossil ghosts can be seen; lower half of 8 ft of core in friable foraminiferal (*Pellatispira*) and algal-coral conglomerate. X-ray analyses showed dolomite content of 42 to 45 percent (fig. 278).				
4, 341–4, 406	No samples.				

TABLE 3.—*Description of samples from the deep holes*—Continued

	F-1		E-1		K-1B
Depth (feet)	Lithologic character	Depth (feet)	Lithologic character	Depth (feet)	Lithologic character
4,406-4,431	Limestone, short core of white porous, moderately cemented, coarse-grained, poorly-sorted, foraminiferal (*Pellatispira*)-algal; contains some coral pebbles (fig. 279); patches of the core are well cemented and show secondary solution voids; a few mollusk and coral molds; X-ray analysis showed 100 percent calcite but thin sections show rare small rhombs of dolomite.				
4,431-4,500	No samples.				
4,500-4,525	Limestone, upper part of core white to buff, fine-grained porous to dense, well-sorted foraminiferal (fig. 280); abundant tests of small benthonic and globigerinid Foraminifera are packed in a matrix of fine mud; fragments of mollusk shells rare; texture coarser below with few unaltered (calcitic) mollusk shells (*Ostrea, Pecten*); lower part of core a vuggy well cemented, breccia with coral molds; X-ray analyses of three pieces showed traces of dolomite; dolomite present as scattered rhombs; some core pieces lack dolomite.				
4,525-4,528	No samples.				
4,528-4,553	Core of limestone, moderately hard, porous, poorly sorted, coarse-grained; made up of Foraminifera and algal debris in a detrital matrix; underlain by limestone with varied assemblage of fossils; algae, Foraminifera, corals, mollusks (*Arca, Pecten*, and molds of *Cypraea* and minute gastropods), echinoid spines, crustacean fragments; corals and most of mollusks as molds; X-ray analyses showed 100 percent calcite, but thin sections reveal scattered rhombs of dolomite.				
4,553-4,610	No samples. Drilling rate comparable with rates in overlying sediments.				
4,610-4,630	No samples; drilled with difficulty; presumably basalt.				

FIGURE 274.—Core (F-1-1-1) from the 170- to 191-foot interval in hole F-1 on Elugelab. Buff-white porous coral and limestone, rich in *Halimeda* fossils; these fossils are still aragonitic. The coarse debris is cemented by a brown filamentous incrustation, probably of organic origin. × 1.

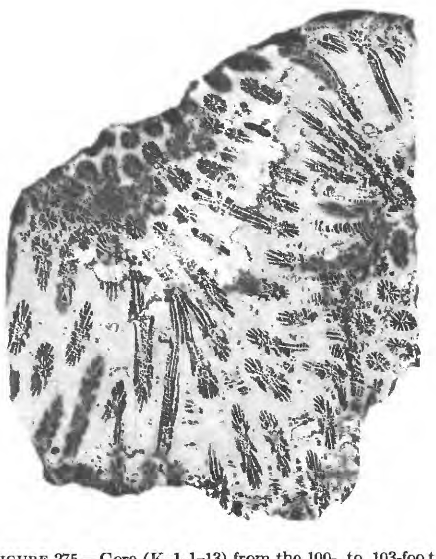

FIGURE 275.—Core (K-1-1-13) from the 100- to 103-foot interval in hole K-1 on Engebi. Coral stained with Meigen's solution to differentiate the aragonite (dark gray) from the calcite (light). The original aragonite corallum is being replaced by coarse calcite crystals along a jagged front and in discrete areas. Addition of calcite has resulted in the filling of interseptal spaces. The boundary between the original skeletal aragonite and the secondary calcite is marked by a thin saw-toothed film of chalky aragonite. × 2.

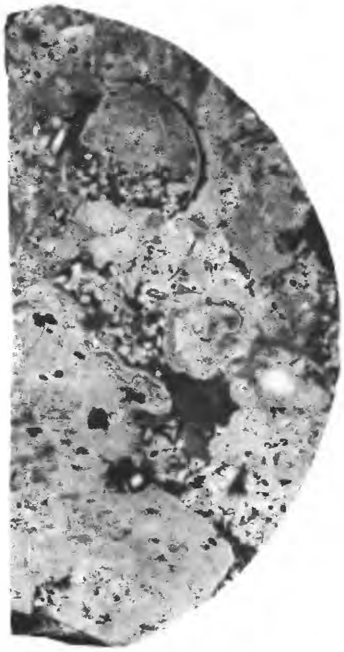

FIGURE 276.—Core (F-1-5-39) from the 1,978- to 2,003-foot interval in hole F-1 on Elugelab. Dense, white, coral-algal limestone containing a section of a pelecypod valve, and foraminiferal-algal sand packed between algal incrustations; original voids still present though lined with drusy calcite. This rock is very similar to limestone from shallow holes on reef. × 1.

FIGURE 277.—Core (F-1-12-5) from the 4,316- to 4,341-foot interval in hole F-1 on Elugelab. Massive secondary dolomite; the original calcite has been completely replaced except for small white flecks in the lighter areas near the bottom of the core. The dolomite is fine grained at the bottom and coarser in the upper, porous section. The elongate pores probably are fossil molds; euhedral dolomite crystals line these voids, × 1.

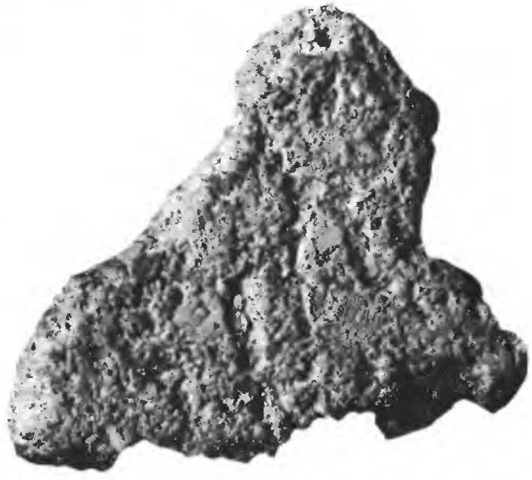

FIGURE 278.—Core (F-1-12-24) of dolomite limestone from the 4,316- to 4,341-foot interval in hole F-1 on Elugelab. Specimen was etched in acid to raise the dolomite in relief. The calcite is present as tests of larger Foraminifera and algal debris. The dolomite crystals surround and penetrate the fossils. Larger Foraminifera are the last fossils to be dolomitized in these rocks. × 2.

FIGURE 279.—Core (F-1-13-3) from the 4,406- to 4,431-foot interval in hole F-1 on Elugelab. Porous, moderately cemented, foraminiferal limestone. Tests of larger Foraminifera are randomly oriented and packed in a sand matrix. Traces of dolomite are present as scattered, euhedral rhombs, × 1.

AGE OF SEDIMENTS

The age determinations shown in plate 265 and figure 287 are based almost entirely on identifications of Foraminifera by W. Storrs Cole (1958, p. 743) and Ruth Todd and Doris Low (in press).

PETROGRAPHY OF BASEMENT ROCK[2]

Three cores of the basement rock, totaling 14 feet, were recovered from hole E-1 (pl. 265). The rock in the first core (4,208–4,211 feet) is hard black olivine basalt

[2] Preliminary description prepared by Ingerson (in Ladd, Ingerson, Townsend, Russell, and Stephenson, 1953, p. 2272–2276); a detailed study of the basement rock is now being made by Gordon Macdonald.

FIGURE 280.—Core (F-1-14-5) from the 4,500- to 4,525-foot interval in hole F-1 on Elugelab. Tan, porous foraminiferal-algal limestone with numerous tests of globigerinids. Traces of dolomite are present, × 1.

(fig. 281). The material appears fresh, but close inspection shows much alteration, especially along fractures. Olivine grains, except in the freshest part of the rock, are sheathed by films of saponite. The olivine has typical glassy luster and conchoidal fracture. It is yellowish to brownish, depending on the size and compactness of the grains, the smaller and more fractured grains showing lighter colors. Parts of the rock are well seamed with calcite veinlets (fig. 282). In the first of the basalt cores there are 12 of these veinlets ranging in position from almost normal to the core axis to angles of almost 45°. One small crosscutting veinlet, connecting two of the flat ones, is almost parallel with the axis of the core. It is 3 inches long and 0.7–2.0 millimeter thick. Some of the veinlets contain enough of the alteration product to color the calcite a light green, and in some of the thicker veinlets there are alternating layers of calcite and green alteration product; in other veinlets the layers of calcite alternate with

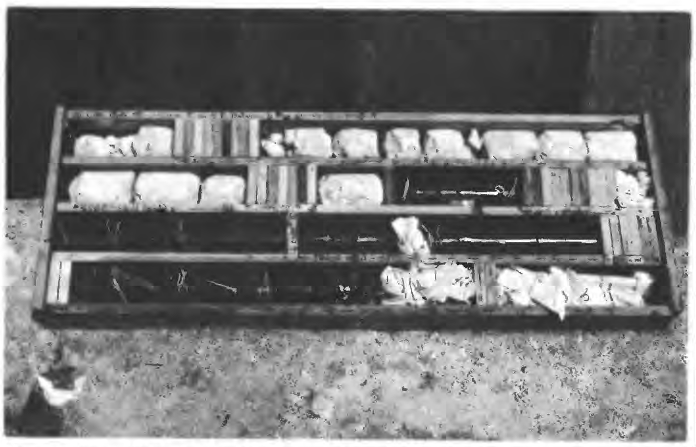

FIGURE 281.—White Eocene limestone and underlying black basalt from 4-inch cores obtained below 4,000 feet on Parry Island.

FIGURE 282.—Outer surface of basalt core showing calcite veins. Scale is in centimeters.

highly altered slivers of rock. Veinlets in the first core are 1 to 14 millimeters thick and are separated by distances of 1 to 8 inches.

The rock of the second basalt core (4,211–4,216 feet) is similar to that of the first, but in the lowest foot the core is so highly fractured, veined, and altered that the orientation of only a few of the larger pieces could be determined with certainty. In the third basalt core (4,216–4,222 feet) relatively massive sections continue to alternate with badly fractured zones, and there is one calcite vein almost an inch thick (about 2.5 centimeters).

In the 14-foot section cored, there are no obvious breaks or changes in lithology or vesicularity that would suggest that more than a single flow had been pierced.

In thin section the massive part of the rock is seen to contain more olivine than is evident in hand specimens. In addition to phenocrysts that range to a maximum size of 3 millimeters in diameter there are many smaller grains not much larger than the pyroxene grains of the groundmass. The following mineral composition was estimated from one thin section of fresh rock.

	Percent
Labradorite	60
Augite	20
Olivine	15
Opaque minerals	5

There is nothing unusual in the properties of the constituent minerals; the rock is a normal Pacific-type olivine basalt. The feldspar laths show a definite flow structure, but thus far no oriented sections have been studied to attempt to determine the angle between the flow layers and the core axis. Figure 283 is a photomicrograph of the fresh basalt.

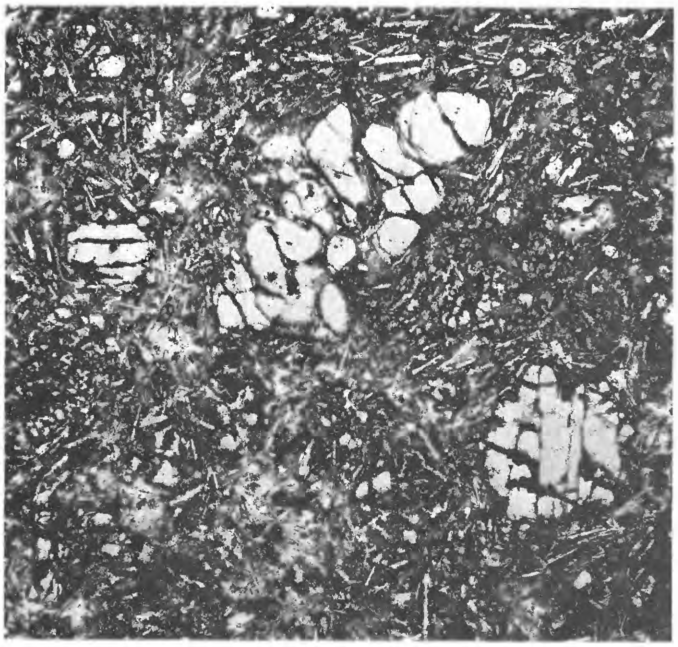

FIGURE 283.—Thin section of fresh basalt showing olivine phenocrysts lightly seamed with saponite. × 20.

Parts of the rock that are intimately veined with calcite also show moderate alteration of the basalt.

Most of the alteration, apart from the formation of carbonate, is saponitic. It is limited almost entirely to the olivine grains near the calcite veinlets. In some places the olivine has been completely altered. Throughout the rock the most common alteration product is a mineral similar to saponite that from its color, birefringence, and indices is probably an iron-rich variety close to griffithite. It is moderately pleochroic from yellow green to green and has a birefringence of about 0.030. Figure 284 shows a photomicrograph of a part of the rock in which the olivine is completely altered.

The occurrence of saponite rather than chlorite indicates that most of the alteration was under ocean-bottom conditions rather than hydrothermal conditions.

TESTS FOLLOWING COMPLETION OF DRILLING

VERTICAL VELOCITY MEASUREMENTS

Following the completion of the deep holes F–1 on Elugelab and E–1 on Parry Island a series of vertical velocity measurements were made by a geophysical party headed by Joel Swartz of the U.S. Geological Survey. Small charges were exploded at varying distances from each drill hole as a geophone was lowered to progressively deeper levels. A final report on the seismic records and their interpretation will appear later.

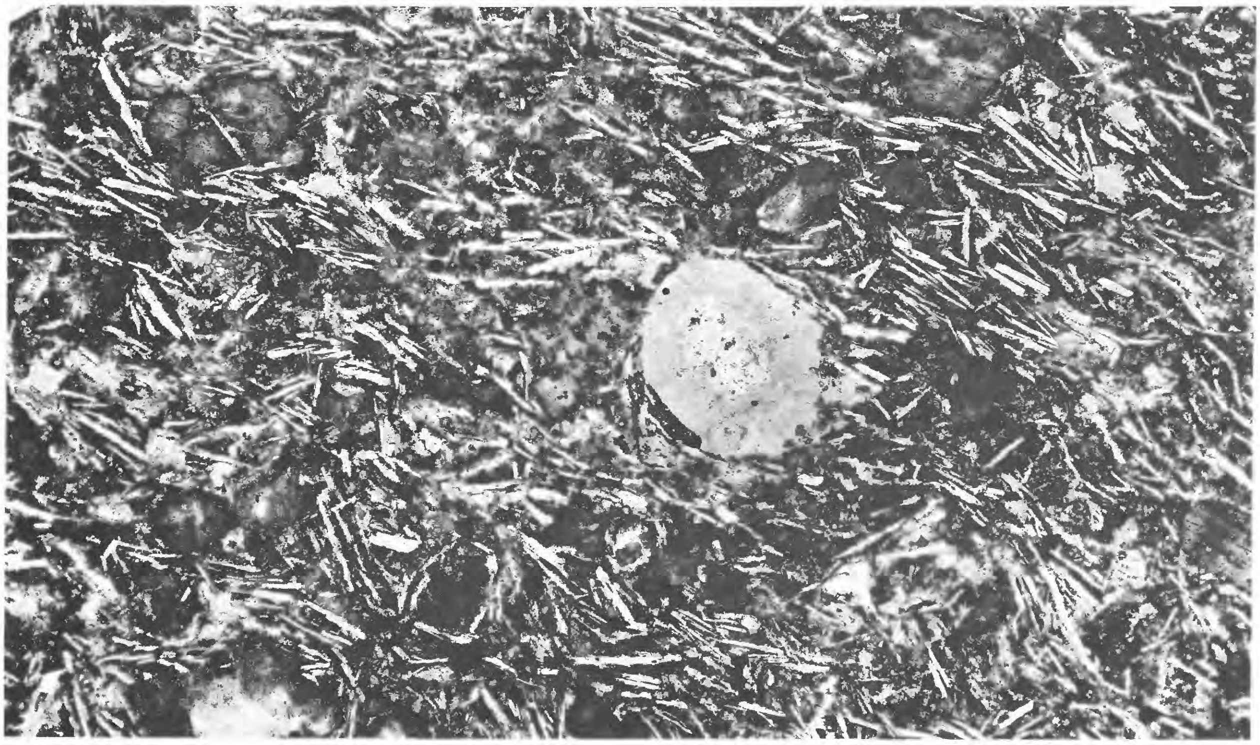

FIGURE 284.—Photomicrograph of section of altered basalt showing olivine phenocryst replaced by saponite. × 35.

TIDAL FLUCTUATIONS

Tidal measurements were made in drill hole F–1 after the completion of drilling. Readings taken on October 19 to 21, 1952, indicated that ebb and flow were in correspondence with the tides as predicted in published tidetables (U.S. Coast and Geodetic Survey, Serial 749, 1951). This result was surprising in view of the fact that the hole was cased solidly from the surface to 1,973 feet. As a check, Kirk Stephenson recorded the drill-hole fluctuations simultaneously with the tidal fluctuations on the ocean side of the island. These measurements indicated a one-to-one correspondence, both in phase and amplitude, with no noticeable time lag. Similar measurements were made on drill hole E–1 by Joel Swartz (1958, fig. 249). This hole, cased to a depth of 4,109 feet, showed a maximum tidal fluctuation of one inch with a lag of approximately 9 hours. These observations support others made during the actual drilling, both indicating that the limestone cap on the volcanic basement is exceedingly porous and cavernous throughout.

THERMAL GRADIENT

Temperatures were read in the deep holes on Elugelab and Parry Island and a thermal cable was maintained in hole E–1 to record the slow establishment of equilibrium. Joel Swartz (1958), who had charge of this work, also made thermal measurements in drill hole 2B drilled on Bikini Atoll in 1947.

STRUCTURE

BASEMENT ROCK

Though the two deepest holes at Eniwetok Atoll were the first to reach the basement rock beneath an atoll, basaltic rocks had previously been dredged from atoll slopes in the Marshall Islands. In 1952—the year the holes were drilled on Eniwetok Atoll—Tayama reported that "black rock, seemingly basalt" had been collected 2,000 meters off Wotje Atoll at a depth of 1,446 meters and to the west of Ailuk Atoll at a depth of 2,486 meters. Both of these atolls are in the Ratak Chain of the Marshall Islands, east of Eniwetok.[3] In 1950 basaltic rocks were dredged from the slopes of Bikini Atoll at depths of 1,000 to 2,010 fathoms (described by Macdonald *in* Emery and others, 1954, p. 120–124).

The deep drilling on Eniwetok, however, firmly established the fact that the foundation of that atoll is a basaltic volcano that rises 2 miles above the floor of the ocean. It thus confirmed one of the most important features of Darwin's subsidence theory, which postulated that atolls may develop on the tops of slowly sinking mountains (Darwin, 1837, 1842). The basaltic foundation and its limestone cap are shown in figure 285. The volcanic basement itself is not a simple one. Hess' early studies showed that the existing atoll appears to rest in part on two guyots whose flat upper surfaces extend out from its southern and northwestern slopes (Hess, 1946, p. 779–781). These observations were taken into account in selecting drill sites. Hole F–1 was located on Elugelab where a guyot adjoins the atoll, hole E–1 on Parry Island where no guyot projects from the atoll.

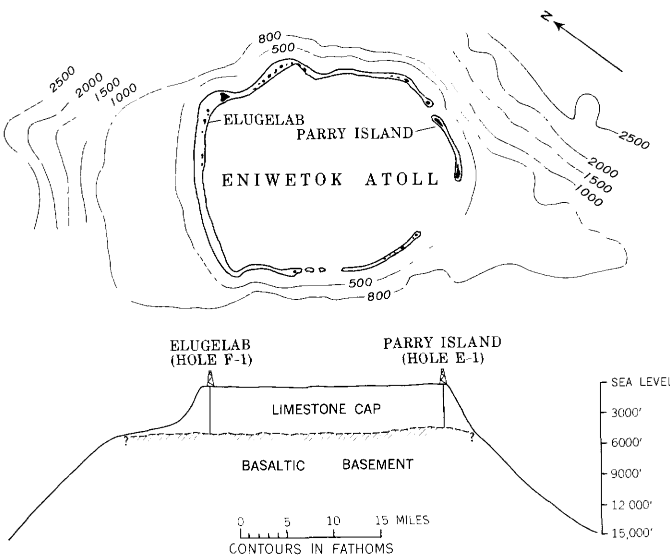

FIGURE 285.—Generalized chart of Eniwetok Atoll and section through Elugelab and Parry Island. Contours from chart prepared by K. O. Emery (Emery and others, 1954, chart 6).

The 14 feet of fractured olivine basalt obtained from the hole drilled on Parry Island apparently formed part of a single flow. Rock of essentially the same type may extend downwards for many hundreds of feet. No pyroclastic material was found, although such material may exist under other parts of the atoll. The exact age of the basalt is uncertain. When volcanic action ceased the summit of the basaltic mound probably projected far above sea level. The first sediments to be laid down were Eocene in age, and they contained reef corals that do not flourish below 150 feet.

OLDER SEDIMENTARY ROCKS

The sedimentary sections in the two deepest holes (F–1 and E–1) were similar to a depth of 1,400 feet and the 1,280 feet of section drilled in K1–B on Engebi Island is much like those of F–1 and E–1. Below 1,400 feet in the two deepest holes there were conspicuous differences in lithologic characters, organic constitution

[3] These figures are given in Tayama's comprehensive bulletin on the Coral Reefs of the South Seas. In the less complete English part of the printed bulletin (p. 267), translated by the U. S. Geological Survey, Tayama mentioned a basalt pebble collected by the survey ship *Kōsū* in 1932 at a depth of only 300 meters on the seaward slope of Wotje. Unfortunately the specimen was lost before being studied in detail.

and the distribution of hard rock and cavities. Some of these differences are shown in plate 265.

As the present report deals primarily with drilling, the 1,400-foot boundary is a convenient one, the rocks below being referred to as the older sediments, those above as the younger. As thus drawn, the boundary falls several hundred feet below the top of the lower Miocene.

In hole F–1, a section of soft chalky beds more than 1,000 feet thick was penetrated, starting at 2,900 feet. It was recognized in the field that this unusual section had no counterpart in hole E–1, 22 miles to the southeast (Ladd, Ingerson, Townsend, Russell, and Stephenson, 1953, p. 2262–2263), but a satisfactory explanation was not forthcoming until cores were examined by Todd and Low. The cores from the soft section were identified as *Globigerina* limestone of late Eocene age (Todd and Low, in press). Drilling showed that the basement rock lay 450 feet lower on the northwest under Elugelab (F–1) than under Parry Island (E–1) to the southeast. It is probable, as Todd and Low suggest, that the *Globigerina*-rich sediments of the northwest were deposited on an outer slope in waters appreciably deeper than those to the southeast. These initial differences persisted until Miocene time.

YOUNGER SEDIMENTARY ROCKS

The younger sedimentary rocks of Eniwetok are better known and better understood than the older sedimentary rocks below them: they are better known because of more nearly complete collections of cores and cuttings from a larger number of drill holes; better understood because the fossils are better preserved and more closely related to types living today than are those found in the older limestones. Lagoonal conditions comparable to those existing today appear to have prevailed at Eniwetok during Tertiary and later times as they did at Bikini 190 miles to the east (Emery and others, 1954, p. 132–152). The Eniwetok section has been tied closely to that of Bikini, most horizons on Eniwetok lying some 100 feet lower than those of Bikini (Cole, 1958, p. 5; Todd and Low, in press).

In both places there appear to have been times when the tops of the atolls stood above the sea for appreciable lengths of time and the shells and skeletons of aragonite-secreting organisms were largely leached or recrystallized to calcite (Ladd, Tracey, and Lill, 1948, Ginsberg, 1957, p. 95–96). Both places have yielded "high-island" land shells (*Ptychodon*) (Ladd and Tracey, 1957; Ladd, 1958) and Estella B. Leopold of the Geological Survey has obtained from the Miocene of Eniwetok, moderate to very dense concentrations of pollen along with spores and other types of plant material—assemblages such as are found in dense, tropical, deciduous forests. These several types of evidence indicate that at both Eniwetok and Bikini the overall history of subsidence was interrupted by periods of emergence.

The drilling on Eniwetok and Bikini seems to indicate that most of the younger sediments are soft and poorly consolidated, resembling deposits that are forming today under lagoonal conditions. It is doubtful, however, if such masses of unconsolidated materials could have accumulated and maintained themselves on a slowly subsiding foundation without some sort of a rigid containing framework. Not much is known about this postulated framework, but it is interesting to speculate about its nature and its importance in atoll development.

The seaward margin of the existing reef, where corals and other skeletal materials are closely bound together by encrusting algae and Foraminifera, appears to be one of the most resistant parts of the reef but the shallow holes put down on the reef flat of Eniwetok indicate that a plate of solid rock may exist beneath the reef flat. It has been assumed that some sort of a solid rimlike structure extends downward from the outer margin of the reef, but this has never been confirmed by drilling nor has the existence of hard rock at depths of more than a few feet below the main reef flat been confirmed. Much of the hard rock beneath the flat has been cemented by intergranular films of drusy calcite, possibly at intertidal levels, but the process is not clearly understood.

Two processes, then, cementation by organisms and cementation by chemically precipitated calcite, appear to be responsible for the hardness of much of the reef surface. A third process, recrystallization and lithification of fine "mud" during periods of emergence, may be responsible for the indurated state of zones that now lie below the reef surface. The effects of emergence are clearly shown by coral islands that today stand well above the sea. In eastern Fiji Islands, for example, there are many islands composed of Tertiary and younger limestones directly comparable to those revealed by drilling beneath Eniwetok and Bikini. Some of these islands clearly were atolls at an earlier stage, others are composed entirely of bedded foraminiferal limestone. Regardless of age or organic composition, however, these islands now show basin shapes (Ladd and Hoffmeister, 1954, p. 167–170). In some cases this shape is a carryover from an atoll stage, in others the basin shape may be the result of subaerial erosion and solution. The limestones composing the islands, particularly those that are rich in corals and algae, are cavernous, recrystallized, and hard, at least on the surface. Many of the steep rims of the basin-shaped islands and the stacks that lie inside the basin are composed of hard limestone that rings under the hammer. In other places only the surface is hardened. The hardened zone may be thick or so thin that the rock seems almost to explode when struck with a hammer. Most of the elevated reef islands of the Fiji Islands are smaller than the Marshall Islands atolls but are believed to be directly comparable in all other respects. Owing to emergence, exposure of the limestone to rainwater has resulted in solution of original material followed by interstitial redeposition of calcite cement, recrystallization, and lithification. Thus the limestone may be made harder but cavernous.

The existence of a rim of hard rock beneath Eniwetok, due in part at least to lithification under subaerial conditions, could be determined only by extensive drilling on the reef. Most of the holes put down to date are not close to the rim. The nearest approach is RU–2 on the island of Runit where the reef is exceedingly narrow (fig. 260). This hole showed a higher percentage of hard rock than any of the other shallow holes and may have been drilled through the postulated rim. Drill hole 3 on Bikini located nearest to the reef rim and showing a comparatively high percentage, of hard rock, may be similarly explained (Emery and others, 1954, p. 83–84).

COMPARISON WITH OTHER DRILL HOLES

The first deep drilling on a Pacific atoll was a hole completed at 1,114 feet on Funafuti in the Ellice Islands in 1898 (David and others, 1904). In 1936 the Japanese cored a hole to a depth of 1,416 feet on Kita-daitō-jima (North Borodino), a small island south of Japan and east of Okinawa (Hanzawa, 1940). The first drilling in the Marshall Islands was done in 1947, the last on Eniwetok in 1952. The above locations are shown in figure 286 and a summary of results is given in figure 287. A preliminary comparison of dolomitized zones beneath Kita-daitō-jima, Funafuti, and Eniwetok (Schlanger, 1956) showed no correlation between the zones from atoll to atoll. Further, textural differences in the dolomitized limestones suggest that the dolomite formed in several ways.

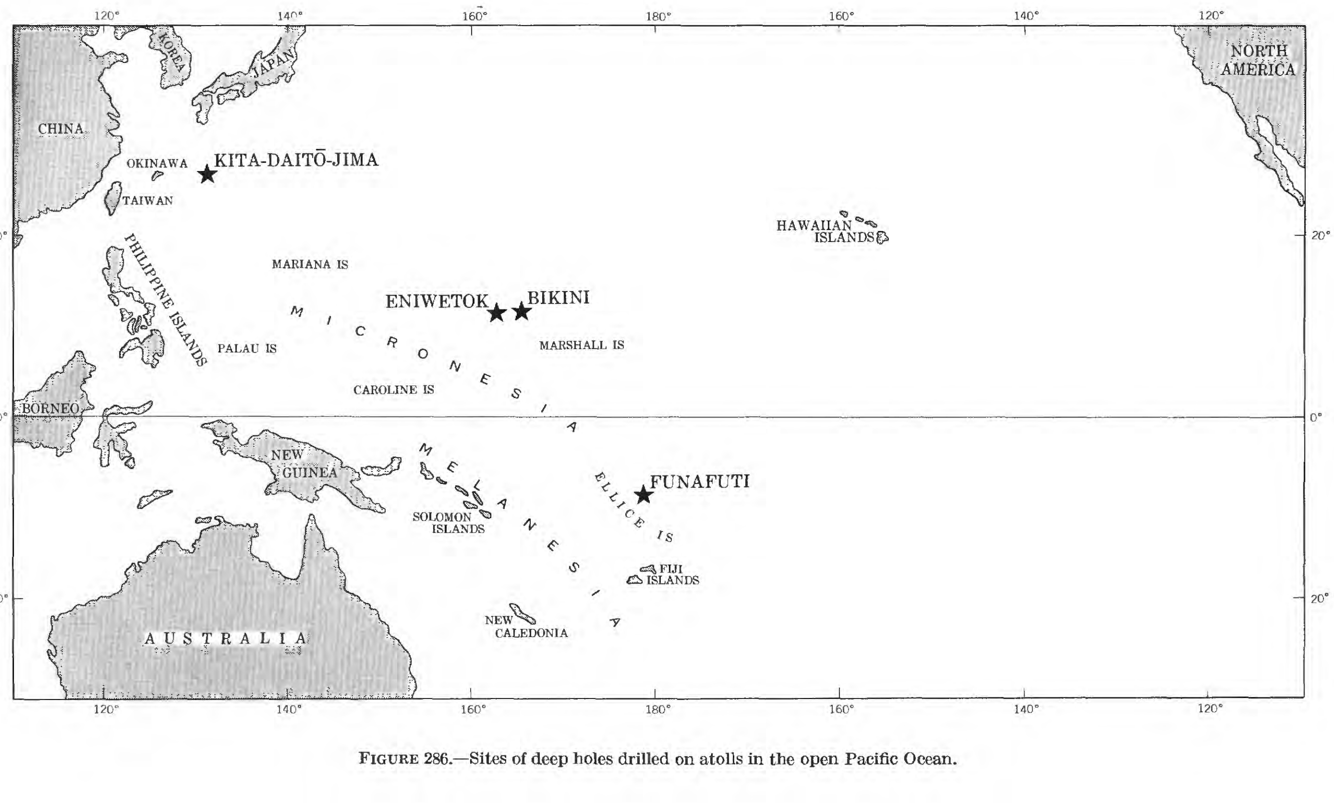

FIGURE 286.—Sites of deep holes drilled on atolls in the open Pacific Ocean.

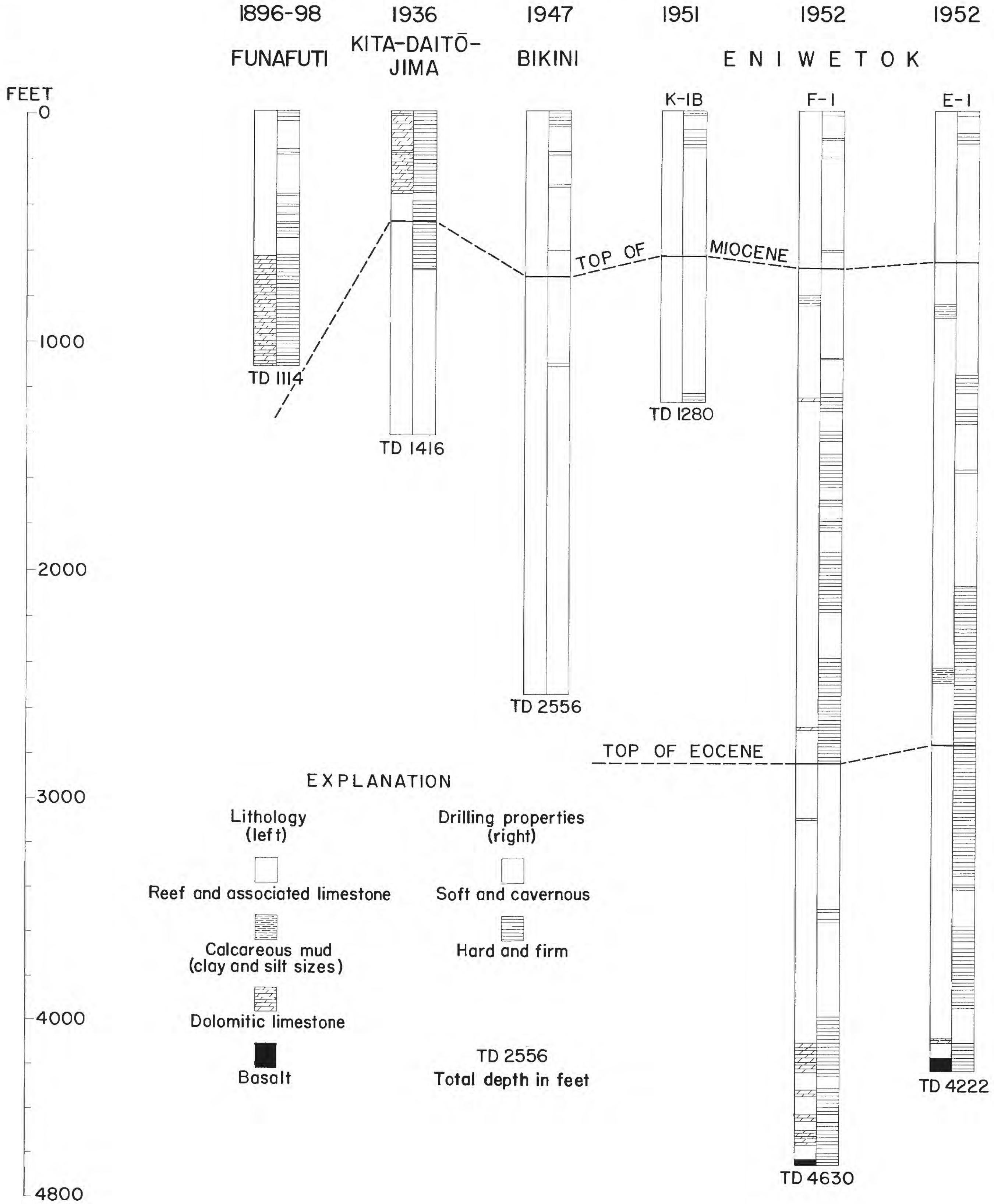

FIGURE 287.—Summary of results of deep drilling on atolls in the open Pacific Ocean.

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[Asterisks indicate names referred to throughout report]