Marine Geology of Kure and Midway Atolls, Hawaii: A Preliminary Report[1]

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ABSTRACT: Midway and Kure islands are the world's northernmost atolls but have flourishing algal-coral reefs with typical coral reef structures. An almost circular outer reef and a broad, shallow (< 5 meters deep), sediment-built lagoon terrace surround the deeper parts of each lagoon (maximum depths: Midway, 21 meters; Kure, 14 meters). Unconsolidated carbonate sand and gravel form islands along the southern margins of the atolls. Patch reefs form a series of intersecting ridges partly covered by sediment. Emergent parts of older presumed reef rock, built primarily of coralline algae, extend about 1 meter above sea level; they are especially well developed on Midway and are present but less conspicuous on Kure.

Sediment grain size decreases lagoonward. Carbonate gravel and coarse sands predominate on the reef flats, on the seaward sides of the islands, and on the lagoon terrace. Fine carbonate sands and silts cover the deeper parts of the lagoon bottom. Major sediment-contributing organisms are (in order of abundance): coralline algae, corals, foraminifers, and mollusks. *Halimeda* is nowhere a major constituent. Most sediment grains deposited in the lagoons are reef-derived, primarily from the windward reefs on the northeastern margin. There is no distinctive lagoonal sediment facies.

THE WORLD'S northernmost atolls—Kure and Midway islands and Pearl and Hermes Reef (Fig. 1)—occur at the northwestern end of the Hawaiian Islands (Bryan, 1953). Of these little-known atolls, only Pearl and Hermes Reef had been studied in any detail before 1965 (Galtsoff, 1933; Thorp, 1936). The published data concerning the reefs, islands, and sediments of Kure and Midway were obtained primarily from brief visits by scientists or from the accounts given by survivors of the many shipwrecks on these atolls (Bryan, 1906; Hitchcock, 1911; Elschner, 1915; Stearns, 1941; Bryan, 1942). Certain aspects of the flora and fauna of the atolls were discussed by Hutchinson (1950) and Bailey (1956).

This report contains the preliminary results obtained from studies of Kure and Midway atolls conducted in summer 1965 as part of the Midway Deep Drilling Project (Ladd, Tracey, and Gross, 1967). These studies were planned to investigate the marine geology of these atolls. Specific objectives were to study reef structure and sediment composition of the atolls to provide data necessary to interpret the significance of materials obtained from the drilling operations, and to determine what effects, if any, result from the northerly position of these atolls.

DESCRIPTION OF THE ATOLLS

Both Kure and Midway atolls are nearly circular; the outer reef almost completely en-

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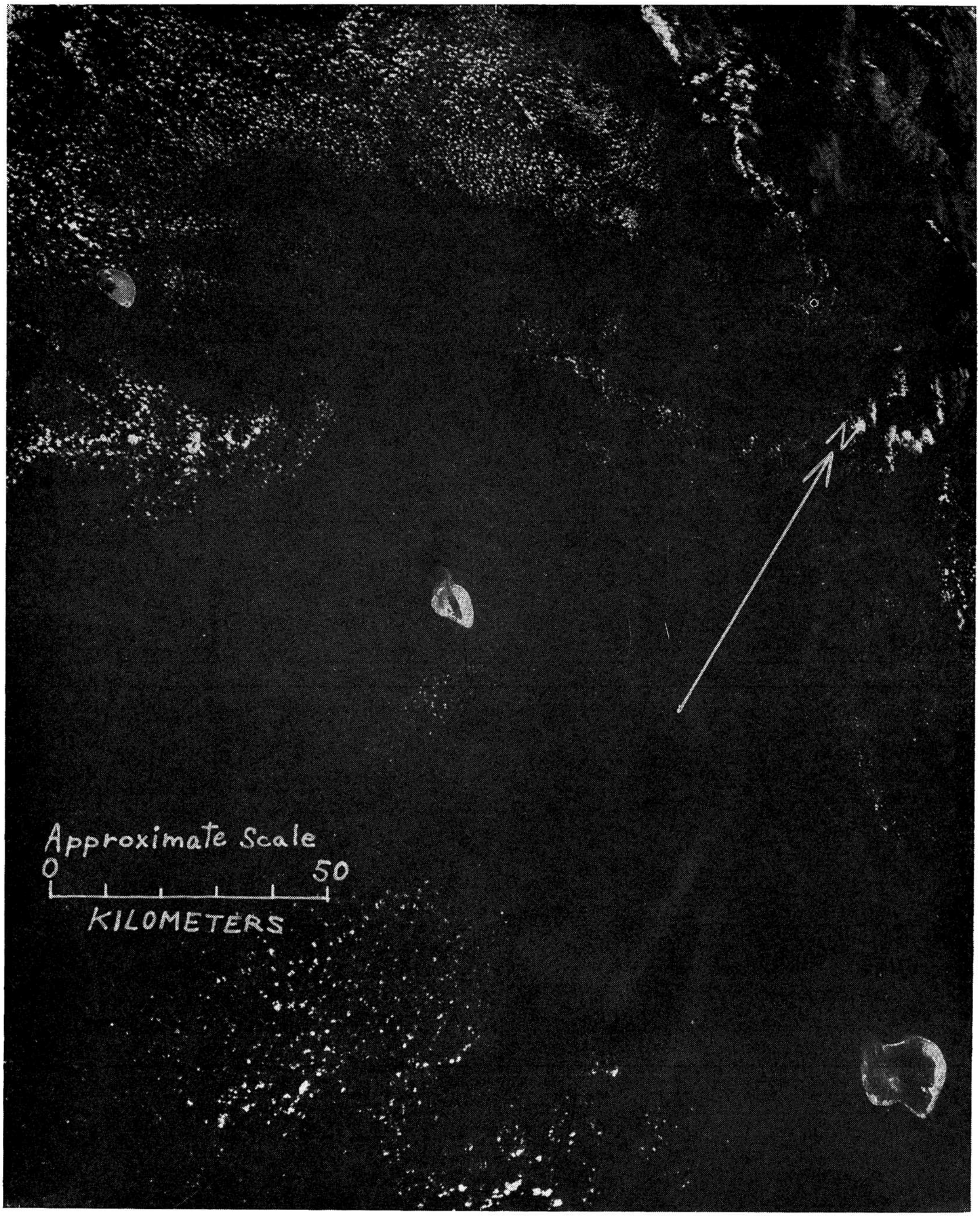

FIG. 1. Photograph taken from Gemini VII spacecraft showing Pearl and Hermes Reef (*lower right*), Midway Islands (*center*) and Kure Island (*upper left*). The shapes of the atolls are distorted owing to the tilt of the camera and the earth's curvature. The reefs (the very light-colored outer rim), the lagoon terrace (the light-colored area inside the atolls), and the deeper parts of the lagoons (darker areas inside the atolls) can be distinguished. The small, irregularly shaped white objects are clouds. The star-like pattern between the Midway Islands and Pearl and Hermes Reef is the sun reflection. Note the plumes of discolored (presumably turbid) water flowing westward out of Pearl and Hermes Reef and the Midway Islands. Photograph taken December 9, 1965 from an altitude between 220 and 320 km.

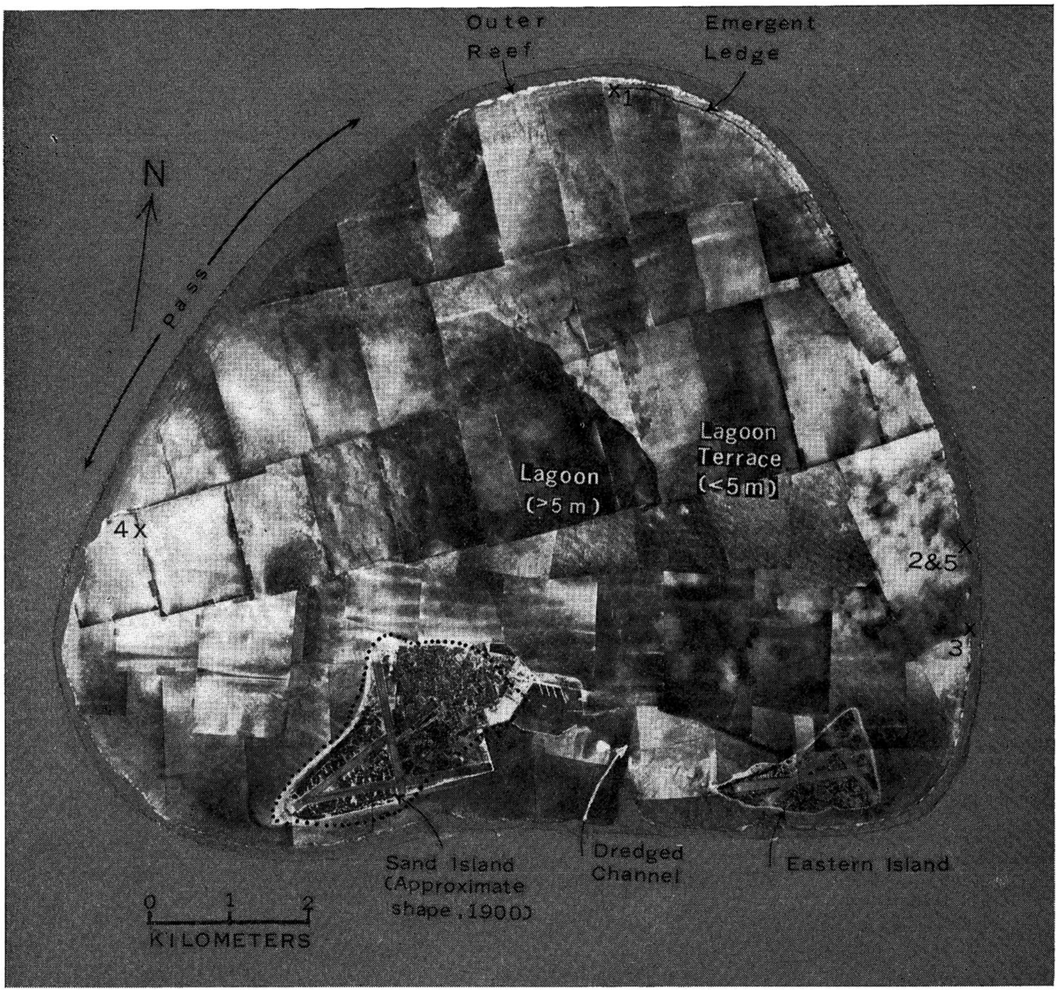

FIG. 2. Uncontrolled photomosaic of the Midway Islands. Note the changes in the lagoon and the eastern part of Sand Island which result from extensive dredging and filling operations. The mosaic was prepared by T. K. Chamberlain from U. S. Navy photographs taken June 4, 1955.

closes the lagoon except for passes on the northwestern side of each atoll (Figs. 2 and 3). A shallow (< 5 meters deep) lagoon terrace composed of sediment occupies about 77 per cent of the lagoon at Kure Atoll and about 67 per cent of the lagoon at Midway (Table 1). This lagoon terrace appears to have built leeward from the windward reef (northeastern side) and to be encroaching upon the deeper parts of the lagoons (Figs. 2 and 3). Figure 1 shows that the sediment-built lagoon terrace (the light-colored area in the lagoon) occupies a much larger part of the lagoon at Kure and Midway than it does in the much larger one of Pearl and Hermes Reef. The maximum depth recorded for the lagoon at Kure is 14 meters and at Midway, 21 meters (Table 1).

On each atoll, the islands, composed of carbonate sand, occur on the southern edges of the atolls (Figs. 2 and 3). Sand Island on Midway originally included a dune standing 13 meters above sea level (Hitchcock, 1911), but it was lowered during airfield construction. Eastern Island on Midway was reported to stand about 6 meters above sea level (Hitchcock, 1911); Green Island on Kure Atoll has a similar height.

Midway was surveyed in 1900 by the USS

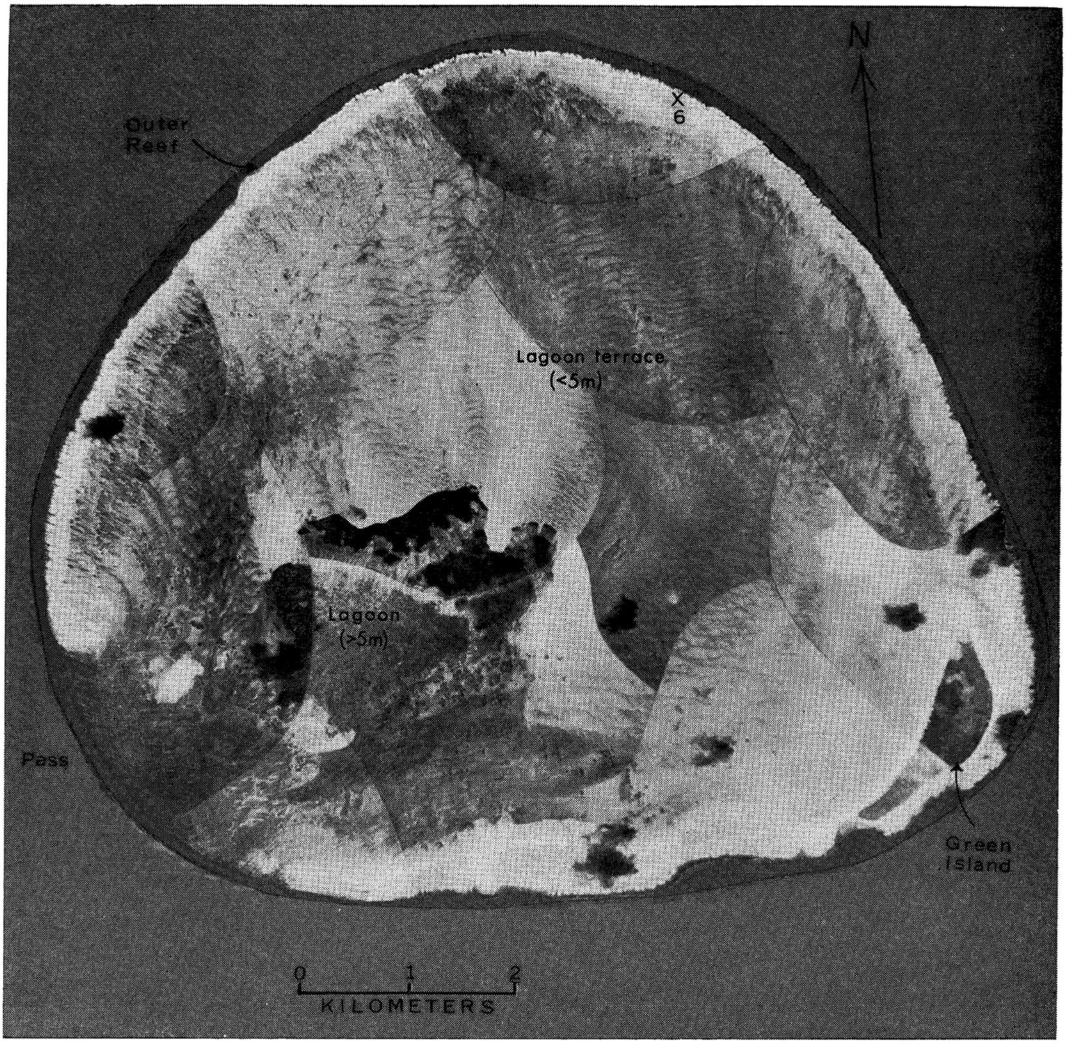

FIG. 3. Uncontrolled photomosaic of Kure Island. Note the ripples on the lagoon terrace bottom. The photomosaic was prepared by T. K. Chamberlain from U. S. Navy photographs taken June 6, 1955.

"Iroquois" (U. S. Navy Hydrographic Office, Chart 1952, dated 1901) and again in 1941 (U. S. Coast and Geodetic Survey, Hydrographic Survey 6755a). Comparison of the charts made from these surveys revealed no significant changes in the outline or size of the lagoon and only minor changes in the shape of Sand Island. The mosaic (Fig. 2) of photographs made in 1955 shows the changes resulting from the extensive dredging operations in the lagoon and the filled areas on the eastern side of Sand Island. Detailed comparison of the Coast and Geodetic Survey chart 4177, prepared from a U. S. Navy survey in 1936, and the uncontrolled photomosaic (Fig. 3) prepared from aerial photographs made in 1955 also failed to reveal any significant changes in the lagoon at Kure during this period. Images of the individual atolls on the Gemini photograph made in 1965 (Fig. 1) were not good enough to permit detailed comparisons. Although these atolls may be changing, the changes are too small to be detectable by these comparisons over a period of 41 years at Midway, or 29 years at Kure.

Two unusual features of the Kure, Midway, and Pearl and Hermes reefs are the elongate

TABLE 1

GEOGRAPHICAL DATA ON HAWAIIAN ATOLLS

ATOLL	MAXIMUM DIAMETER (km)	MAXIMUM DIAMETER DIRECTION	PASS WIDTH (km)	MAXIMUM LAGOON DEPTH (m)	MAXIMUM DUNE HEIGHT (m)	AREA (km²) ISLANDS	OUTER REEF	LAGOON TERRACE (< 5m)	LAGOON (> 5m)	TOTAL
Kure (28°25′N 178°20′W)	9.5	NW-SE	2	14	6	1	5	40	6	52
Midway (28°13′N 177°23′W)	10.5	NE-SW	5	21	13*	5.5	5	43	11	64
Pearl and Hermes (27°50′N 175°50′W)	30	NE-SW	11	24	3.5	2	13	50	305	370

* Original height (Hitchcock, 1911), but lowered during construction of the airfield.

reef patches and coral ridges in the lagoons and the presence of an emergent rock ledge on the outer reef of each atoll. The pattern of elongate and intersecting reef patches, as observed from the air, is especially well developed at Pearl and Hermes Reef; this pattern can also be observed at Midway and Kure where the elongate reefs occur in the deeper parts of the lagoon and appear to be nearly covered by the sediment that forms the lagoon terrace (see Fig. 3).

We have no direct evidence indicating the origin of these coral ridges although it is tempting to assume that the present pattern is a remnant of some preexisting topography on which the corals grew as sea level rose following the last retreat of the continental glaciers. The absence, however, of extensive alteration in the cores from drill holes (Ladd et al., 1967) at the depths equal to the maximum depths of Midway's lagoon (Table 1) would seem to rule out the possibility of an extensive erosional or karst topography.

A narrow rock ledge (2 to 10 meters wide) is present along approximately half of the outer reef at Midway. The flat eroded upper surface of the ledge is about 0.5 to 0.75 meters above the sea surface at low tide and nearly 2 meters above the surface of the living algal margin of the reef. The diurnal tidal range at Midway is 0.36 meters and the spring tidal range is 0.64 meters, so that the highest parts of the ledge are not submerged at the highest tides. A rock ledge is present but much less extensive on Kure, and a similar ledge was reported (Galtsoff, 1933) to be well developed on the northeastern corner of Pearl and Hermes Reef and to project about 5 feet (1.5 meters) above sea surface.

At Midway, the rock ledge is especially conspicuous and is nearly continuous along the northern and eastern sides of the atoll but poorly developed or absent on the southeastern and southwestern portions. The ledge is cut in some places by relatively narrow shallow grooves, some of which are continuous with the well developed buttress-and-groove structure of the outer reef. The rock is notched at about low tide level and no living algal growth is present above the notch.

The rock comprising the emergent ledge consists primarily of coralline algae, and of algally bound and encrusted pieces of coral and other carbonate materials, which are apparently little altered, still consisting of aragonite and magnesian calcite. The rock in the ledge closely resembles the algally encrusted rock of the present reef margin and is not cemented rubble on top of the reef. From the description it appears that the emergent ledge on Pearl and Hermes Reef (Galtsoff, 1933) is similar.

Carbon-14 dates (Table 2) were obtained for samples of the emergent rock ledge on Midway and Kure atolls. For each sample the total rock was analyzed after the obviously bored outer portion had been removed to minimize contami-

TABLE 2

CARBON-14 AGES OF REEF SAMPLES, MIDWAY AND KURE ATOLLS

SAMPLE NUMBER[a]	DESCRIPTION AND LOCATION	AGE[b] (years BP)
	MIDWAY ATOLL	
1	Emergent rock,[c] north reef (W1846)	2,090 ± 200
2	Emergent rock,[c] east reef (W1956)	1,230 ± 250
3	Emergent rock,[c] east reef (W1954), ca. 1 km south of sample 2	2,420 ± 300
4	Emergent rock,[c] southwest reef (W1962)	2,180 ± 250
5	Living coralline algae, east reef near W1956, at sea level (W1851)	< 200
	KURE ATOLL	
6	Emergent rock,[c] northeast reef (W1952)	1,480 ± 250

[a] See Figure 2 for sample locations on Midway Atoll and Figure 3 for sample locations on Kure Atoll.
[b] Analyses by Meyer Rubin, U. S. Geological Survey. The uncertainty in the age due to counting statistics is indicated.
[c] Samples collected about ½ meter above sea level.

nation of the sample by modern carbonate. For the ledge at Midway, the C-14 ages range from 2,420 to 1,230 years Before Present (BP) and the one sample from Kure had a C-14 age of 1,480 years BP. We believe that the ledges on these atolls formed as living reefs with their surfaces at or slightly below low tide level. Either these atolls were elevated 1 to 2 meters, or sea level dropped by that amount to its present level in the last thousand years.

FAUNA AND ENVIRONMENTAL FACTORS

Examination of the reefs revealed that they are flourishing and are built primarily of coralline algae and corals. The groove-and-buttress structure typical of more tropical reefs (Emery, Tracey, and Ladd, 1954) is well developed. There is no outward manifestation of abnormality of structure owing to the northerly location of the reefs. We found no evidence to support reports (Stearns, 1946; 1966:24, 217) that barnacles are major reef-building organisms at Midway, although a large species of *Balanus* is locally abundant on algal terraces near the reef edge on both atolls.

Studies of marine organisms collected from the two atolls are not yet complete. The available data indicate that the faunas contain relatively few species. For example, only 9 coral genera were found living in these atolls whereas 15 genera are known from the Hawaiian islands further south (J. W. Wells, quoted by Ladd, Tracey, and Gross, 1967) and 52 genera are known from the Marshall Islands (Wells, 1954).

The molluscan fauna is also poorer in number of individuals and in species than the faunas in the more southerly Hawaiian islands. A fair variety of mollusks has been recorded for Midway and Kure, but most of the species are rare, and many are represented only by dead shells picked up on the beach. A limited number of species of mollusks can be found alive in abundance on the reef margin. These include small littorinids, neritids, and limpets, and two species of *Drupa,* but even those are not everywhere abundant. Dredging in the sands of the lagoon terrace was even less rewarding. Many dredge hauls recovered no living mollusks, others contained only a *Polinices* or one or two species of venerid or tellen.

The mean monthly salinity (Table 3) of the surface sea water in the lagoon varies from 35.4 ‰ in February to 35.9 ‰ in August. The extreme recorded values for the period 1950–1961 are a low of 35.0 ‰ in August 1958 and a maximum of 36.6 ‰ in June and July 1958. These values, calculated from sea water densities observed in the partly enclosed boat harbor on Sand Island, Midway, are probably somewhat higher than the salinity values in surface sea water of the surrounding ocean. Furthermore, the salinity of the water in the submarine basin is likely to respond more rapidly to extreme environmental conditions (periods of drought or excessive rainfall) than is the surrounding open ocean. Nonetheless, the reported salinity values are well within the tolerance limits for common reef-building corals in the Hawaiian Islands (Edmondson, 1928:35).

The low winter temperatures are undoubtedly a primary cause of the paucity of faunas. The mean monthly values (Table 3) of 19.2°C in February and 26.9°C in August are within the observed tolerance limits for vigorous coral reef growth (Wells, 1957). However, Midway and

TABLE 3

AIR AND WATER TEMPERATURES AND SURFACE SALINITIES, SAND ISLAND, MIDWAY

	MEAN MONTHLY AIR TEMPERATURE[a] (°C)	MEAN MONTHLY VALUES, LAGOON SURFACE WATER	
		TEMPERATURE[b] (°C)	SALINITY[c] (‰)
January	18.9	19.9	35.5
February	18.8	19.2	35.4
March	19.1	20.1	35.6
April	19.5	21.0	35.6
May	21.5	22.6	35.8
June	24.2	24.9	35.8
July	25.3	26.2	35.9
August	25.8	26.9	35.8
September	25.9	26.8	35.8
October	24.2	25.1	35.8
November	22.2	23.0	35.8
December	20.2	21.5	35.5
Mean Annual	22.1	23.1	35.7

[a] Extreme air temperatures (1951–1965): 31.7°C, August 1959; 11.1°C, March 1951 (U. S. Weather Bureau records, revised May 1965).

[b] Extreme water temperatures (1944–1963): 29.4°C, July 1950; 16.7°C, March 1948, 1949, February 1957, 1959 (U. S. Coast and Geodetic Survey, 1956, and unpublished data).

[c] Extreme mean monthly surface salinities (1949–1961): 36.6 ‰, June–July 1958; 35.0 ‰, August 1958.

Kure lie at the northern edge of the tradewind belt, and during the winter months they experience the storms typical of the westerlies, many of which bring colder temperatures. Surface sea water temperatures of 16.7°C were reported in February or March in four different years between 1944 and 1963. After slow cooling to such temperatures, only 7 of 19 common coral species at Waikiki Beach were capable of capturing and ingesting food at the end of 1 hour of exposure (Edmondson, 1928:33). It would be interesting to have similar experiments performed using common Midway or Kure corals.

SEDIMENT TEXTURE AND COMPOSITION

For this preliminary investigation, grain size analyses were made by sieving techniques (Krumbein and Pettijohn, 1938:136–143) to separate gravel (coarser than 2000 μ), coarse sand (2000 to 500 μ), fine sand (500 to 125 μ), and finer-grained material (less than 125 μ). Aliquots of the fine sand and coarse size fractions were impregnated with a polyester resin, and thin sections were cut. Composition was determined by point counting with a petrographic microscope, using techniques similar to those described by Ginsburg (1956). Particles larger than 2000 μ were identified using a binocular microscope and reflected light.

Mineral composition of the sediment was estimated using X-ray diffraction analysis of ground representative samples. The diffraction data were analyzed using techniques similar to those employed by Lowenstam (1954). Magnesium and strontium contents of the sediments were determined by X-ray fluorescence techniques. (See Liebhafsky, Pfeiffer, Winslow, and Zemany, 1960, for a discussion of the general procedures). Standards were prepared by mixing known amounts of reagent grade $MgCO_3$ or $SrCO_3$ with $CaCO_3$. Analyses were made by S. Wienke, University of Washington.

On the outer reefs, the lagoon terrace, and seaward island beaches, gravel and coarse sand are the dominant textural types. On the lagoonward sides of islands, coarse sand or medium to fine sand generally predominate. In the lagoon, medium to fine sand and fine debris (finer than 125 μ) are the common sediment types.

Pronounced local variations occur in the gravel-sized sediment grains within each atoll. On the outer reefs, coralline algae dominate; in the lagoons, fragments of *Halimeda* and mollusks are more common. The abundance of skeletal fragments in sands shows little variation across either atoll (Fig. 4).

No significant differences were observed in the relative abundance of skeletal fragments accumulating in the sediments of the two atolls. The dominant sediment-contributing organisms are (in order of abundance): coralline algae, corals, benthic Foraminifera, mollusks, and *Halimeda* (Fig. 4). The composition of the sediment from Kure and Midway atolls is similar to that reported for sediment from Pearl and Hermes Reef (Thorp, 1936).

The scarcity of *Halimeda* fragments in the sediment is notable, for living *Halimeda* were only moderately common in protected shallow water on the outer reef and reef flat and on the coral ridges in the lagoon. *Halimeda* is an important sediment contributor in most reefs and atolls at lower latitudes.

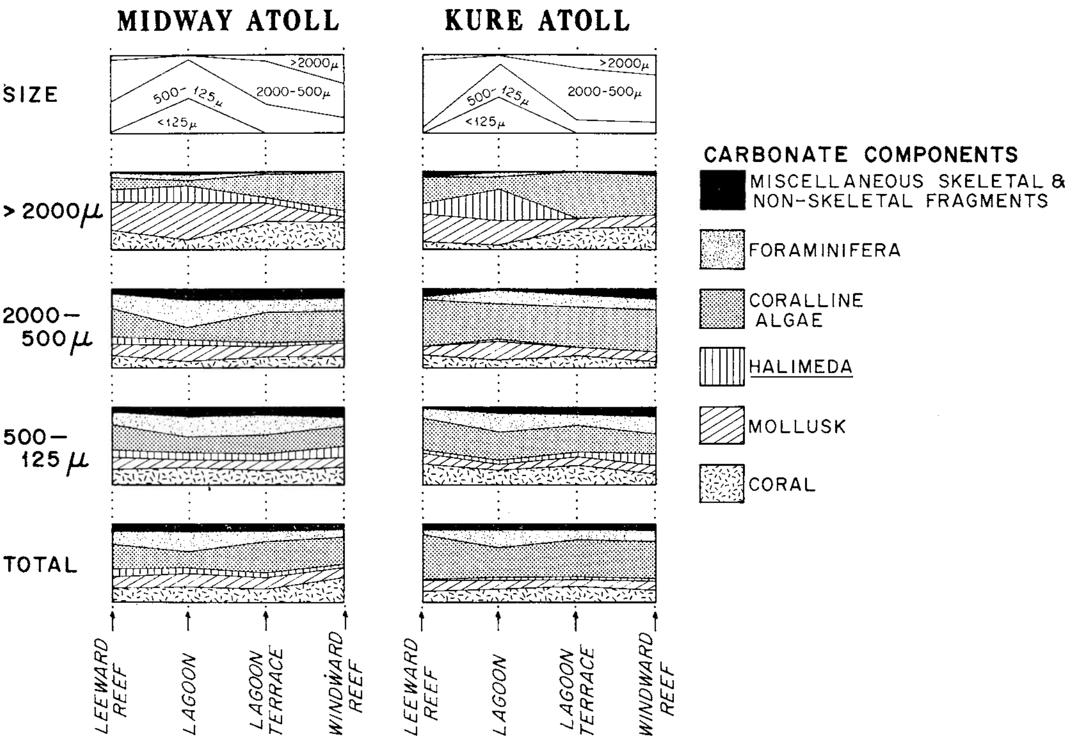

FIG. 4. Size and origin of sediment grains in various depositional environments, Kure and Midway Islands.

The abundance of mollusk shell fragments in the coarse sediments of reef and lagoon is probably due to the resistant nature of the shells rather than to their abundance at present.

The bulk mineral and chemical compositions of the sediment at Kure and Midway atolls are nearly identical. A typical sediment from these atolls is nearly pure carbonate, consisting of 10 per cent calcite, 40 per cent magnesian calcite (containing more than 4 mole per cent $MgCO_3$ in solid solution with calcite), and 50 per cent aragonite. The bulk chemical composition is: $CaCO_3$, 94 per cent; $MgCO_3$, 5.2 per cent, and $SrCO_3$, 0.8 per cent. Particles less than 125 μ in diameter, which are relatively rare except in the deeper lagoon sediments (Fig. 4), consist primarily of aragonite and contain about 1 per cent $SrCO_3$. This fine-grained material appears to be derived primarily from the breakdown of coral skeletons, as indicated by the relatively high $SrCO_3$ content.

The composition of carbonate sand and its uniformity throughout both atolls suggest that most sediment is derived from the peripheral reefs and is widely redistributed within the atoll by wave action or currents. This hypothesis is supported by the general shape of the broad, shallow lagoon terrace and its relation to the outer reef (see Fig. 3). The incoming reef sediment tends to mask locally derived sediment.

Relatively little fine-grained (< 125 μ) material is deposited in the lagoon. Much of this material apparently remains in suspension to be transported out of the lagoon, leaving behind coarse-grained sediment in shallow water and near the leeward passes. A photograph (Fig. 1) of the three atolls, taken from the Gemini VII spacecraft, shows distinct plumes of turbid water flowing out through the leeward passes of Midway and of Pearl and Hermes Reef. The image of Kure Atoll is too poor to indicate the presence of such a plume. We suggest that the turbidity of the water may be caused, in large part, by the suspended, silt-sized particles being carried out of the atolls.

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