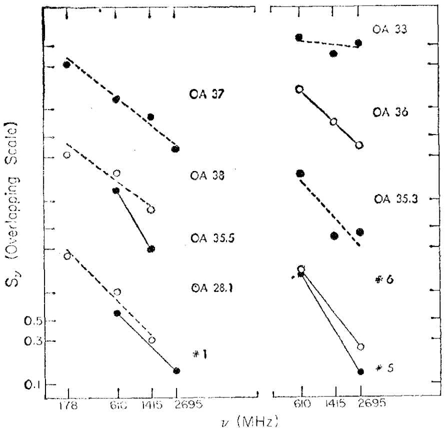

Fig. 2. Spectra of sources. Spectra are arbitrarily displaced for clarity.

gion. Following this line of reasoning one finds the average spectral index within the optical outline of M31 to be −1.4 and outside the optical outline to be −0.9. If one omits the source OA33, which is anomalous, the average index outside the optical outline is −1.1.

Source OA33 has a flat spectrum, similar to the spectra of thermal sources and many quasars. Preliminary measurement at Green Bank at 6-cm wavelength gives a flux density for OA33 of 0.5 flux unit (*9*).

No obvious HII region in the area of OA33 is visible on the atlas prints from the 48-inch (1.2-m) Palomar telescope. This source deserves further study.

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10. Support for R.C.C. was supplied by grant Nonr 1834(22). The National Radio Astronomy Observatory is operated by Associated Universities, Inc. under contract with the National Science Foundation.
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13 March 1967

Drilling on Midway Atoll, Hawaii

Abstract. *Two holes drilled through reef sediments into basalt have established a geologic section through the Miocene. Midway was built above the sea by flows that were weathered and partially truncated in pre-Miocene time. After submergence, volcanic clays were reworked and covered by limestones. Overall submergence was interrupted at least twice by emergence. The limestones have been leached, recrystallized, and partially dolomitized.*

Midway atoll and its neighbor Kure, at the northwest end of the Hawaiian chain that stretches for 1600 miles (2550 km) across the central Pacific (Figs. 1 and 2), have long been regarded by geologists as the oldest members of this island group. Field evidence suggests that volcanism was initiated on the northwest, progressing southeastward to the Island of Hawaii, where volcanic activity still persists (*1*). As lavas were piled upon the sea floor to form the first islands, the load depressed the crust and the islands slowly subsided. This apparently was a slow process; coral reefs capping some of the former islands were able to maintain their tops near sea level by growing upward. Thus the islands at the northwest end of the chain are now atolls: the younger islands to the southeast are composed of volcanic mountains fringed with coral reefs. If such, in brief, has been the history of the Hawaiian Islands, there should be a geologic section beneath the reef islands recording much of Hawaii's history. To test this postulated history, Ladd proposed in 1960 that a deep hole be drilled on Midway, this atoll being selected over its neighbor Kure for logistical reasons.

Before the expensive process of drilling was attempted, seismic and magnetic surveys were carried out to determine the approximate thickness of the postulated cap of reef rock. Two brief seismic surveys were made by George Shor and his associates of the Scripps Institution of Oceanography. The first, strictly a land survey along the south side of Sand Island, was made in 1963 (*2*); the second survey was made in the lagoon, in December 1964, specifically to determine the thickness of coral beneath the northern part of the lagoon (*3*), where a magnetic low had been reported by the Naval Oceanographic Office (Project Magnet) (*4*). The geophysical surveys indicated the presence of a significant section of sediments beneath the islands on the south, with a progressive thickening northward under the lagoon.

Two holes were drilled during the summer of 1965 (Fig. 1). The first, on Sand Island, entered basalt at 516 feet (1550 m) and was continued to 568 feet. The second, the Reef hole, was drilled from a barge resting on the northern edge of the lagoon floor. It entered basalt at 1261 feet and was continued to 1654 feet. In each hole some 400 feet of post-Miocene limestones were penetrated, below which was a thin zone of upper Miocene (Tertiary *g*) sediments. In the Reef hole the upper Miocene sediments were underlain by approximately 500 feet of lower Miocene limestones (Tertiary *e*), and these, by about 170 feet of reworked volcanic clays, some lignitic, also of early Miocene age.

The drill was a truck-mounted Failing Model 2500 with reinforced tower (*5*). Cuttings and cores to a depth of 70 feet were taken with rock bit and conventional diamond core barrel. At depths greater than 70 feet a rubber-sleeve core barrel, yielding a 3-inch (7½-cm) core, was used almost exclusively. In the deeper of the two holes, three 1-inch oriented cores were taken (*6*). The size and amount of casing used and the amounts of core recovered are shown in Table 1. Sea water was used as drilling fluid with salt-water mud.

The first hole was drilled on Sand Island without difficulty. The geophysical surveys had indicated a thickening of the section to the north under the lagoon; consequently the site for the second hole was a flat sandy area just inside the reef on the north side of the lagoon, where the depth of water at high tide was 8 feet. This site was cleared of minor coral growth, and a course through the coral-studded lagoonal terrace was mapped by divers and marked with buoys.

The drill and all equipment, weighing 120 tons, were loaded aboard a steel barge measuring 120 by 30 feet. The barge, furnished by the U.S. Navy, was then towed to the drill site by a Navy LCM. After being jockeyed into position at the drill site, the barge was pumped full of sea water so that it settled to rest firmly on the sand bottom (Fig. 3). The drill tower, when raised, was guyed to nearby massive coral heads and steel piling.

The sediment sections cored on Midway are calcareous except in zones near the contact with the underlying basalts. The upper 200 feet in each hole is composed of unlithified material consisting mostly of aragonite and magnesian-calcite ($MgCo_3$, 12 to 16 percent, molar). Below 200 feet, calcite dominates, and much of the limestone is hardened by recrystallization. In the Reef core, parts of the limestone section are dolomitized. Below the calcareous section in both holes are zones of reworked volcanic clays, some of them calcareous, along with a few thin seams of lignitic clay and beds of basalt conglomerate. These relations are shown in Fig. 4 (*7*) and are briefly described in Table 2.

Table 1. Summary of depths, casing, and core recovery.

Hole	Depth (feet)	Casing (feet)	Footage cored (rubber sleeve) (feet)	Core recovery (feet)	Core recovery (%)
Sand Island	568	122*	481.5	346.85	72
Reef	1654	190†	1358.5	1254.8	92
		800‡			

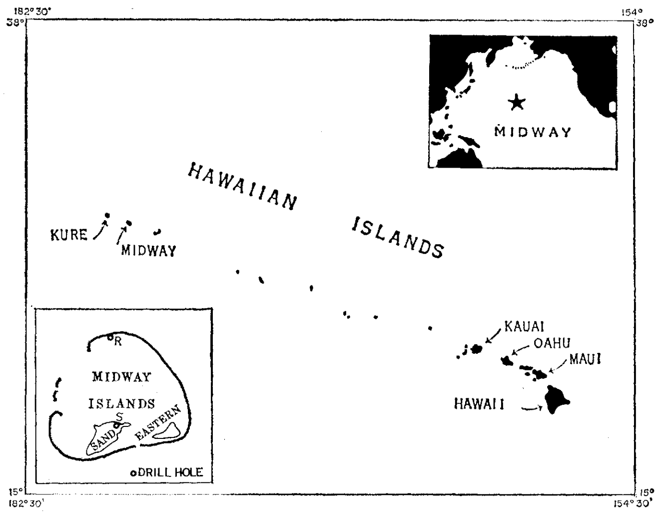
* Casing diameter, 12¾ inches. † Casing diameter, 16 inches. ‡ Casing diameter, 12 inches.

In the Reef core, dolomite and dolomitic limestone occurred at intervals between 426 and 930 feet; the 64-foot section from 426 to 490 feet is almost solid dolomite. Calcium-rich dolomite occurs as isolated crystals and in orange-colored crusts of crystals from 560 feet to 811 feet. We found no evidence that dolomite is forming on Midway today (*8*).

Preliminary determinations of the ages of the sediments in the cores are based primarily on the occurrence of diagnostic Foraminifera. Cole is studying the larger forms; Ruth Todd and Doris Low, the smaller ones. Their findings to date are summarized below.

Cole states (*9*):

Five species of larger Foraminifera were recovered. In the lower part of the Reef hole two zones of larger Foraminifera were encountered. The upper zone had abundant specimens of *Miogypsinoides dehaartii* (van der Vlerk), and *Austrotrillina striata* Todd and Post, and was followed by a zone of *Spiroclypeus margaritatus* (Schlumberger). These three species are known markers for upper Tertiary *e* (early Miocene) in the western Pacific. This low-



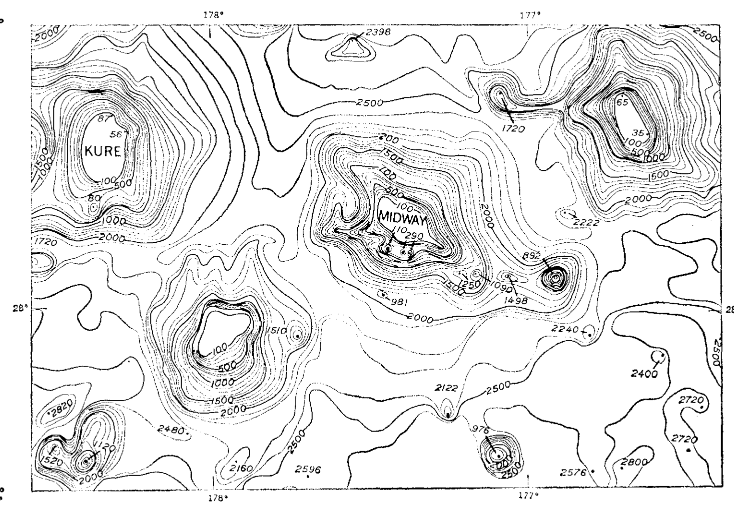


Fig. 1 (above). Location of Midway and of the holes drilled.

Fig. 2 (above right). Bathymetric chart of Midway area; depths are given in fathoms. [U.S. Naval Oceanographic Office]

Fig. 3 (right). Drill rig on steel barge resting on lagoon floor in 8 feet of water near the northern edge of Midway's lagoon. The lighter areas around the barge are sand; the darker areas are living corals and algae. The dark-bordered irregular areas (upper left) are eroded remnants of an older reef now several feet above sea level. Beyond the old reef lies a narrow reef platform on which the waves of the open sea are breaking. [Photograph by Commander N. R. Wooden, U.S.N.]

er section is correlated with sections in the Kita-Daitō-Jima (North Borodino Island), the Bikini and Eniwetok holes, and with surface outcrops of Saipan, Guam, and Borneo.

In the upper part of the drill holes *Heterostegina suborbicularis* d'Orbigny, *Marginopora vertebralis* Quoy and Gaimard, and *Sorites orbiculus* (Forskål) were recovered. These species with a known, relatively long stratigraphic range in the Indo-Pacific region are not especially diagnostic, except to suggest that the sediments in which they occur are Tertiary *e* (early Miocene) or younger.

Ruth Todd and Doris Low recognize several assemblages of smaller Foraminifera. They report (*10*):

> The reworked clays that underlie the limestones in the Reef hole contain a fauna fairly rich in specimens but poor in species (total 19). The age appears to be early Miocene (Tertiary *e*). The assemblage is dominated by bolivinids and buliminids, is definitely marine and was probably deposited in shallow, relatively calm water, near shore or within a lagoon. . . .
>
> In the lower part of the deeper hole we find *Austrotrillina*, a genus believed to have become extinct in the early Miocene (Tertiary *e*). Its presence at Midway is noteworthy because it is unknown in North or South America and thus far has been reported only from the Tethys basin, from Spain through the Near East, and into Australia and the western Pacific (Saipan, Eniwetok, Bikini). . . .
>
> Near 450 feet in both cores, the presence of *Valvulammina marshallana* Todd and Post and other forms suggests a correlation with beds assigned to the late Miocene (Tertiary *g*) at Bikini and Eniwetok. . . .
>
> Rich and varied assemblages of smaller Foraminifera occur in the post-Miocene sediments at both sites.

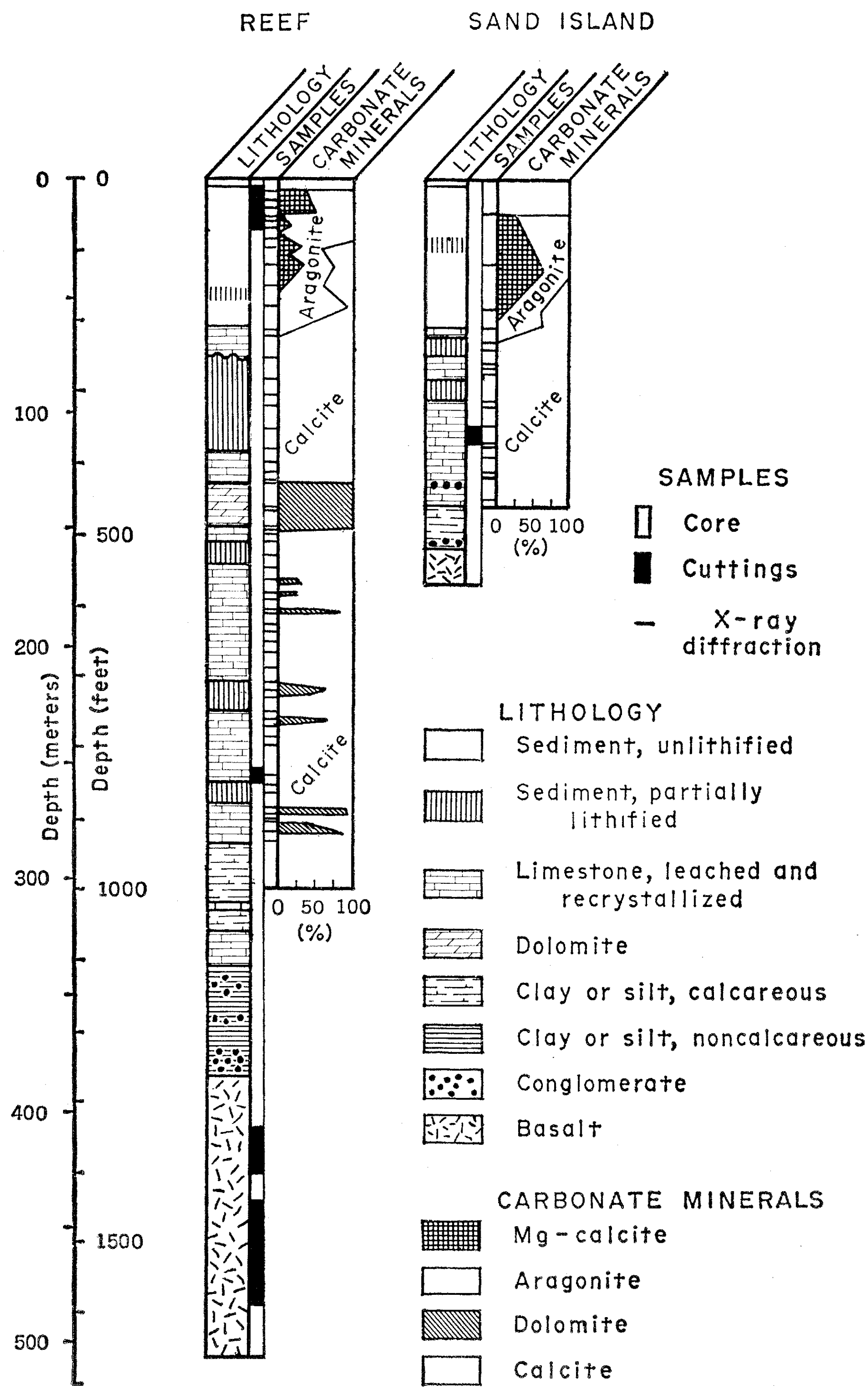


Fig. 4. Preliminary logs of drill holes showing lithology, core recovery, and carbonate-mineral composition (*7*).

Hazel (*11*) reports that many cores from both sites have yielded large numbers of ostracods, particularly hemicytherids, bairdiids, and loxoconchids. These are not of immediate value in determining the age of the deposits, as no information is available on the fossil ostracods of the islands of the open Pacific. Five assemblages are recognized, their generic composition suggesting early Miocene to Quaternary ages. All assemblages are normal marine assemblages except those from certain beds in the middle part (137 to 260 feet) of the Sand Island core, where the brackish-water ostracod *Cyprideis* occurs in abundance. The limestones containing this fauna were probably deposited in a mesohaline lagoon.

The corals that are an important constituent of the existing reefs were at least equally important in earlier periods of Midway's history. Wells, who is studying both the living reef corals and the fossils from the cores, states (*12*) that the Recent reef coral fauna of Midway is slightly attenuated, as would be expected from its latitude (28°14′N) and its position as an outpost of the Hawaiian fauna. Of the 15 coral genera known to live in more southerly parts of Hawaii, nine occur at Midway. Most of the genera are widely distributed in the Indo-Pacific, to the outer limits of the tropical zone. The six Recent genera from Hawaii that have not been found at Midway are exceedingly rare in the Hawaiian Islands. The Miocene coral fauna, according to Wells, was more diversified than later assemblages, suggesting a more favorable regime.

Reef-building coralline algae, like the reef corals, appear to have been at least as important in the early history of Midway as they are today. Other less abundant groups of fossils—brachiopods, echinoids, bryozoans, and crustacea—are all represented in the cores and are being studied. It is hoped that much may be learned about the vegetation of Midway during Miocene and later times from an examination of the several lignitic zones.

In the upper 200 feet of the post-Miocene section, the mollusks are well preserved, many retaining traces of their original color pattern. They represent reef and lagoon assemblages that are somewhat restricted in number and variety, as is the fauna found on the atoll today. Included, however, are some interesting occurrences. In the Sand Island hole at depths of 175 to 180 feet, for example, three shells of a species of *Pisulina* were recovered. This neritid is known only from a few species living today in India and Ceylon and from one fossil species recovered from beds of late Miocene (Tertiary *g*) age in a drill hole on Bikini Atoll (*13*).

Also in the Sand Island hole, at depths of 137 to 165 feet, eight specimens of a minute land shell, *Ptychodon*, were found, and a single specimen of a larger and distinctly different species of the same genus was recovered from the Reef hole at a depth of 116 to 130 feet. Land snails of this type do not live on existing atolls but they are widely distributed on high volcanic islands and on limestone islands rising 200 feet or more above the sea (*14*).

In the recrystallized and partly dolomitized limestones below 200 feet, larger mollusks are fairly abundant, but most of them are poorly preserved as molds or calcite casts. Like the young-

Table 2. Description of cores and cuttings from the Sand Island hole and the Reef hole.

Sand Island hole		Reef hole	
Depth*	Description	Depth†	Description
9–36 (0–6.0)	Fill, coral-algal sand, and gravel		
36–208 (6.0–58.4)	Sediment, unlithified, with coral-algal fragments and soft calcareous mud; land snail shells at 116 to 130 feet; brackish water ostracods at 137 to 208 feet; *Pisulina* sp. at 175 to 180 feet	16–210 (1.7–60.8)	Sediment, unlithified, and coral-algal limestone; minor lithification at 150 feet; possible soil zone at 77 feet; land snail shell (*Ptychodon*) at 116 to 130 feet
208–337 (58.4–97.7)	Limestone, partially leached and recrystallized, and partially lithified calcareous sand and mud; aragonitic shells at 238, 243, and 258 feet may be derived from younger deposits above; brackish-water ostracods *Cyprideis* at 208 to 260 feet, very abundant at 242 to 259 feet	210–296 (60.8–87.0)	Limestone, partially leached and recrystallized and partially lithified calcareous sand
		296–386 (87.0–114.4)	Partially lithified calcareous mud and sand; some solution features
337–443 (97.7–130.0)	Limestone, leached and recrystallized and partially lithified calcareous sand; basalt pebbles at 428 to 443 feet	386–426 (114.4–126.6)	Limestone, friable, algal-foraminiferal
		426–489 (126.6–145.8)	Dolomite, algal-foraminiferal, leached and recrystallized
443–460 (130.0–135.2)	Limestone, brown, recrystallized irregularly lithified calcareous sand near base; Foraminifera: *Valvulammina marshallana* at 445 to 446 feet		
460–502 (135.2—148.0)	Volcanic marl; oyster shells in green clay at 483 to 484 feet	489–563 (145.8–168.5)	Limestone, dolomitic, leached and recrystallized and partially lithified sand; porcellanous dolomite at 489 to 505 feet; Foraminifera: *Valvulammina marshallana*, *Asterigerina tentoria*, and *Cribrogoesella parvula* at 495 to 500 feet
502–516 (148.0–152.2)	Sandy basalt conglomerate; green clay and many mollusk impressions, probable base of marine section at 502.4 feet		
516–568 (152.2–168.1)	Basalt, dark gray, palagonite and calcite in vesicles	563 (168.5)	Carbonaceous clay
		563–711 (168.5–213.5)	Dolomitic limestone, leached and recrystallized; brown sparry calcite abundant; dolomite occurs as rhombs. Foraminifera: *Miogypsinoides dehaartii* at 590 to 600 feet
		711–751 (213.5–225.7)	Partially lithified dolomitic sand; dolomite occurs as rhombs
		751–845 (225.7–254.3)	Limestone, leached and recrystallized; dolomite rhombs in cavities
		845–885 (254.3–266.5)	Partially lithified calcareous sand and mud
		885–934 (266.5–281.5)	Dolomitic limestone; orange dolomite rhombs; clay layer, reddish brown at 914 feet; partially lithified dolomitic sand, argillaceous at 925 to 930 feet; Foraminifera: *Miogypsinoides dehaartii* at 901 to 906 and 926 to 927 feet, *Austrotrillina striata* at 901 to 927 feet
		934 (281.5)	Gray-to-black carbonaceous clay
		934–995 (281.5–300.1)	Tuffaceous limestone leached and recrystallized; Foraminifera: *Miogypsinoides dehaartii* at 946 and 956 feet, *Spiroclypeus margaritatus* at 960 to 961 feet
		995–1121 (300.1–338.5)	Reworked volcanic clays; some carbonaceous silt and clay layers; Foraminifera: abundant *Amphistegina* at 1045 feet, *Spiroclypeus margaritatus* at 1029 to 1091 feet, *Austrotrillina* sand at 1117 feet
		1121–1261 (338.5–381.4)	Volcanic clay, variable color; basalt conglomerate layers abundant; brown clay with small Foraminifera and ostracods at 1165 feet; lignitic clay layers at 1242 and 1255 feet
		1261–1654 (381.4–500.9)	Basalt, dark gray, vesicular

* Depths of top and bottom of core, in feet below drilling platform, which was 16.5 feet (5.0 m) above mean lower low water; figures in parentheses are depths in meters below mean lower low water. † Depth in feet below drilling platform, which was 10.5 feet (3.2 m) above mean lower low water; figures in parentheses are depths in meters below mean lower low water. Water depth at drilling site was approximately 5.5 feet below mean lower low water.

Table 3. Deep drilling on atolls in the open Pacific Ocean.

Place and date	Latitude	Total sediments	Ages	Stratigraphic intervals: Post-Miocene section	Tertiary *f*	Tertiary *e*	Amount of lithification	Dolomitization	Faunal sequences*	Solution unconformities†
Ellice Islands:										
Funafuti, 1896–98	8°30′S	1114+	Pleistocene to Recent	1114+			Extensive	Extensive	Absent	Present
Kita-Daito-Jimō, 1936	26°N	1416+	Tertiary *e* to Recent	340	Absent	1076+	Moderate	Extensive	Present	Not recognized
Marshall Islands:										
Bikini, 1947	11°30′N	2556+	Tertiary *e* to Recent	700	186	1390+	Slight	None	Present	Present
Eniwetok, 1951–52	11°35′N	4610	Tertiary *b* to Recent	615	220	1700	Moderate	Slight	Present	Present
Midway, 1965	28°N	1261	Tertiary *e* to Recent	462	Absent	501, limestone; 110, clay	Extensive	Moderate	Present	Present

*See *18*. †See *19*.

er mollusks they represent assemblages of reef and lagoon genera. The clays and tuffaceous beds below the limestones contain a few layers literally covered with fragile mollusk impressions, and other beds of heavy oyster shells record brackish conditions.

The sediments drilled on Midway rest on a series of weathered basalt flows. Depths to the basalt are greater on the north side of the atoll than on the south. Probably Midway's volcanic foundation was partially truncated by wave action on the northeast or windward side before the mound was completely submerged and covered by sediments. This northward thickening of the sediment section, indicated by preliminary seismic and magnetic surveys, was confirmed by drilling. The sediment thicknesses drilled were only about half the thickness predicted by geophysical means (*15*).

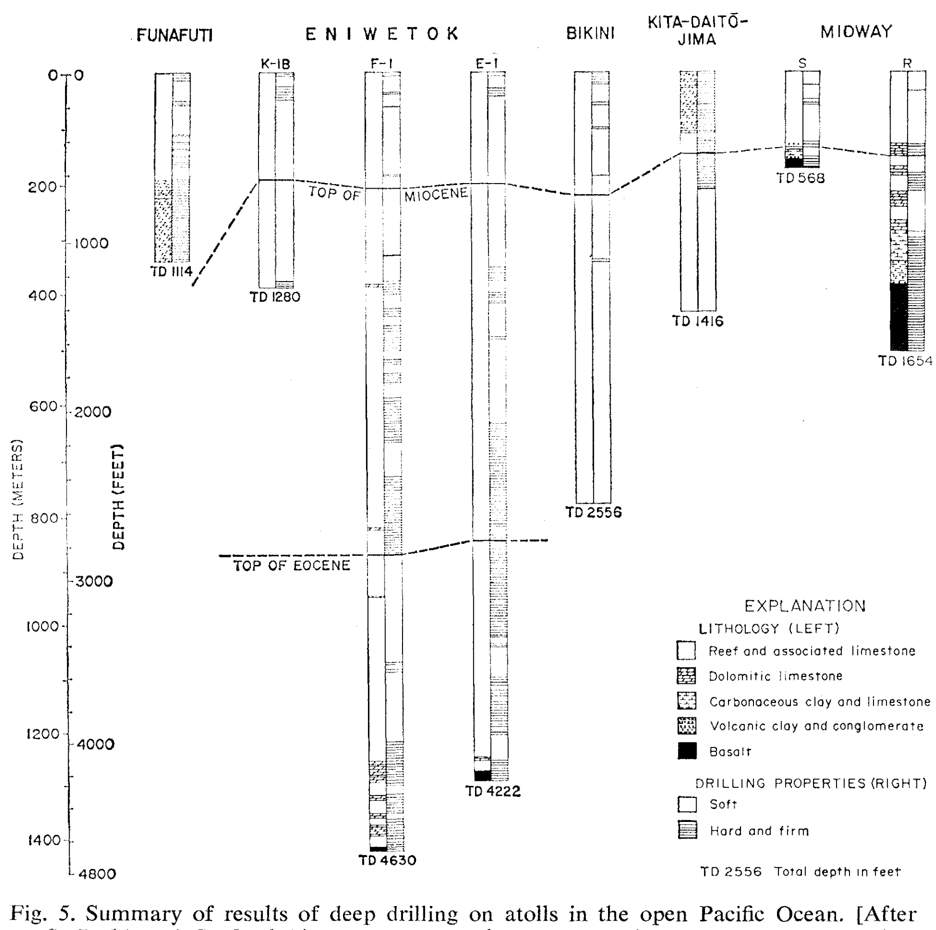


Fig. 5. Summary of results of deep drilling on atolls in the open Pacific Ocean. [After H. S. Ladd and S. O. Schlanger, *U.S. Geol. Survey Profess. Paper 260-Y* (1960), fig. 287]

The bathymetric chart (Fig. 2) indicates that volcanic material was erupted from a number of vents in the vicinity of Midway and Kure. If the resulting seamounts ever reached the surface or were capped by reefs, they have since been truncated by wave action. One prominent seamount, comparable in size to Midway, lies to the northeast; others lie to the southwest.

All flows reached by the drill under Midway appear to have issued from vents on land or in very shallow water. Vesicular zones are well developed, and no pillow structures have been recognized. Macdonald, who has made a preliminary examination of all volcanic cores, states (*16*) that in gross petrographic features the Midway basalts closely resemble subaerial flows exposed on the island of Oahu.

In an attempt to determine the age of the basalts, samples from three of the freshest-looking cores from the Reef hole were submitted to Marvin A. Lanphere of the U.S. Geological Survey for potassium-argon age determinations. Two of these samples looked promising, as they contained no devitrified glass or alteration minerals in the groundmass. The age of one sample from a depth of 1594 feet (333 feet below the top of the basalt) is 15.7 ± 0.9 million years. That of the second sample, from a depth of 1600 feet (330 feet below the top of the basalt) is 16.6 ± 0.9 million years. There is no reason to believe that the dated basalts analyzed represent younger material injected into the basalt sequence as dikes or sills. The basalts above and below the samples tested do show evidence of weathering, and apparently the samples selected had also lost argon during weathering.

Midway is the fifth open-sea atoll to be studied by deep drilling and the second atoll whose limestone cap has been completely penetrated. Certain stratigraphic features of the sedimentary sections drilled are listed in Table 3 and represented graphically in Fig. 5.

The post-Miocene limestones at Midway and at Kita-Daitō-Jima are thinner than those in the Ellice and Marshall Island areas. This is of interest in that both Midway and Kita-Daitō-Jima lie outside the tropics in what may be called the marginal zones of present reef growth. Funafuti, which lies closest to the equator, has by far the thickest section of post-Miocene rocks. These differences suggest that the varied reef assemblages of the tropics lead to a more rapid rate of reef growth, but the controlling factors probably are rates of subsidence and duration of periods of emergence. Neither the Midway nor the Kita-Daitō-Jima sections contain any sediments formed during Tertiary *f*. Both atolls may have been above the sea and undergoing erosion during this part of the early Miocene.

The limestone sections drilled on Midway (Fig. 5) resemble those in the two deepest holes (E-1 and F-1) drilled on Eniwetok in that they contain appreciable thicknesses of hard and firm recrystallized reef rock, but they differ from those sections in that they contain no intervals of aragonitic sediments below the recrystallized limestones. The partially dolomitized carbonate section in the Reef core from Midway is intermediate between the extensively dolomitized sections at Funafuti and Kita-Daitō-Jima and the slightly dolomitized section at Eniwetok. Dolomite was not detected in the carbonate section at Bikini.

The Midway sections contain beds of volcanic clay and conglomerate. The 170-foot section of bedded volcanic and lignitic clays found below the limestones in the Reef core on Midway have no counterpart in the other atoll sections.

At Midway, basaltic lavas were poured out to build a mound rising nearly 3 miles above the ocean floor. The exact date at which the mound reached the surface is not known, but the subaerial or shallow-water lava flows that cap it were weathered and at least partially truncated by wave action prior to the Miocene.

In the early Miocene (Tertiary *e*) the northern part of the eroded mound was covered by swamps. The mound subsided, and the swamps were covered by shallow marine waters in which ostracods and smaller foraminifera lived on a muddy bottom. Altogether, 170 feet of lignitic beds and clays were accumulated.

As the waters cleared, reef corals and calcareous algae became established on the reworked volcanic clays, moving in, probably, from a more northerly site to windward. As subsidence continued, 500 feet of reef limestone were accumulated, apparently under lagoonal conditions. Water circulation may at times have been restricted, permitting the formation of dolomitizing solutions (*8*).

At or near the end of Tertiary *e*, the reef emerged, and the entire limestone section stood above water during Tertiary *f*. The limestones were thoroughly leached and recrystallized. Resubmergence followed in the late Miocene (Tertiary *g*), and more than 100 feet of shallow-water lagoonal limestones were deposited. These deposits covered the altered limestones on the north side of the atoll and the higher area to the south. This interval of limestone deposition appears to have continued into the Pleistocene.

Altogether, about 250 feet of post-Miocene beds were accumulated before there was another major interruption. This change—like the one that interrupted the early Miocene sequence—was caused by emergence of the atoll. In this instance the withdrawal may have been due to the eustatic lowering of the sea caused by Pleistocene glaciation. It may be possible to tie the 200-foot solution unconformity of Midway to the extensive submarine platform lying 180 feet below sea level off the island of Molokai and elsewhere in Hawaii (*17*). During this period of emergence the newly formed limestones were leached and recrystallized.

When subsidence recommenced, the altered limestones were covered by about 200 feet of reef and lagoonal sediments. These beds have not been emergent for long periods and exhibit no evidence of leaching or extensive recrystallization.

The last recorded event was the growth of a now-emergent reef, remnants of which are found on most of Midway's rim (Fig. 3). This reef apparently flourished when the sea stood several feet higher than it does now. The earliest date obtained in several carbon-14 determinations made on the exposed reef rock by Meyer Rubin of the Geological Survey was 2400 years ago. The old reef is now eroded and no part now rises more than 3 feet above high-tide level, but it probably represents the Recent negative shift in sea level of 5 to 6 feet, evidence for which, from many parts of the Pacific, has been described.

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5. The drilling equipment and a seven-man crew were furnished by Layne International, Inc.; all the drilling was done under the supervision of William Craddick. The drill was operated continuously in 12-hour shifts. A geologist or geological assistant was on duty at all times. In this work we were assisted by Theodore K. Chamberlain, W. Storrs Cole, William Ebersole, and Ted Murphy.
6. The oriented cores were taken under the direction of Charles E. Ward of Christensen Diamond Products Company.
7. X-ray diffraction analysis was used to identify and to estimate the abundance of the carbonate minerals in finely ground samples, 69 from the Reef core, 21 from the Sand Island core. The results of six to ten analyses of each sample were averaged. The $MgCO_3$ content of the magnesian calcites was estimated from the data of J. R. Goldsmith *et al.* [*Geochim. Cosmochim. Acta* **7**, 212 (1955)]. The dolomites were shown, from the data of J. R. Goldsmith and D. L. Graf [*J. Geol.* **66**, 678 (1958)], to be rich in calcium.
8. N. D. Newell *et al.*, *The Permian Reef Complex of the Guadalupe Mountains Region, Texas and New Mexico—A Study in Paleoecology* (Freeman, San Francisco, 1953); J. E. Adams and M. L. Rhodes, *Bull. Amer. Assoc. Petrol. Geologists* **44**, 1912 (1960); K. S. Deffeyes, F. J. Lucia, P. K. Weyl, *Science* **143**, 678 (1964); R. A. Berner, *ibid.* **147**, 1297 (1965); S. O. Schlanger, *Sci. Rep. Tohoku Univ., Second Ser.* **37**, 15 (1965).
9. W. S. Cole, unpublished manuscript.
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11. J. E. Hazel, written communication.
12. J. W. Wells, written communication.
13. H. Ladd, *U.S. Geol. Survey Profess. Paper 531* (1966), p. 59.
14. ——, *J. Paleontol.* **32**, 183 (1958).
15. Preliminary seismic surveys suggested a thickness of sediment beneath Sand Island of 0.26 to 0.29 km (853 to 951 feet) (see

2), but basalt was found at 516 feet. Under the north half of the Midway lagoon, volcanic rock was predicted between 0.63 and 0.71 km (2067 and 2329 feet), but the drill entered basalt at 1261 feet. George Shor, who was in charge of the preliminary seismic surveys and who made additional observations at Midway after the drilling was completed, is preparing a further report on this matter.
16. G. A. Macdonald, oral communication.
17. H. T. Stearns, *Z. Geomorphol. Supp.* **3**, 9 (1961).
18. These are primarily zones of diagnostic larger Foraminifera that match the sequences established in Indonesia.
19. S. O. Schlanger, *U.S. Geol. Surv. Profess. Paper 260-BB* (1963), p. 994.
20. The project discussed here was carried out under the auspices of the Hawaii Institute of Geophysics, University of Hawaii, with financial support (grant No. GP4728) from the National Science Foundation. Other agencies collaborating included the U.S. Geological Survey and the Office of Naval Research. In planning the work, Ladd was assisted by George P. Woollard and Gordon A. Macdonald, co-investigators in the project. In connection with planning, thanks are also due to Dr. William E. Benson of the National Science Foundation, V. C. Mickle of the George E. Failing Company, and Rear Admiral Charles W. Thomas (Ret.) of the University of Hawaii. During our stay at Midway, Captain F. D. Milner, Commanding Officer, and his associates cooperated fully. The cores and cuttings obtained during the drilling have been placed on permanent deposit at the Hawaii Institute of Geophysics, University of Hawaii. Publication of this report is authorized by the Director of the U.S. Geological Survey and by the Secretary of the Smithsonian Institution.

16 March 1967

Sudbury Structure, Ontario: Some Petrographic Evidence for Origin by Meteorite Impact

Abstract. *Unusual deformation structures, similar to those observed in rocks from known and suspected meteorite impact craters, are observed in inclusions of basement rock in the Onaping formation at Sudbury, Ontario. These features, which include planar sets in quartz parallel to the (0001) and (10$\bar{1}$3) planes, suggest that the Onaping formation consists of shocked and melted material deposited immediately after a meteorite impact which formed the Sudbury basin.*

Recently, studies of rock specimens subjected to hypervelocity shock waves generated by artificial explosions and by meteorite impacts have established some petrographic and mineralogical criteria which appear to be unique indicators of such processes (*1–3*). These effects include (i) high-pressure silica polymorphs, (ii) high-temperature fusion and decomposition reactions, (iii) multiple sets of planar lamellae in quartz, commonly oriented parallel to the (0001) and (10$\bar{1}$3) planes, and (iv) intense disordering of single crystals of quartz and feldspar, often producing glasslike phases. Such effects, observed in rocks of older circular structures, have been cited as evidence of meteorite impact (*4–8*).

This report describes some unusual microdeformational features observed in rocks from the Sudbury structure in southern Ontario, Canada; these features are similar to those developed in rocks associated with accepted meteorite craters and with older circular structures for which an origin by meteorite impact has been proposed.

The Sudbury structure is a kidney-shaped basin approximately 60 km (37 miles) long in an east-northeast direction and 27 km (17 miles) across (Fig. 1). The basin is outlined, both topographically and geologically, by an igneous irruptive (*9*) between 2 and 5 km thick, which is divided into an upper felsic micropegmatite and a lower, more mafic norite. Whole-rock Rb-Sr methods have determined an age of approximately 1700 million years for the irruptive (*10*). The irruptive and the basin are surrounded by older rocks—metasediments on the south and east, granitic rocks on the north and west. Near the margin of the basin, these rocks are locally intensely shattered and brecciated, forming a unit called the Sudbury breccia (*11*, *12*). The inner part of the basin is filled with a series of sediments (the Whitewater series) at least 1830 m (6000 feet) thick, composed of, in ascending order, the Onaping tuff-breccia, the Onwatin slate, and the Chelmsford sandstone.

Since the discovery of nickel ore in 1883, the mines associated with the Sudbury irruptive have produced several billion dollars worth of nickel, copper, iron, and platinum group metals. During this period, and especially within the last few years, the Sudbury structure has been the subject of a continuing geological debate concerning its origin and age, the timing of the igneous phenomena, the relationships with rocks outside the basin, and the origin of the ore deposits themselves (*13*).

The possibility that the Sudbury structure was formed by a large meteorite impact was formulated in detail by Dietz (*14*), who argued that such an origin would explain both the presence of the Sudbury breccia and some of the other puzzling structural features (*12*). Dietz also predicted and later discovered shatter cones, a possible indicator of impact, in the older rocks adjacent to the basin. Further investigations (*15*) indicated that a zone of shatter-coned older rocks surrounds the entire Sudbury structure to distances as great as 18 km. The development of a consistent theory for the origin of the Sudbury structure has been hampered by uncertainty about the origin of the Onaping formation, the lowest member of the Whitewater series, which lies within the Sudbury basin immediately above the irruptive (Fig. 1). This unit has generally been considered an unusual pyroclastic rock deposited by tremendous volcanic eruptions that predated or immediately preceded emplacement of the irruptive (*16–18*). The Onaping formation has an estimated thickness of 1220 m and an estimated minimum volume of 630 to 1050 km^3 (150 to 250 cubic miles) (*16*).

Various investigators (*16–18*) have concluded that the Onaping formation: (i) contains numerous fragments of devitrified glassy material; (ii) also contains numerous inclusions of basement rocks up to tens of feet (several meters) in size; (iii) exhibits a uniform gradation in fragment size, with large blocks at the base and fine material at the upper contact; (iv) exhibits concentric zoning of rock types with respect to the basin margin; (v) cannot be definitely correlated with formations outside the Sudbury basin; (vi) was apparently deposited as a single unit during a brief period of time; and (vii) has been involved in at least one period of postdepositional deformation and metamorphism.

The long-accepted volcanic origin of the Onaping formation has recently been unsettled by the discovery (*19*, *20*) that a unit at the base of the formation, originally identified as rhyolite feeder dikes (*16*, *17*) is composed of large blocks of quartzite in a matrix of micropegmatite (*21*). The present research was undertaken to exam-