University of California
Scripps Institution of Oceanography

Shipboard Report, Capricorn Expedition 26
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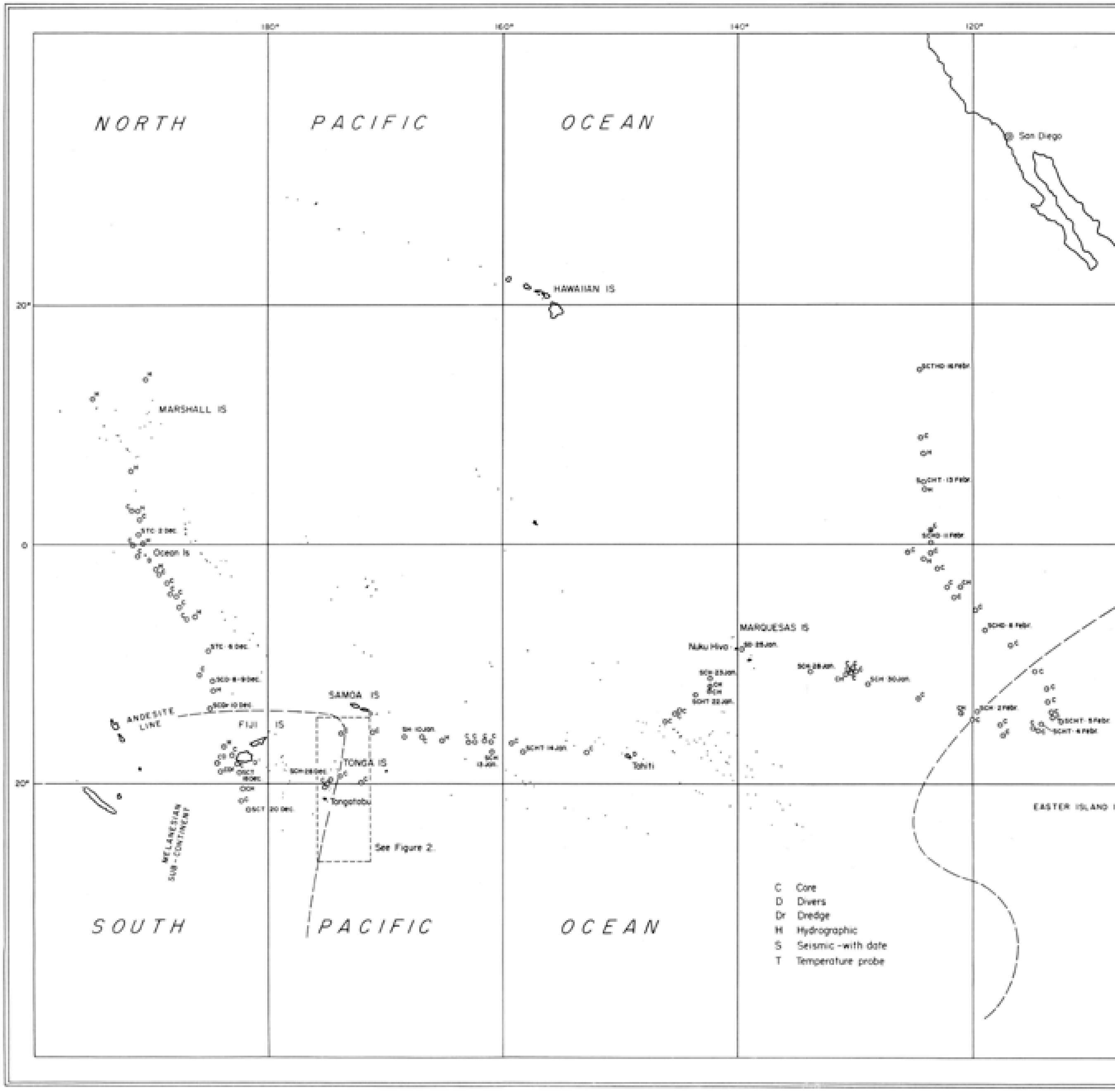
PREFACE

CAPRICORN was the fourth of a series of oceanographic expeditions into the deep Pacific sponsored by the Navy Department and the University of California. In 1950, the MID-PACIFIC Expedition was devoted largely to exploration of the sea floor in the area between Cape Mendocino, the Marshall Islands, and the Equator. In 1951, NORTHERN HOLIDAY conducted hydrographic and geologic studies in the eastern North Pacific between San Diego and the Aleutian Islands. Hydrographic exploration of the eastern Central Pacific was the principal objective of SHELLBACK, in 1952.

On the present expedition we ventured farther south than on any of our previous cruises, and most of the work was done between the Equator and the Tropic of Capricorn. Hence the name, CAPRICORN.

CAPRICORN, like the preceding expeditions, was generously supported by the Office of Naval Research and the Bureau of Ships of the Navy Department. The meteorological program was supported by the Air Force Cambridge Research Center.



CAPRICORN station chart. The chart shows BAIRD's position on seism
also stations for both HORIZON and BAIRD where a temperature probe
series, core, or dredge haul was taken or where a dive was made. BT
observations, echo soundings and magnetometer surveys, net hauls, SOF
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shown on chart in Figure 2.

FIGURE 1
CAPRICORN station chart. The chart shows BAIRD's position on seismic stations and also stations for both HORIZON and BAIRD where a temperature probe, hydrographic series, core, or dredge haul was taken or where a dive was made. BT lowerings, GEK observations, echo

soundings and magnetometer surveys, net hauls, SOFAR bomb drops, and meteorological observations are not indicated. The stations in the Tonga area are shown on chart in Figure 2.

INTRODUCTION

This report was assembled during the last leg of the CAPRICORN Expedition and was completed before our return to the home port of San Diego. Such a shipboard report must have obvious shortcomings. Subsequent analysis of the collected samples and data (some of it not to be completed for years) will certainly change the emphasis of many of the thoughts expressed here. In some instances the preliminary conclusions may turn out to be altogether wrong. There is no need to emphasize repeatedly how preliminary this report is. We shall put down what we have done and learned, as best we can, while the voyage is still fresh in our minds.

The principal aim of CAPRICORN was to study the deep Pacific basin by seismic shooting, echo sounding, coring, magnetic surveys, measurements of heat flux, and other means. But the character of the sediment blanket is so closely interwoven with the life and movement of the water above the sea floor that certain biological and physical observations, in addition to the geological measurements, seemed mandatory. Again, the movement of the ocean water is caused largely by the movement of the atmosphere above the sea, and accordingly a meteorological program was incorporated into the expedition plans.

With regard to the seismic work, the present expedition represents a continuation of a broadly conceived seismic survey of the Pacific Ocean which was started by Dr. Raitt in 1948. It was because of this work that two ships were used; HORIZON did the firing, and BAIRD the listening.

NARRATIVE

SAN DIEGO TO KWAJALEIN, MARSHALL ISLANDS

HORIZON, with Holter as chief scientist, and Barr, Beckwith, Darsey, Hamilton, Horton, Jones, MacFall, Palmer, Payne, and Ruttenberg as members of the scientific party, left San Diego on 26 September 1952 and went directly to Eniwetok in the Marshall Islands, where she arrived on 15 October. SPENCER F. BAIRD made a similar trip between 26 October and 15 November, with Maxwell as chief scientist, and Larimore, Raff, Silverman, and Von Herzen in the scientific party. BAIRD had just been outfitted with a new dredging winch, and a 30,000-ft tapered cable was wound on the drum the night before her departure. Two unavoidable circumstances, the delay in the delivery of this cable due to the steel strike, and a fixed date for arrival in the Marshall Islands area, made it impossible to give the new winch a sea trial before leaving on the expedition.

On the way to the Marshall Islands, both ships took continuous fathograms, and bathythermograms every two hours. HORIZON occupied two hydrographic stations in the Marshall Islands area.

A large contingent of the scientific party[*] flew to the Marshall Islands to meet HORIZON there, among them Bascom, Gibson, Hendrix, Isaacs, Johnson, Munk, and Raitt. After the completion of work under the direction of Isaacs, both ships embarked for Kwajalein. There they were met by a second contingent of the scientific party, consisting of Bramlette, Dill, Fisher, Folsom, Hilleary, Jackson, Knauss, Livingston, Menard, Nicholson, North, Revelle, Riedel, Rotschi, Stewart, and Taylor. At about this time Beckwith, Darsey, Gibson, Hamilton, Hendrix, Holter, Knauss, Palmer and Raff departed for the United States. Revelle took over the leadership of the expedition, and Isaacs and Riedel became senior scientists aboard BAIRD and HORIZON, respectively.

After our departure from Kwajalein the extent of air travel settled down to more reasonable proportions, and we may as well dispense with it here. Bramlette and Barr departed at Suva. Isaacs departed at Nukualofa and Bascom took his place as senior scientist aboard BAIRD. Mrs. Raitt joined the expedition at Nukualofa. Arrhenius, Swedish marine geologist, Fairbridge, Australian geologist and expert on coral reefs, and Mason, British geophysicist specializing in the earth's magnetism, joined the expedition at Suva. Riedel, Australian geologist specializing in radiolaria and deep-sea sedimentation, and Rotschi, chemical oceanographer from France, had previously joined us. Thus nearly a fourth of the senior scientific party came from countries outside the United States, and they played a very important role in the life of the expedition. We hope that on future expeditions our sea-going facilities may again be shared with qualified investigators from other countries.

KWAJALEIN, MARSHALL ISLANDS, TO SUVA ON VITI LEVU, FIJI ISLANDS

HORIZON left Kwajalein on the evening of 26 November, steaming south and taking hydrographic stations and several cores of the bottom sediments. At the magnetic Equator, Munk ran a series of squares to determine the GEK "droop factor." Next day, at the geographic Equator, there was also a droop, this time in the spirits of those unfortunate few who had not participated in HORIZON's crossings of the Equator several months earlier. On 29 November, HORIZON reached Ocean Island, just one degree south of the Equator. This island, which has extensive phosphate deposits, is administered jointly by Britain, New Zealand, and Austrailia. Officials of the Government and of the British Phosphate Company were most hospitable during our brief visit there. Bramlette, Fisher, Menard, and Riedel made a reconnaissance survey, hoping to learn something of the geologic history of this raised coral reef, and of the origin of the phosphate. Livingston, MacFall, and Munk made a series of dives all around the island, collecting coral samples, and observing the surge channels on the windward side. Hilleary, MacFall, and Ruttenberg set up a station to measure the diurnal variation of the earth's magnetic field, using the site originally occupied by the Carnegie Institution in 1915. Ruttenberg also took measurements of the vertical gradient of electrical potential in the atmosphere. The shore party was left on Ocean Island until 2 December. Several of its members witnessed a Gilbertese wedding ceremony, with impressive native dancing and singing.

After making a two-day survey of the underwater topography around Ocean Island, HORIZON steamed north for a rendezvous with BAIRD just above the Equator. During this trip she took a deep-water trawl. In the meanwhile, BAIRD had been beset with winch problems. After leaving Kwajalein on 28 November, she had made an experimental cable lowering and developed a kink in the cable as a result of slack between the winding and storage drums. A second kink was formed while lying in the lee of Namorik Island and running off the cable on a wooden reel preliminary to splicing. Thereupon an accumulator was rigged ahead of the storage drum to prevent slacking. This accumulator, after being strengthened several times, was reasonably successful during the remainder of the expedition.

On 2 December the two ships rendezvoused for the first seismic station. As this station was similar in pattern to subsequent ones, we shall review the procedure. HORIZON started at daybreak about 50 miles from BAIRD, and steaming towards her dropped explosive charges at intervals, beginning with 80 lb every 4 miles, decreasing to 1/2 lb each mile as she approached BAIRD. At noon HORIZON reached BAIRD (on some stations a transfer of gear and personnel took place at this time). Then HORIZON continued on her course and dropped charges until dusk. In the meantime, BAIRD had stopped at daybreak, streamed her hydrophones, and while lying to had taken a piston core and a measurement of the temperature gradient in the bottom sediments. At most seismic stations a hydrographic cast, or a vertical series of water samples for colloid content, was made as well (see Fig. 1).

After completing the first seismic station both ships sailed south over a shoaling, then a deepening bottom, taking GEK (current) measurements, hydrographic stations, and cores of the bottom sediments. Several of the longer cores consisted of Tertiary sediments near the bottom, underlying Recent material containing redeposited Tertiary fossils. The second seismic station was occupied on, 6 December west of the Ellice Islands. Thereupon BAIRD went south and HORIZON southeast in order to explore the escarpment which we believed to extend from the Santa Cruz islands to the west to somewhere between Horn and Wallis Islands to the east. This escarpment and the depression to the south are among the important features associated with the Andesite line.[*] BAIRD found the escarpment northwest of Alexa Bank and spent part of 7, 8, and 9 December exploring it and the basin to the south.

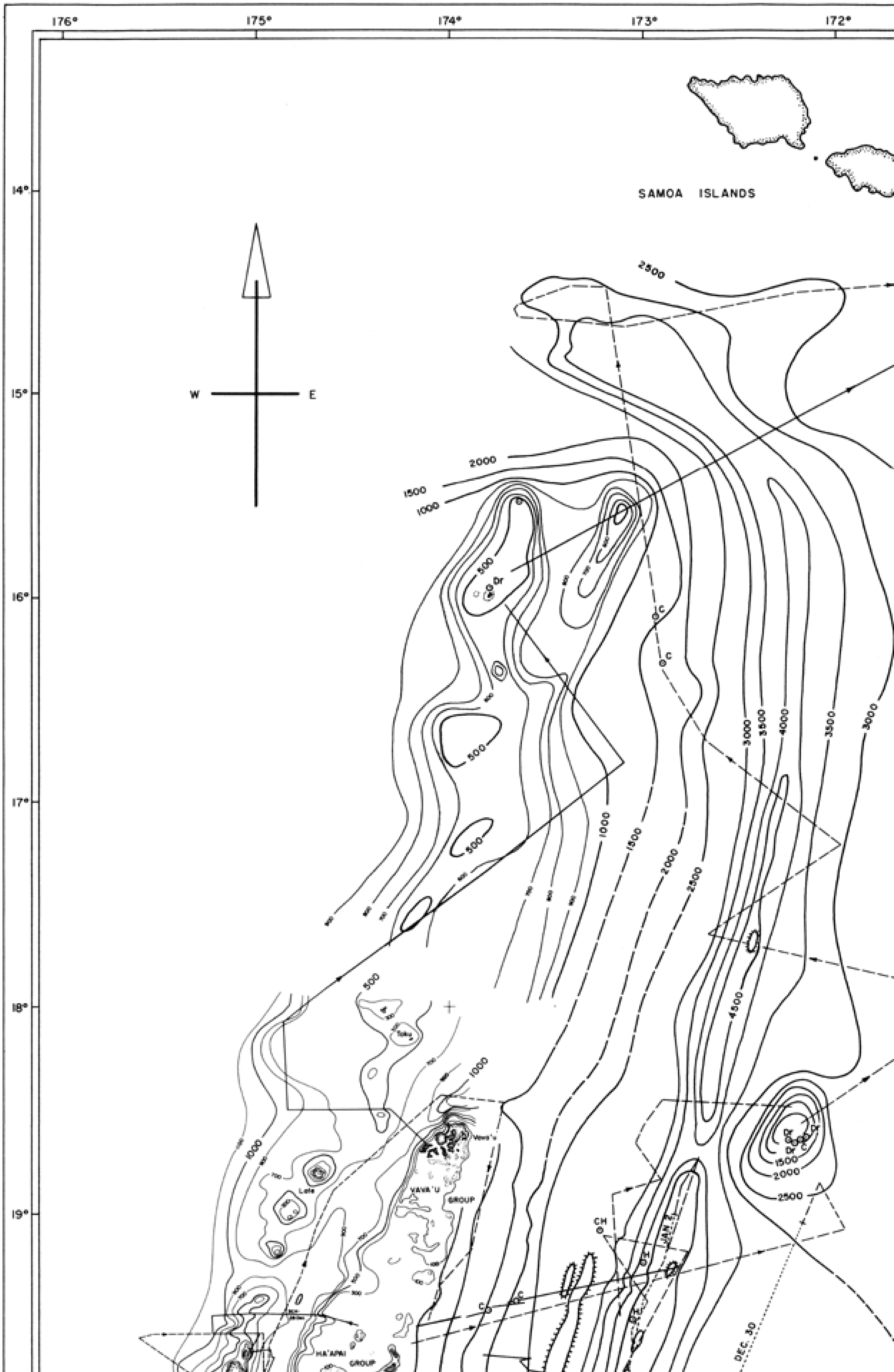

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FIGURE 2
Bathymetry of the Tonga area, showing (west to east) the volcanic island ridge, Tofua trough, main ridge of the Tonga Islands with their insular shelves separated by deep channels, the trench, and the deep-sea floor. Note large seamount on east flank of trench. Tracks of both ships and stations for seismic, temperature probe, hydrographic, diving, coring and dredging operations are also shown.

HORIZON did not find the escarpment until she was in sight of Rotuma Island. A small party was put ashore just before sundown, and rock samples were collected. Several members of the party considered this small volcanic island one of the most beautiful visited during the entire expedition.

The two ships met on top of Alexa Bank at noon of 8 December. The diving group, consisting of Bascom, Dill, Jackson, Livingston, MacFall, and Munk, inspected this "abortive atoll," collecting many specimens from the desert-like landscape 120 ft beneath the sea surface, and taking underwater photographs (Fig. 3). Seismic and bathymetric surveys of the bank were made. The seismic survey indicated a depth of calcareous material of several thousand feet, the same order as that found at Bikini and Eniwetok atolls. During the night of 8 December HORIZON dredged the slope to the north. Leaving Alexa Bank the ships steamed south to occupy another seismic station and then proceeded over an extremely hilly terrain towards the main Fiji Island of Viti Levu.

The expedition remained at Suva from 12 to 17 December. During this time two long splices were made on BAIRD's cable. Dr. Janek Skiba, geologist for the Fijian Government, arranged a trip around the island for the expedition's geologists, during which sedimentary and igneous rock formations were studied. Fairbridge examined petroglyphs on the neighboring island of Vanua Levu. Arrhenius and Mason visited the gold mine district at Vatu Koula in the northern interior of the island, where Mason, using a vertical force magnetometer loaned by the Division of Geology at Stanford University, demonstrated dramatically the practical value of magnetometer surveys, and Arrhenius discussed the expedition before the local chapter of the Australian Institute of Mining and Metallurgy. Mason made arrangements to have a series of oriented specimens of the basalt flows and tuffs collected, for use in studies of changes in the earth's magnetic field during the geologic past. The accessibility of unweathered flows through mine shafts offers considerable advantages over studies confined to surface outcrops. The divers were guests of the native village of Serua, where they explored the reef in company with native divers. Several divers collected specimens on the coral reef of Korolevu. Members of the expedition enjoyed the hospitality of Sir Ronald Garvey, Governor of the Fiji Islands, Harold Gatty, Morris Hedstrom, W.G. Johnson, and other citizens of Suva. Others visited native villages where they attended kava ceremonies and recorded native songs. A reception aboard the expedition's ships was given for about 200 people, including Governor and Lady Garvey.

SUVA ON VITI LEVU, FIJI ISLANDS, TO NUKUALOFA ON TONGATABU, TONGA ISLANDS

HORIZON left Suva on 15 December and surveyed the area to the southwest, taking a number of cores and dredge hauls. BAIRD departed two days later, and the ships met on 18 December for a seismic station in the flat-bottomed Kandavu Trough about 60 miles south of Suva. That night, while a 10-ft core of volcanic sand was being collected, a large number of squids and dolphin fish were observed, and numerous small fragments of grass-like material floated near the surface.

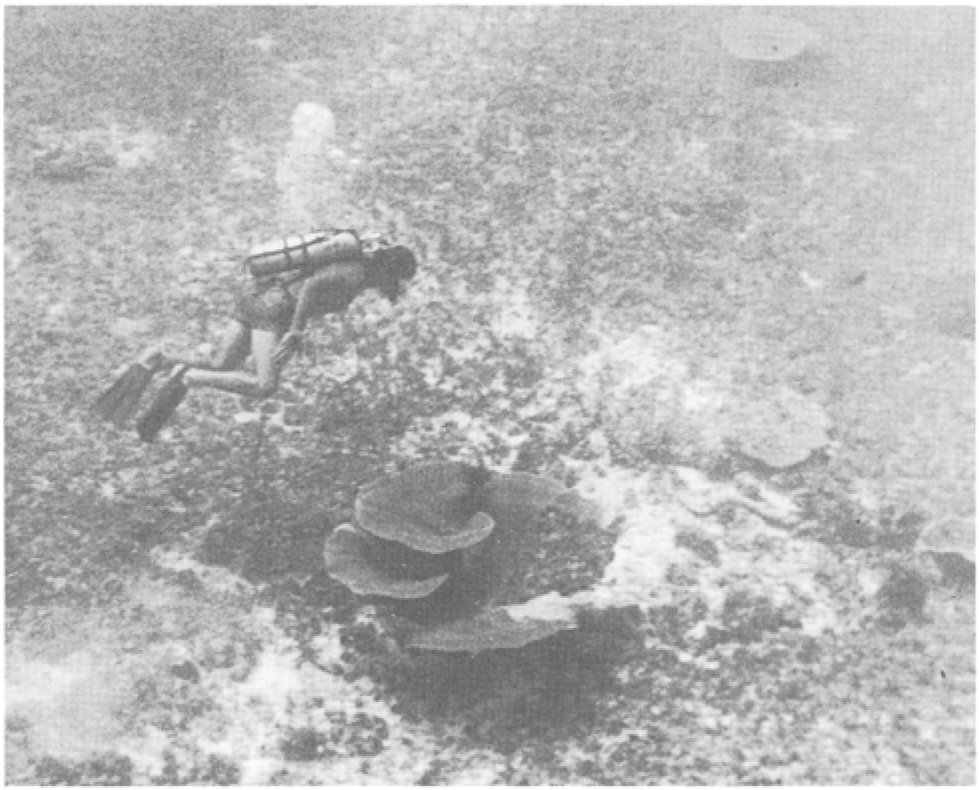

FIGURE 3. Underwater photograph by MacFall showing the floor of Alexa Bank at a depth of 20 fathoms just inside the eastern rim. The coral is Echinopora lamellosa, the man is Munk.

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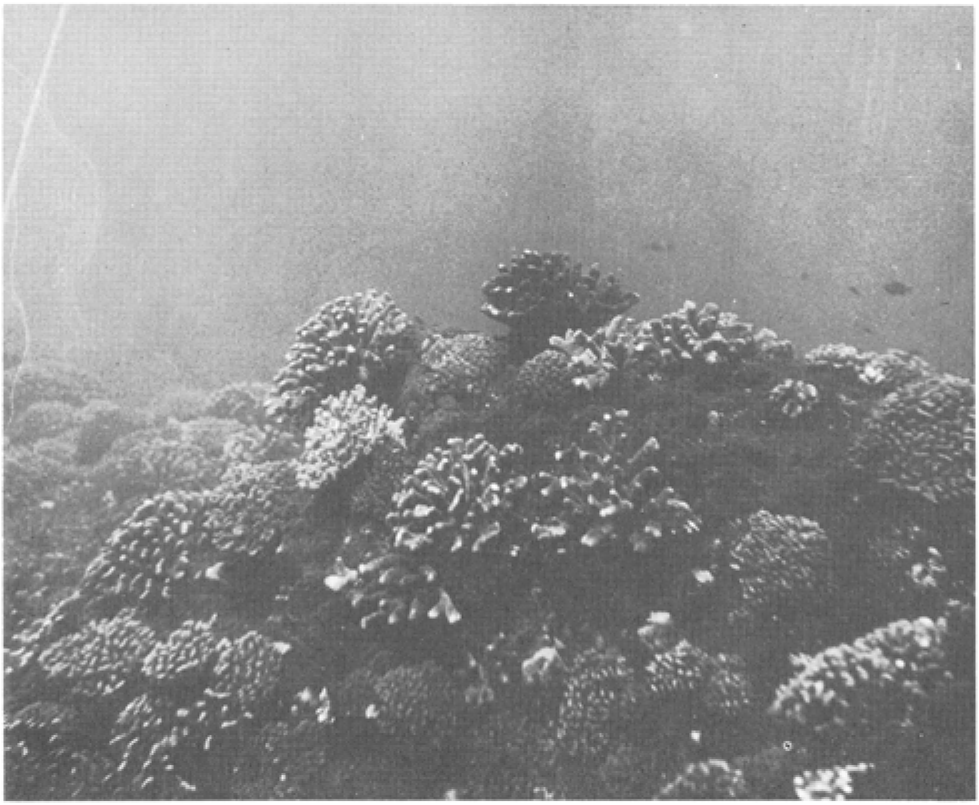

FIGURE 4. Underwater photograph by Jackson showing reef corals growing at three fathoms on a rocky pinnacle of Falcon Bank. Note luxuriant growth compared to Alexa Bank (Fig. 3) even though this area was a volcanic island several hundred feet above water only 20 years ago.

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The next seismic station was occupied two days later in the Fiji Basin, a large depression far on the "continental" side of the Andesite line. The temperature gradient in the bottom sediments was the second largest yet recorded from the sea floor, about 15°C per meter. The lowest opening in the rim surrounding the 4500-m deep basin appears to lie at 3000 m, according to a hydrographic cast taken at this station.

The two ships then continued on different tracks. BAIRD steamed towards the Lau Islands to the northeast. At the dateline she ran into patches of discolored water, due to high concentrations of algae. The contamination was confined to the very surface and was extremely rich in surface active agents. Microscopic examination revealed bundles of fine threads. Arrhenius made acetone extracts and found the presence of chlorophyl and carotenoids. He also centrifuged some samples and used the concentrate to bake a reasonably digestible pie. BAIRD continued northeast up the Lau Island ridge, making a near approach to Fulanga Island, thence through the passages between Fulanga and Ongea Islands, and between Ongea and Thakau Nasokesoke reef.

Our echo sounding profiles of this area, in which only one previous sounding deeper than 100 fm had been taken, reveal these islands as rising sharply from a broad platform at about 250 fm. The steep underwater slopes above this depth indicate that around these uplifted limestone islands on the continental side of the Andesite line, coral reefs have been built upward on foundations that have subsided relative to sea level. But the depth of relative subsidence is less than in the coral atolls of the deep Pacific basin.

During the following night, a cursory survey of an undersea ridge east of Lau confirmed other evidence of the northeast-southwest trend of structure between Fiji and Tonga. BAIRD then proceeded eastward, made two crossings of the Tonga Trench, the first giving a maximum depth of 5300 fm, and arrived at Tongatabu at noon on 24 December.

Meanwhile, HORIZON had steamed southeast towards the separation between the Kermadec and Tonga Trenches. She found a saddle point, not as deep as had been thought, but still well beneath the general level of the deep Pacific to the east. This shallow area may be on the flank of a seamount. She then surveyed the southern part of the Tonga Trench till Christmas Eve, recording on 23 December an uncorrected depth of 5440 fm, the deepest sounding yet made in the southern hemisphere.

At Tongatabu, field parties studied the limestones of which the island is constructed, the evidence of uplift as shown by terraces, and some of the features of the so-called 10-ft shelf around the island, including blowholes and nips at the base of sea cliffs. Several expedition members observed the curious flying foxes; others spent the night in hospitable native villages. The expedition divers, accompanied by native divers, made some collections within the lagoon inside the barrier reef. Prince Tungi, Regent and Premier of the Kingdom of Tonga, received us at an unforgettable Tongan feast. We reciprocated with a shipboard reception for the Prince and prominent citizens the night before our departure.

NUKUALOFA ON TONGATABU, TONGA ISLANDS, TO PAGO PAGO ON TUTUILA, AMERICAN SAMOA

The expedition left Tongatabu on Boxing Day and was occupied with the study of the Tonga area until 7 January 1953.

During the first few days, the emphasis was on the area west of the trench. We first investigated the island shelf north of Tongatabu. It was hoped that this area might show potentialities as a worthwhile fishing ground, which could be used to improve the protein-poor diet of the Tongan people. Several of the divers were suspended from the ship by a rope reaching to 120 ft, where they drifted just above the shelf bottom at a speed of 1.5 kt. They reported sparse coral growth over a desert-like bottom.

The first satisfactory magnetometer records were obtained by Mason at this time. After an unsuccessful piston core, BAIRD surveyed Fonua Fo'ou, or Falcon Island, which is now totally submerged, but which was an active volcano 200 ft high and 2 miles long in 1936. Bascom, Jackson, Livingston, and Munk descended onto a fantastic landscape with sharp pinnacles and vertical cliffs reaching up to within 17 ft of the surface, and already richly grown over with young coral (Fig. 4). On the eastern side of the bank they found a green river of suspended material which carried enough sediment to correspond to a lowering of the submerged island by several feet per year.

In the meantime, HORIZON had explored the shelf to the north and dredged living coral and calcareous algae. On 28 December the ships met for a seismic station in the Tofua Trough. This was the last of a series of four stations on the continental side of the Andesite line. Raitt's preliminary analysis shows that at two of these stations, between Alexa Bank and Fiji, and in the Fiji Basin, the earth's crust is thin; that is velocities greater than 8 km/sec occur, respectively, below 7 and 10.5 km beneath the sea floor. The maximum velocities observed at the other two stations are 7.6 and 7.9 km/sec, indicating either a thicker crust or a different type of mantle material.

After a bathymetric and magnetic survey of the ridge capped by volcanic islands west of the main Tonga archipelago, and of the intervening Tofua Trough (see Fig. 2), in which a series of short cores were taken, BAIRD crossed the trench and occupied a seismic station about 85 miles to the east. The turn of the year found BAIRD steering west to a seismic station over the trench axis. The first and second days of January were devoted to two reversed seismic profiles along this axis at an average depth of 5100 fm. These revealed a considerable thickening of the earth's crust relative to what had been found on either side of the deep trench. Our attempt to core the trench bottom did not succeed. A 150-lb gravity corer was lowered at 0730 on 1 January, and had reached the maximum depth of 9800 m by 1400. On the way up two bad kinks developed with 9720 m out, and the cable had to be eased in with emergency tackle. Two additional kinks formed at 7200 m. The remains of the coring apparatus were finally brought aboard at 0230 the next day. The core barrel was broken off about 2 in. below the

lead weight, the valve was missing, and the bail was badly bent. The weight was severely battered and scarred, and small pieces of black volcanic rock were imbedded in the lead. Evidently the equipment had bounced along a hard, rough volcanic bottom for a considerable distance.

During and between seismic stations BAIRD took a shallow, intermediate, and deep hydrographic cast in the trench. The water samples were analyzed by Rotschi for oxygen, phosphate, silicate, and alkalinity. The temperature showed an approximately adiabatic gradient beneath 6000 m.

Meanwhile HORIZON had made a brief landing at Lifuka, where deep-sea sediments (globigerina ooze with manganese incrustations) have been reported. These turned out to be beach rocks made up of shallow-water Foraminifera. On New Year's Eve she made the deepest rock dredging yet attempted in the Pacific. The western slope of the trench yielded pumice and sand at a depth of 2000 fm. Under Fisher's direction, HORIZON also carried out a very extensive bathymetric survey of the area east of the Tonga Islands. A dramatic finding was a seamount on the eastern edge of the trench, with an abrupt, uninterrupted rise of 4-1/2 miles on its western slopes. The seamount was not flat-topped, but had pinnacles. HORIZON attempted three dredge hauls and two cores, lost two dredges, and obtained only one short core of consolidated calcareous sand. She also surveyed the northern extremity of the trench, which hooks sharply to the northwest, and made a series of jog-log (GEK) current measurements. These reveal a southward displacement in the South Equatorial Current in the region over the trench.

We may sum up the work on the Tonga Trench system by referring to successful seismic, bathymetric, magnetic, and hydrographic surveys, but to poor returns on coring. In particular, the bottom and west slope of the trench appear to be singularly unimpressionable. All of the cores obtained here consist principally of unweathered volcanic sand and silt.

On 5 January BAIRD put in for daylight hours at Neiafu in the Vava'u Islands, the northernmost group of the main Tonga Islands. The numerous steep-sided islands remind one of the coast of western Norway, except for the cocoanut palms. On these remote and little visited islands, the natives were among the most attractive met on the entire voyage. Geologic parties made a brief reconnaissance and found no volcanic rock. The islands visited by us appear to be constructed entirely of shallow-water limestones. The divers did some collecting in the lagoon. They also hooked the anchor line of their skiff onto the mast of a sunken copra schooner, and Bascom had a look at it in spite of barracuda.

Leaving Vava'u and streaming the magnetometer, BAIRD made a reconnaissance bathymetric and magnetic survey of the northern extension of the Tonga Island ridge between Vava'u and Niuatobutabu (Keppel Island). A party was

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put ashore on Niuatobutabu to collect rock samples. During the night the submarine base of the steep volcanic cone Tafahi was sounded and found to be a broad ridge about 200 fm deep. On 7 January BAIRD put into the lovely harbor of Pago-Pago. HORIZON had preceded BAIRD by one full day.

This was our first American port since we had left Kwajalein. Within a few hours after our arrival we were entertained by Governor and Mrs. Ewing. The following day a working party (with a large fraction of Ph.D.'s) transferred 17,000 lb of TNT from BAIRD to HORIZON. Informed that the tanker CHEHALIS had been sunk in the harbor in 1949, the divers obtained permission from Governor Ewing to attempt to locate and examine the craft. On 9 January Livingston and Dill, and on 10 January the same divers with Bascom, Jackson, and Munk, succeeded in reaching the ship and exploring the decks and pilot house in 165 ft of water. They gave a report of the ship's position and condition to the governor.

Again many of us had the opportunity of visiting native villages, which seemed to us to have retained to a remarkable degree their traditional way of life through the long years of American occupation. After replenishing our supplies, and acquiring the usual myriad of kava bowls, outrigger canoes, drums, tapa cloths, and foram necklaces, the expedition regretfully left Pago-Pago on 9 January.

PAGO-PAGO ON TUTUILA, AMERICAN SAMOA, TO PAPEETE, ON TAHITI, SOCIETY ISLANDS

Leaving Pago-Pago on 9 January, we proceeded towards the southeast over a smooth, steep slope with apparent slump structure at the bottom. Between here and Tahiti three widely spaced seismic stations were occupied. During the first of these stations we were able to get a successful record from an 80-lb charge fired 100 miles away. This is the longest transmission through the sea floor that Raitt's group has yet been able to achieve. On land, with similar size charges, refraction shooting over a distance of 10 miles is considered very good.

During this leg of the expedition 13 cores were taken, bottom temperature gradients were recorded, and a number of hydrographic casts made. The magnetometer was towed most of the time as a matter of routine. Using plastic bottles for sampling water, designed by Isaacs and his associates, and a tripping device invented aboard ship by Folsom, water samples were collected at distances of 1.3 and 5 m above the bottom. These samples were filtered aboard ship in an attempt to learn something about suspended matter immediately above the bottom. GEK current measurements were made simultaneously by the two ships, under Munk's direction, in order to study the coherence of the random horizontal water motion. Regular collections of air samples at mast and boat-deck level were initiated by Arrhenius. These samples are to be analyzed for fixed nitrogen content. HORIZON trailed a kytoon at 1000 ft altitude, supporting an instrument designed by Hilleary to record temperature and pressure against time.

On 12 January BAIRD visited Palmerston Atoll, discovered just before the American revolution by Captain Cook and first settled in 1862 by William Masters. Nearly all of the atoll's present 78 inhabitants are named Masters, and a sizable fraction of them visited us aboard the ship. In working up our bathymetric and magnetic survey of the atoll, Bascom discovered it to be several miles larger than shown on the only available chart, the one based upon the survey of 1774 made by Captain Cook during his second voyage.

We arrived in Papeete in the evening of 16 January. Because of our previous visit to Tonga we were potential carriers of the rhinoceros beetle, a deadly enemy of the cocoanut palm. These beetles fly only by night, and then only over distances of 400 yd at most. Accordingly we had to stand out in the lagoon an hour before sunset, anchoring at least 500 yd from shore, and not return until an hour after sunrise.

In Papeete the expedition took on fuel, water, and supplies for the last and longest leg of the expedition. Some of us had cocktails with Governor and Mme. Petibon; others were entertained by Mrs. James Norman Hall, Mr. and Mrs. Lou Hershon, and Mr. and Mrs. John Reasin, prominent American citizens on the island. Several expedition members bicycled around the island, examining sea caves and other geologic features. Revelle, Rotschi, and Fairbridge examined some solution basins on the outer reef. But it must be admitted that the scientific aspects of our Tahitian visit were hard put to compete with other attractions.

Just before our departure, a 60-kt wind-gust tore the roof off a local restaurant called "The Yacht Club," an event that was suitably observed and recorded by our meteorology party who in their usual prognostic frame of mind had chosen to lunch there.

PAPEETE, ON TAHITI, SOCIETY ISLANDS, TO TAIOHAE BAY, ON NUKU HIVA, MARQUESAS IS LANDS

On 19 January the expedition left the calm waters of Papeete harbor and sailed into the teeth of a northeast gale. The ships followed divergent courses over a steep slope descending into a smooth basin, with occasional sea knolls rising above the sedimentary plain. HORIZON stood in close to Makatea Island, an elevated coral reef not unlike Ocean Island, with elevated solution cavities giving evidence of former stands of sea level. Unfortunately the weather was too rough to put a party ashore. HORIZON then crossed the Tuamotu Archipelago for a rendezvous with BAIRD. In coring between the Society and Tuamotu Islands, she found evidence of Tertiary sediments mixed with Recent sediments on the sea floor, just as in the area between Ocean Island and the Fiji Islands.

BAIRD in the meantime made a bathymetric and magnetic survey of Takaroa, one of the King George group of atolls in the Tuamotus, and a party went ashore at Takaroa to interview and observe pearl divers. A brief geologic survey of the island was made.

Two seismic stations were occupied between the Tuamotu and the Marquesas Islands. During the second station, winch trouble developed on BAIRD while the Bottom Temperature Gradient Recorder was being lowered. When the instrument was recovered five hours later, it was found that the 0-ring seal had leaked, and that many of the internal components had collapsed. The instrument had to be virtually rebuilt, and was not back in operation until 4 February.

Both ships arrived in Taiohae bay on 24 January. Expedition members climbed the steep mountains, on foot and horseback, to enjoy the wonderful view of the deeply cut bays below. Next day a refraction profile was run over the shelf south of Nuku Hiva. The volcanic rock beneath this shelf was found to transmit sound at a velocity of roughly 3.7 km/sec, a value in good agreement with the results of similar profiles off Guadalupe Island and Hawaii. This provides additional confirmation for identification of the volcanic layer beneath Bikini and Eniwetok Atolls and Alexa Bank. Just before the survey, Fisher, Johnson, Menard, and Riedel were set ashore at Typee valley, made famous by Herman Melville. Unfortunately the party was not able to view the celebrated man-size Tikis as the local entrepreneur had established admission fees beyond reach of the impoverished scientists. That evening the French Administrator and Mme. Reboul had dinner aboard BAIRD. Afterward we viewed a performance of pre-missionary dancing.

TAIOHAE BAY, ON NUKU HIVA, MARQUESAS ISLANDS, TO SAN DIEGO

The expedition left at daybreak on 26 January. BAIRD spent most of the day making a detailed bathymetric and magnetic survey around Ua Huka Island, particularly to the southwest of the island near Invisible Bay, where Munk hopes to place a wave recorder. HORIZON went south and found a seamount in line with the western Marquesas, and two seamounts in line with the eastern Marquesas. The latter two continue the more or less regular spacing, evident in the islands, of one volcano per 50 miles. Our echo sounding profiles in the Marquesas area throw light upon two alternative views proposed by geologists regarding the structure of the Marquesas Islands: 1) that the chain of islands and the connecting ridge are entirely volcanic in origin, in the sense that they consist of materials extruded through the sea floor, or; 2) that there has been an upbowing of the crust to form a platform on top of which volcanoes have been built. Our soundings favor the first view.

From the Marquesas area the ships steamed east-southeast towards the Easter Island Rise (sometimes called Albatross Plateau). Enroute, a series of simultaneous GEK current measurements was taken by the two ships to study the

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coherence of the currents over distances up to 100 miles. As we approached the Rise, HORIZON found a gradual shoaling of the sea bottom with a 300-fm relief, but BAIRD's fathograms indicated somewhat more step-like changes in depth. On both tracks the average slope ascending the Rise was only about 0.2 percent. Near the shoal area there was a noticable increase in biological activity. Squid and flying fish were abundant, and birds were more persistent. BAIRD had winch trouble on 28 January and all hands spent most of the day making a long splice. After this date the heavy winch behaved very well. Eight full-length piston cores and 42 gravity cores were taken on the two ships during this last leg of the expedition, between 15°S and 15°N Latitude over a range of depths from 2900 to 4700 m. These should permit construction of a fairly detailed profile of the sediments on an 1800-mile section across the east Pacific equatorial region.

All but one of the long cores showed marked stratification. Both those from shallower depths and from near the Equator were very high in calcium carbonate. In the deep water between the Marquesas and the Easter Island Rise the non-calcareous component was chocolate brown clay, high in manganese and iron. On top of the Rise, a 9-m long core of globigerina ooze, grayish brown in color and without evident stratification, was collected. Miscroscopic examination showed that the Foraminifera shells are coated with a thin layer of managanese. BAIRD continued to take cores until 16 February.

Two gravity cores were collected near the Equator with a special, large-diameter (66 mm) barrel. These are to be used for radiocarbon dating. It is hoped that the large diameter will permit a time resolution of better than a thousand years, but this may not be possible because of disturbance of the stratification by small burrowing organisms. Some of these could be seen through the plastic core liner actively digging their way along the side of the core.

In a 9-m long core collected at 9°N, alternating layers of buff-colored and dark gray non-calcareous clay were found with a transition downward into several meters of dark gray clay. Fossil radiolaria skeletons in the latter show that it is Pliocene or Miocene in age. Similar gray clay was found in a long core at 15°N but below it there is an abrupt transition (probably representing a period of non-deposition or erosion), to a reddish brown, fine material which continues to the bottom of the core at about 9 m. This lower layer is probably Oligocene in age.

At all BAIRD stations from the Marquesas to San Diego, quantitative phytoplankton samples were taken between the surface and 100 m. These were supplemented by sub-surface samples at 4 hour intervals while the ship was underway. Large variations in the total phytoplankton population, or "standing crop," were found in the region of the equatorial currents; it is believed that these can be correlated with variations in the zooplankton and fish populations, and with the rate of deposition of organic skeletons in the surface layers of the sediments. In addition, samples of the colloidal material suspended in the water, much of which must be settling to the sea floor, were collected at depths of a few meters above bottom and 250–2000 m beneath the sea surface.

Nine seismic stations were occupied between the Marquesas and 15°N. Two stations were located over the Easter Island Rise; these revealed a relatively thick crust, indicating that the Rise may be intermediate in structure between oceanic and continental areas. The remaining seven stations gave results not unlike those found during the MID-PACIFIC Expedition in the eastern North Pacific. The thickness of the sediments was found to be less than 500 m, probably much less than this value.

Three successful lowerings of the Bottom Temperature Gradient Recorder were made, one of these over the Easter Island Rise. The latter yielded the largest temperature gradient yet measured, about three times the average value. Perhaps this is the result of nearby volcanic activity (manganese-coated volcanic pebbles were brought up with the probe at this station), or it may be a characteristic value for the Rise.

HORIZON's large winch had failed on 4 February, and on 10 February she lost half of her hydrographic cable and had to abandon her coring program. These losses turned out to be a boon to her meteorological, hydrographic, and biological programs. Between 4 and 15 February she took many zooplankton tows, used her kytoon for studies of the lower atmosphere, occupied hydrographic stations, and took GEK current measurements.

Between the Easter Island Rise and San Diego, sounding lines approximately 50 miles apart were run by the two ships. Two 200-m troughs were crossed, one at about 4°N, the other at 8°N.

The latter may upon further examination, turn out to fall along the Christmas-Clipperton Escarpment. Seamounts were crossed at about 17°50'N; the positions indicate that these may be part of the feature we have tentatively called the Clarion Trough. Both the Christmas-Clipperton Escarpment and the Clarion Trough, were discovered and explored at different longitudes on our previous cruises.

During the seismic station at the Equator, Bascom, Dill, Livingston, and Munk gained some experience concerning the effect of underwater explosions on submerged swimmers. The last seismic station was occupied and the last samples collected on 16 February. From then until 21 February the ships clawed their way into San Diego against strong head winds and a heavy northeast swell.

It is indicative of the vastness of the Pacific Ocean that not until we were three days out of San Diego did we sight another vessel in the open sea, the first since we had left Kwajalein nearly three months earlier.

THE TOOLS

Here we shall describe briefly the tools that were available and the extent to which they were used. In the next section we shall consider how these tools contributed to the study of various problems under consideration. The biological and meteorological programs, lying somewhat apart from the principal effort of the expedition, are considered separately in other sections.

SEISMIC SURVEY

The seismic equipment was to a considerable extent similar to that used on the MID-PACIFIC Expedition. Three hydrophones, suspended at a depth of 200 ft from buoys, were streamed at distances up to about 800 ft from the ship. Their outputs were recorded on a 15-channel Miller oscillograph in three frequency bands, centered roughly at 10 cps, 100 cps, and 1000 cps, and at two levels of sensitivity on the low- and high-frequency bands.

Partly as a result of experience gained on the MID-PACIFIC Expedition and on subsequent shorter cruises near San Diego, and partly from extensive studies by Arthur D. Raff on the sources of hydrophone "dangling noise," significant improvements were made in the hydrophone suspensions. As a consequence it was possible to increase the range of reception of the refracted ground wave by approximately 50 percent without increasing the size of the explosive charge. This, coupled with the fact that the type of ammunition carried was convenient to fire in somewhat larger charges than on previous cruises, made it possible to reach velocities below the Mohorovićic discontinuity at al most all stations instead of the 50 percent of stations on the MID-PACIFIC Expedition.

Recording on the high-frequency channels was significantly improved by use of rectified signals driving low-frequency galvanometers instead of the direct drive to high-frequency galvanometers used previously. Additional equipment designed by Victor Anderson provided for recording on magnetic tape by pulse position modulation, a system particularly advantageous for the very low frequencies transmitted by the refracted ground wave, too low to be recorded on a conventional magnetic tape system.

The previously used system of monitoring the reception with a pen-and-ink Brush oscillograph provided an immediate record of each shot. This gave essential information as to the quality of the record, and also yielded travel time distance data which could be plotted immediately for a rough shipboard interpretation of results. The necessity for developing the thousands of feet of photographic oscillograms aboard the ship was thereby eliminated.

Raitt, who was in charge of the work, was assisted by Jones and Von Herzen on BAIRD, and by North, Smith, Silverman, and Taylor on HORIZON, Altogether 25 stations were occupied, and 41, 409 lb of explosives were fired on 2133 shots. Silverman, assisted by Taylor, carried out the firing without a mishap. The total number of duds was 25, or 1.1 percent.

ECHO SOUNDERS

Both ships were equipped with EDO and NMC recording echo sounders, but the EDO was used al most exclusively. It had been modified by W. Smith of NEL for alternate keying on both the 600-ft and the 600-fm scales. The latter proved to be the more convenient. The EDO sound head was mounted on a projecting column which was lowered to well beneath keel depth to reduce water noises. A constant-frequency unit was incorporated in the keying and recording circuits. It was found advisable to remove the door of the recorder and to add a fan for better ventilation. The lubricant in the gear box was inadequate for tropical conditions, and was replaced by Dow Corning 4 compound. With Jones's and R.J. Smith's constant care, the instruments functioned satisfactorily in spite of almost continuous use throughout the expedition.

On the basis of the experience gained, several additional modifications seem indicated. A variable reference point would avoid the need for constantly switching from one scale to another when the depth happens to be very near 600, 1200, 1800, etc, fm. By using alternate pings and not recording the outgoing ping it should be possible to get good bottom echoes in the presence of a strong scattering layer. It was found that the stylus needed continuous adjustment and frequent replacement.

CORERS, DREDGES, AND BOTTOM SAMPLERS

The following bottom collecting gear was built or readied by Silverman, Dill, and Stewart:

- 2 gravity corers, 150 lb, 2-in. diameter

- 2 gravity corers, 150 lb, 1.5-in. diameter
- 8 gravity corers, 40 lb, 1.5-in. diameter
- 1 gravity corer 2.75-in. diameter (for Carbon 14 analysis)

Total - 13 gravity corers

- 2 piston corers with 10 barrels 29 ft long and 2 in. inside diameter; 2600 lb of cast iron weights
- 7 rock dredges of various types
- 4 snapper samplers
- 1 German type underway bottom sampler

The following equipment was lost or damaged for a variety of reasons:

- 4 gravity corers, 150 lb
- 2 gravity corers, 40 lb
- 4 piston corer barrels
- 3 dredges

Ball-breakers were used to give an audible signal when a corer had reached bottom. Various combinations of gravity and piston corers, and gravity corers and near-bottom water-samplers were used with variable degrees of success.

Dill was in charge of a team (Blumberg, Jackson, Maxwell) for rigging and handling the coring devices aboard BAIRD. Bramlette and Arrhenius were in charge of all other matters pertaining to these cores. With most gravity cores, Arrhenius and Rotschi extracted small samples from the bottom of the core and determined the amount of interstitial water, and its chemical composition, including ammonia, nitrate, sometimes phosphate, and pH. For comparison, a similar chemical analysis was made of the supernatant water. One gravity core 1 m long was cut into 26 thin slices, all of which were analyzed as above. Other gravity cores were kept inside their plastic liners, labeled, laquered, sealed, waxed, and stored away. Piston cores were extruded from the steel barrel in 70 cm sections. A field description was made, samples were extracted for analysis of interstitial water, and the core sections were then wrapped in acetate sheets and wrapping paper, placed inside mailing tubes, sealed with tropic wax, and stored. In two cores, 0.5-in. cubes were cut for studies of fossil magnetism. BAIRD took 20 piston cores, with a total length of 90 m. Full length (9m) cores were obtained, using a tight, leather-cupped piston, 650 lb of cast iron weights on the piston core barrel, 6 ft of free fall, and a 150 lb 6 ft gravity corer suspended from a ball-breaker, as the tripping weight. During the early part of the expedition, a lighter tripping weight was used and frequent pre-tripping was experienced. A loose fitting piston was also tried at first, with the result that several cores slipped out of the barrel just as it was brought above the water surface.

HORIZON was not equipped with piston corers, but 52 of the expedition's 93 gravity cores were taken aboard that ship under direction of Riedel. The cores were treated as described above, and placed in a cold room as additional precaution against deterioration. After losing two corers owing to breaking of the cable when snarls entered the sheave, a large white messenger was sent down the cable so that a snarl could be easily seen when the corer was being brought in. Also, a flange was put near the upper end of the barrel to prevent penetration of the corer past the top of the plastic liner.

Twelve dredge hauls were made from HORIZON, under direction of Menard and Stewart, using a chain bag rock dredge. The first eight hauls brought up bottom samples, the deepest from 2000 fm. Three dredges were lost on the last four lowerings, one because too much strain was put on the wire, one because the wire clips on the end of the wire slipped, and the last because the winch motor burned out during a lowering and 1400 m of wire had to be cut off.

BOTTOM TEMPERATURE-GRADIENT RECORDER

A first attempt to measure temperature gradients in the sea bottom was made on the Swedish ALBATROSS Expedition. Bullard and Maxwell designed a gradient recorder during Bullard's stay at the Scripps Institution in 1949. Further development was carried out by Isaacs, Snodgrass, and Maxwell, and the instrument was first used successfully on the MID-PACIFIC Expedition; an improved model was used by Maxwell during CAPRICORN.

The instrument measures the difference in temperature between two points in the bottom sediments; one about 2 and the other 8 ft beneath the sea bottom. It consists of a hollow steel spear 10 ft long and 1.64 in. in outside diameter, in which thermistors have been placed near each end. The spear is attached at its upper end to a water- and pressure-tight chamber, within which there is a battery-powered, self-balancing, null-type potentiometric recorder. From a 30-minute continuous record of the temperature difference between the two thermistors it is possible to deduce the undisturbed temperature gradient in the sediments. A core is obtained at the same station and samples of the sediments are carefully preserved for laboratory determination of thermal conductivity. The product of the conductivity and the temperature gradient gives the heat flux through the sea floor.

Altogether, nine measurements of bottom temperature gradient were made. Assuming that the thermal conductivity of the sediments is about that found on the MID-PACIFIC Expedition, the seven measurements made in oceanic areas yield an average value for the heat flow of 1.3×10^{-6} cal $cm^{-2} sec^{-1}$. Two measurements made over sub-continental areas average more than twice this value. Six measurements obtained on the MID-PACIFIC Expedition gave an average value of 1.2×10^{-6} cal cm^{-2} sec^{-1}.

UNDERWATER PHOTOGRAPHY

The underwater cameras used were of two types, those lowered by cable and those used by divers. Of the former type, there were two. The Mark I camera, built at NEL, was an improved model of the one used on the MID-PACIFIC Expedition. It is designed for a maximum depth of 1500 fm and consists of three basic components: the upper unit contains a 35 mm robot camera capable of taking 45 consecutive pictures, the middle unit a strobe light, the lower unit a mercury switch which actuates the camera and light upon contact with the bottom. The camera was pointed downward 35° from the horizontal, the light about 20°. Under Dill's direction, four photographs were taken just off Fiji, two of which show ripple marks at 1500 fm – the greatest depth at which they have been observed. The photographs are usable, but not of good quality.

The Mark II camera, built at NEL under Dill's supervision, was designed to reach the greatest depths of the sea. The tubes are made of hardened Timken steel, and the total weight in air is 2300 lb. It contains a strobe light 20 times as powerful as the one used in Mark I, and a modified 70 mm Photronic camera capable of taking 375 consecutive pictures. It can be triggered either by a clock mechanism (intended to be used on the way down) or by striking bottom. Because of difficulties with the control mechanism of the dredging winch on BAIRD it was considered unsafe to use this heavy instrument, and we must consider it a winch casualty.

Several types of hand-held underwater cameras were used by the divers. MacFall used a Rolleiflex and a Leica still camera in underwater cases purchased from U.S. Divers Company. The reflex focusing system in the Rolleiflex is a great advantage in underwater work. With a pressurized case, MacFall was able to take pictures down to a depth of 80 ft though the camera is supposed to be used only above 35 ft.

Bascom used a Fenjon underwater movie camera, and exposed 1500 ft of 16 mm color film. None of this film has as yet been developed. The camera leaked during a dive beyond a depth of 60 ft over Alexa Bank, and from then on worked only intermittently.

Dill used a 16-mm Bell and Howell movie camera in a watertight case built at NEL. He took 280 ft of colored film (not yet developed) up to depths of 120 ft, and found the camera and case satisfactory.

DIRECT UNDERWATER OBSERVATIONS BY FREE-SWIMMING DIVERS

CAPRICORN was the first Scripps Institution expedition during which scientists as free-swimming divers made direct observations of the underwater world. The warm, clear waters of the South Pacific are ideally suited for this work, and the divers were able to contribute effectively to the principal expedition tasks.

The diving team consisted of Bascom, Dill, Jackson, Livingston, MacFall, and Munk, with Livingston in charge. There were no mishaps, or even near-mishaps, thanks partly to the sympathetic attitude displayed by sharks, barracuda, and other members of our attentive nektonic audience.

The principal functions of the divers were to explore, photograph, and sample the sea bottom in areas that were inaccessible to the larger vessels, including most of the important sublittoral zone close to the shore line; and also those areas that could be investigated more effectively by the divers than by blind use of overside instruments. Such areas include all of the lagoons of coral atolls, submerged banks, and island shelves within 150 ft of the surface.

In addition to free swimming, underwater exploration was accomplished by trailing the diver behind a slowly moving or drifting vessel at the end of a weighted line extending close to the sea bottom. The divers also inspected, repaired, and calibrated underwater instruments; they assessed damage to HORIZON's EDO dome and propeller and freed the fouled propeller of one of the ship's tenders; they also located and inspected a Navy tanker at the bottom of Pago-Pago harbor. Bascom conducted an underwater search for a ditched plane. The divers conducted tests regarding the effect of underwater explosions upon submerged swimmers.

Except for minor modifications, we depended on standard French aqualung equipment, available from the U.S. Divers Company. The equipment functioned reasonably well throughout the expedition with only routine maintenance.

Altogether there were 20 diving days consisting of about 75 man-hours of actual diving. A list follows below. A log and summary of the observations was prepared by Livingston for each of these.

DIVING DAYS	DATES	LOCATION
1 and 2	29–30 Nov.	Ocean Island
3 and 4	8–9 Dec.	Alexa Bank
5 and 6	13–14 Dec.	Korolevu, Fiji Islands
7	15 Dec.	Serua, Fiji Islands
8	25 Dec.	Kanacupolu, Haatafu; Tonga
9	26 Dec.	Nukualofa, Tonga
10	27 Dec.	Island shelf N of Tongatabu, Tonga
11	27 Dec.	Falcon Island, Tonga
12	5 Jan.	Vava'u, Tonga
13 and 14	8–9 Jan.	Pago-Pago, American Samoa
15	18 Jan.	Arue, Tahiti
16	20 Jan.	Takaroa, Tuamotus

17	25 Jan.	Nuku Hiva, Marquesas
18	8 Feb.	Equatorial Eastern Pacific
19	11 Feb.	Equatorial Eastern Pacific
20	16 Feb.	Equatorial Eastern Pacific

HYDROGRAPHIC CASTS

In addition to casts with standard Nansen bottles and reversing thermometers, made on HORIZON by Payne, Larimore and Horton, and on BAIRD under Folsom's direction, the following special equipment, designed by isaacs, was used:

1) Metal reversing frame. This frame was suitable not only for attaching ordinary reversing thermometers but also for

2) pressure-bombs in which protected thermometers were enclosed for extremely deep casts, and

3) plastic water samplers used to collect colloidal and suspended materials in the water, where special precaution had to be taken to avoid flocculation or contamination by metal surfaces.

To sample the water very near the sea floor, Folsom devised a method for tripping the sampling bottles when the ball-breaker struck bottom. This was used in conjunction with the gravity corer. Folsom also developed a heavy, rapidly falling messenger (go-devil) together with a messenger exchanger and splice jumper. All equipment was modified to fit the heavy winch cable as well as the hydrographic cable.

Folsom found that under tropical conditions thermometers have temporary calibration shifts and show unusual signs of aging. He therefore undertook occasional ice-point calibrations and detected changes up to 0.05°C.

CURRENT DRAG

The current drag is an adaptation by Knauss of a device used by Pritchard and Burt in Chesapeake Bay. A 12 sq ft wooden cross with 100 lb of weight attached is lowered to various depths between 4 and 300 m, and the vertical and horizontal wire angles measured. An allowance is made for the resistance of the wire. The measurements give relative current only.

Munk used the cross at two locations in the South Equatorial Current, and found a tendency for the current to slow down, or possibly even reverse, with depth. Because of the large differences obtained during the lowering and raising of the current cross, the measurements were considered rather unreliable.

GEK

Small type GEK electrodes were used. One hundred and twenty-six measurements of surface current were made; 24 of these were made simultaneously by the two ships, to study the coherence of the random horizontal motion in the sea. In addition, a study of the currents over Tonga Trench was carried out in some detail by HORIZON. Munk was in charge of this work.

BATHYTHERMOGRAPHS

Bathythermograms were taken from both vessels every 2 hours while the ships were under way. Altogether, 1170 BT slides were collected.

THERMOGRAPH

Taylor recording thermometers were installed on both vessels. These record the temperature at a depth of about 10 ft to an accuracy of about 0.2°C.

TOWED MAGNETOMETER

The towed magnetometer is basically a type AN/ASQ-3A magnetic airborne detector, modified in the first place for airborne geophysical work and further modified so that the detecting element may be towed behind a ship. The Lamont Geological Observatory kindly loaned us the detecting mechanism, a waterproof housing designed by Mr. Edward T. Miller, and a suitable tow cable, while the associated electronic equipment was obtained on loan from the U.S. Geological Survey.

Some difficulty was at first experienced in towing the instrument smoothly at our standard speed of 11.5 kt. As supplied, it was intended to be towed at rather lower speeds, but we found that by re-arranging the weight distribution and by replacing the keel by tail fins we were able to achieve adequate stability at our maximum speed. Altogether, the magnetic survey covered 7800 miles.

The instrument records the total magnetic field of the earth. Its accuracy is limited by the stability of the electronic circuits and by record noise of mechanical, electrical, and magnetic origin. It is estimated that under normally favorable circumstances a relative accuracy of ± 2 gammas is possible over periods of the order of a few hours and that, with careful calibration, the absolute accuracy might be ± 20 gammas. Regional anomalies of the order of 100 gammas were encountered; in the neighborhood of volcanic islands local anomalies reached several times this value. The instrument therefore possesses adequate sensitivity.

Our general feeling is that the instrument could be re-designed more compactly for ease of handling and for greater stability of towing. Some consideration should be given to the possibility of combining magnetometer and GEK electrodes so that the two can be towed simultaneously without danger of becoming entangled. This work was done by Mason, who was assisted by Blumberg.

SPINNING MAGNETOMETER

The spinning magnetometer is intended for shipboard measurement of the directions of residual magnetization in cores of deep-sea sediments. It was designed and constructed at the Radiation Laboratory of the University of

California, Berkeley, and owes much to the dynamic enthusiasm of Dr. Hugh Bradner and the electronic ingenuity of Mr. Ray Robertson.

It is now generally accepted that most igneous rocks as they cool become permanently magnetized in the direction of the earth's magnetic field. The work of the Carnegie Institution suggests that in the process of deposition the magnetic particles of sediments also tend to align themselves in the direction of the earth's field, so that measurement of the residual magnetism of cores should yield information concerning the magnetic history of the earth. Besides throwing light on the vexed question of past reversals of the field, such measurements may be of value in the dating of sediments, particularly as a method of correlation.

Previous attempts to measure the residual magnetism of cores have met with limited success. One reason maybe that stray AC fields modify the direction of magnetization during the interval between taking the core and making the measurement. We therefore decided to attempt to make the measurement on the ship as soon as possible after a core was taken aboard. The design of the instrument was dictated to a certain extent by considerations of ship movement and restricted space.

The magnetometer follows the general principle underlying earlier instruments, a sample of the core being spun close to a pickup coil and the amplitude and phase of the induced emf measured. Two such measurements with the specimen in different orientations suffice to establish the direction of magnetization. The specimen is rotated at 6000 rpm by means of a horizontal air turbine. A small permanent magnet mounted on the same shaft, in conjunction with a second coil which can be rotated relative to the shaft, provides a reference voltage of variable phase. The two signals are compared by a potentiometer method, using as detector a phase-sensitive lock-in amplifier designed to discriminate sharply against unwanted signals. Using 10 cm^3 samples the magnetometer was estimated to be capable of measuring intensities of 10^{-6} cgs units with an accuracy of ± 5 percent and the direction of magnetization with an accuracy of ± 3 degrees.

For various reasons the instrument was not set up until the latter part of the cruise, when the most suitable cores were expected to be taken. At this stage it was discovered that the ship's supply of compressed air, which was to have been the primary source of power, was not capable of supplying air at the required rate. It was necessary therefore to fall back on bottles of oxygen and nitrogen, but the rate of consumption proved to be higher than anticipated and the available supply was insufficient for more than a few hours running. Difficulty was experienced in controlling the speed of the turbine and after certain modifications had been made to the electronic circuit, little bottled gas was left for serious measurement of the core specimens. Although perfectly satisfactory measurements were made of basalt and sandstone test specimens, it was not found possible to make any reliable measurement of

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the cores. Whether or not this was due to low intensities of magnetization or imperfect adjustment of the electronic circuits through lack of air is not known. However, it is proposed to continue work on the magnetometer, aiming particularly at greater stability and a higher rate of rotation. This work will be paralleled by attempts to determine the magnetite content of the cores (if any) and the magnetite content and magnetic parameters of typical terrigenous sediments (in which the oxidation-reduction potential may be more favorable for preservation of magnetite).

THE MAGNETOMETER USED AT OCEAN ISLAND

The instrument used at Ocean Island was a La Cour quartz horizontal-force magnetometer, better known as the QHM, which was loaned to us by the Carnegie Institution of Washington. The principle underlying the QHM is the balance of the horizontal magnetic couple acting on a magnet suspended from a quartz fiber. Although simple and robust, and easily manipulated, the QHM is capable of great accuracy.

SOME EXPEDITION TOPICS

In this section we shall discuss four topics to which the work of the expedition has contributed. The first deals with the physical structure of oceans and sub-continents, the second with sedimentation, the third with coral reefs, and the fourth with the use of the towed magnetometer as a geophysical and navigational tool.

OCEANS, SUB-CONTINENTS, AND CONTINENTS

Why are there continents and oceans? Have the ocean basins existed with substantially their present location and depth throughout geologic time? These questions are fundamental to an understanding of the origin and geologic history of the earth. They have not been satisfactorily answered.

A *description* of the "first order" features of the Pacific Ocean must necessarily precede any attempt to answer these questions. The results from recent expeditions have made it clear that only five years ago our picture of these principal features was inadequate.

Among the puzzling features of the Pacific are large, relatively shallow "sub-continental" areas which appear to be intermediate in character between the true oceanic basins and the continents. We have visited two such areas, the Melanesian sub-continent west of the Tonga Islands, and the Easter Island Rise (sometimes called "Albatross Plateau") to the east of the Marquesas. Are these sub-continental areas relatively stable features, or are they continents that were, or will be?

Characteristics of the Ocean Basins

Thickness and Character of Crust. Evidence from earthquakes has indicated that the crust beneath the Pacific Basin is thinner than beneath continents. Our seismic work on the MID-PACIFIC and CAPRICORN Expeditions has shown quantitatively how remarkably thin the crust beneath the Pacific really is. Typical values of this thickness (defined as the distance between sea bottom and the Mohorovićic "discontinuity") are 5 to 9 km, compared to a thickness of 30 to 40 km beneath continents. Above the discontinuity, a zone averaging 5.5 km in thickness with an average sound velocity of 6.8 km/sec underlies about 1.5 km of material with a velocity close to 5.2 km/sec. Between this layer and the sea floor there is usually a thin veneer of sediments.

Bathymetry of Sea Bottom. One outstanding characteristic is the relative absence of folded structures. The Cook, Society, and Marquesas Islands appear to rise as chains of volcanoes directly from the deep-sea floor, rather than as peaks on a broad arch or swell. However, such a broad submerged structure is characteristic of the Hawaiian Islands and the Mid-Pacific Mountains in the North Pacific. In the South Pacific, an uplifted block underlies the atolls of the Tuamotus (see Fig. 5).

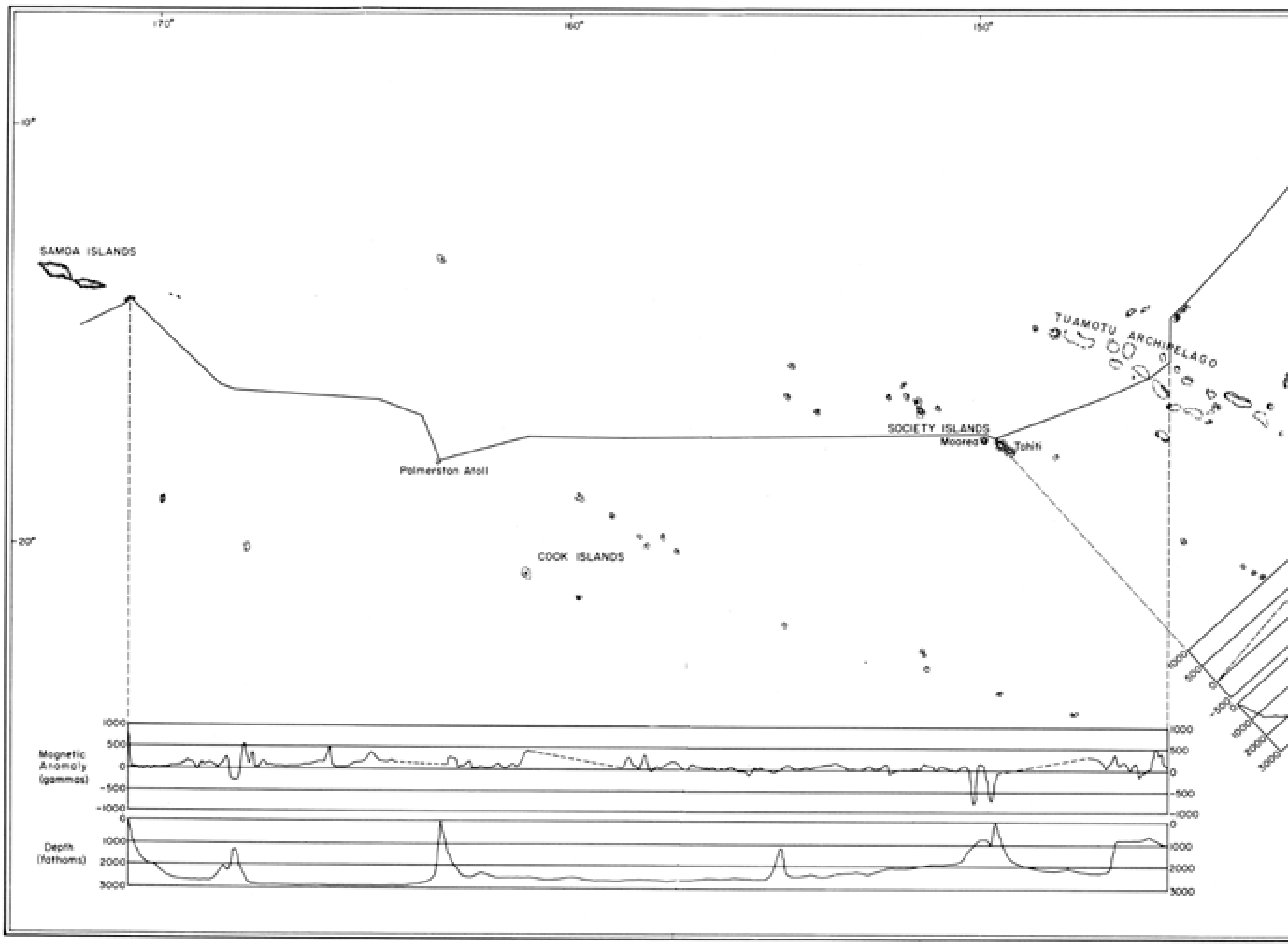

FIGURE 5. Bathymetric and magnetic profiles from Samoa to east of Marques
the Cook, Society, Tuamotu, and Marquesas Archipelagoes. Note that the Sa
and Marquesas Islands rise abruptly from the deep and nearly flat Pacific Ba
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parallel to the islands' trend. The coral atolls of the Tuamotus evidently ris
uplifted block.

FIGURE 5. Bathymetric and magnetic profiles from Samoa to east of Marquesas across the Cook, Society, Tuamotu, and Marquesas Archipelagoes. Note that the Samoa, Cook, and Marquesas Islands rise abruptly from the deep and nearly flat Pacific Basin. This probably

applies also to the Society Islands, where our track west of Tahiti was nearly parallel to the islands' trend. The coral atolls of the Tuamotus evidently rise from an uplifted block.

On the other hand, major zones of fracture are found. For example, the Mid-Pacific Mountains and the Murray Escarpment appear to be parts of one great structure. The latter feature was established during the NORTHERN HOLIDAY Expedition as an escarpment extending from off southern California towards the Hawaiian Islands, following that particular great circle which is the most direct route between San Diego and the Marshall Islands. On CAPRICORN, HORIZON and BAIRD each made ten crossings of the Murray Escarpment on their way to the Marshalls. It turned out to reach almost to the Hawaiian Islands; a continuation of the same great circle leads directly along the eastern segment of the Mid-Pacific Mountains, which start just west of the Hawaiian Islands.

Two major features to the south were explored on the last leg of the expedition. These had been crossed previously on the SHELLBACK and MID-PACIFIC expeditions. The Clarion Trough is a narrow trough about 2000 miles long, and the Christmas-Clipperton Escarpment is a low escarpment more than 2000 miles long. Both seem to fall along great circles. If these features and the Murray and Mendocino Escarpments are plotted on a great circle chart, they appear as four nearly straight parallel lines.

One may argue in analogy with experiments on the fracture of variously shaped bodies under stress that these quasi-parallel features are the result of a single planetary stress system. If they are, they do not correspond, as far as we know, to any stress system that has been proposed in the literature.

Heat Flux. Six measurements on the MID-PACIFIC Expedition clustered closely around a value of 1.2×10^{-6} cal cm^{-2}sec^{-1}, a value typical also of continental heat flow. Assuming that the thermal conductivities of the sediments are about the same as those found previously, the seven measurements of thermal gradients over oceanic areas on CAPRICORN average 1.3×10^{-6} cal cm^{-2}sec^{-1}. The scatter is however much larger, with values ranging from 0.5 in the relatively shallow area between the Tuamotu and Marquesas Islands, to 2.0 at 15° N in the Eastern Pacific.

CAPRICORN measurements covered a far larger area than those on the MID-PACIFIC Expedition and this might account for the larger scatter. A greater number of measurements might show a systematic pattern of variations.

Evidence for Subsidence. The evidence at Bikini now consists of (a) a bore hole showing shallow-water limestone down to at least 2500 ft; (b) dredging at Sylvania seamount (adjoining Bikini) yielding volcanic rock at 4000 ft; (c) cores on the outer slope of Bikini bringing up volcanic rock at 6000 and 9000 ft; (d) seismic measurements giving the same velocity in Sylvania seamount as in the rock 3200 to 4500 ft beneath Bikini.

At Eniwetok, a bore hole yielded (a) shallow-water limestone to 4200 ft, and (b) igneous basement at 4200 ft. CAPRICORN seismic measurements indicate an igneous basement at this depth with an irregular surface, like an old volcano.

In the North Pacific many flat-topped seamounts have been found by Hess and on previous NEL and Scripps expeditions, being submerged to the same order of depth as Sylvania Seamount and the depth of the igneous basement beneath Bikini and Eniwetok. On the MID-PACIFIC Expedition, shallow water reef coral and molluscan faunas of Cretaceous age were dredged from three flat-topped peaks, now at depths of 5000 to 6000 ft, which crown the Mid-Pacific Mountains. The comparatively flat tops of other seamounts strongly indicate that they once reached to the surface where they were planed off by surface waves. They then subsided, either by a rise in sea level or a drop in the sea bottom. On some seamounts coral built upward at the same rate as the seamounts subsided, and these became coral atolls. On others, the coral either could not get started, or failed to keep up with subsidence; and these became the flat-topped seamounts.

We did not find flat-topped seamounts in the South Pacific, although many atolls exist there, and their steep slopes down to depths of 500 to 800 fm indicate considerable subsidence. Perhaps the environment is more favorable for the growth of coral.

Thickness of Sediments. As pointed out in the section on sediments, our seismic refraction work indicates that the thickness of unmetamorphosed sediments over a large part of the deep Pacific basin is at most a few hundred meters. Geochemical considerations require that the total thickness of deep-sea deposits laid down throughout the geologic past should be five to ten times this value. From the estimated rate of deposition during and since the Tertiary we find that the observed thickness of sediments corresponds at most to deposition over one or two hundred million years. We are thus almost forced to the conclusion that if deposition of sediments was taking place in the deep sea prior to the late Mesozoic, these earlier deposits are not now present in unmetamorphosed form.

Characteristics of Sub-Continental Areas

One of the principal tasks of CAPRICORN was to investigate two sub-continental areas, the Melanesian sub-continent and the Easter Island Rise. These areas were previously known to differ from typical oceanic areas in a number of ways: 1) the sub-continental areas are a mile shoaler, on the average; 2) their rocks are of the andesitic type, rather than the typical olivine basaltic type of the Pacific basin; 3) the sub-continental areas are seismically much more active than the oceanic area; 4) they are characterized by relatively slow seismic surface waves, and relatively large energy losses from surface reflections of deeper-travelling waves.

CAPRICORN has supplemented our knowledge with regard to the first two of these criteria, by extensive soundings and the collection of rocks from the sea floor and from islands. With regard to the criteria used above for describing typical oceanic areas, the following can be said:

Thickness and Character of Crust. Over the Easter Island Rise seismic velocities greater than 8 km/sec were not observed; the maximum velocities at depths greater than about 7 km were 7.2 and 7.9 km/sec. The thickness of the crust may be intermediate between deep oceanic and continental areas or the mantle may be different in character from that elsewhere. Over the Melanesian sub-continent, two stations gave maximum velocities of 7.5 and 7.9 km/sec at depths greater than about 7 km, while two others (one in the Fiji basin where the water depth is more than 2000 fm, the other between Alexa Bank and Fiji) gave typical "Moho" velocities at depths of 10.5 and 7 km. Above 7 km, velocities and thicknesses in both sub-continental areas are essentially similar to those in the deep Pacific basin. Thus if these areas are in isostatic equilibrium, there must be significant differences in density distribution below 7 km between the sub-continental and the oceanic areas.

Bathymetry of Sea Bottom. The small part of the Easter Island Rise which was explored during CAPRICORN resembles the topography of the deep-sea floor off Oregon and northern California, another "sub-continental" region. The Melanesian sub-continent appears to consist of a series of basins and ranges, with individual ranges about 10 to 20 miles across. These two sub-continental areas, though differing from one another, were quite different in topography from the Pacific basin.

Heat Flux. Two out of the nine measurements on CAPRICORN were taken over sub-continental areas, and these gave the two largest values of heat flux. Over the Easter Island Rise the value was 3.6×10^{-6} cal $cm^{-2} sec^{-1}$; in the Fiji Basin within the Melanesian sub-continent the value was 2.1×10^{-6}. These values compare to 1.2×10^{-6} and 1.3×10^{-6} for the average heat flux on the MID-PACIFIC Expedition, and the oceanic stations on CAPRICORN, respectively. It should be pointed out, however, that the largest oceanic value on CAPRICORN, 2.0×10^{-6} in the eastern North Pacific, was nearly as large as the value in the Fiji Basin.

Evidence for Relative Changes in Sea Level. The evidence here is less conclusive than in the deep Pacific Basin. The seismic profile across Alexa Bank indicated that calcareous sediments extend down to 800 m, overlying an irregular volcanic surface. The channels between broad island shelves off the Tonga Islands at depths of about 300 fm, and sharp increase in slope above 250 fm around islands of the Lau Island Ridge, may also be the result of relative subsidence. On the other hand, both the Lau Islands and the limestone islands of Tonga also exhibit uplift of the order of 600 ft.

The Boundary Features

First we may refer briefly to the remarkably gradual rise from the deep basin onto the Easter Island Rise. This sub-continental slope is roughly 0.1°, as compared to continental slopes of the order of 5°.

Our principal concern here is with the CAPRICORN study of the Tonga Trench system, one of several similar systems surrounding the Pacific Basin. These remarkable features at the boundary of the oceanic area may well contain the clues to the questions raised at the start of this discussion.

Like the Aleutian Trench, and other great foredeeps of the Pacific, the Tonga Trench is part of a deep-reaching structure characterized by contemporary and extinct volcanism, large gravity anomalies, and a very high seismic activity. A typical section across the Tonga area from west to east includes the following features:

- (a) *Melanesian sub-continent* at a depth of 1000–1500 fm.
- (b) *Volcanic ridge* rising to about 700 fm, capped by volcanic islands and seamounts.
- (c) *Tofua Trough* with a maximum depth of about 1000 fm. Our seismic results show that the thickness of sediments in the trough is more than 2000 m.
- (d) *Main island ridge* reaching up to 30 to 50 fm, from which the elevated limestone islands of the eastern Tonga Archipelago rise to heights of 100 to 600 ft.
- (e) *Tonga Trench*, extending to depths of more than 5000 fm.
- (f) *East ridge*, rising about 200 fm above the
- (g) *Pacific basin* to the east, with average depth of 2500 fm.

Thickness of Crust. Our seismic surveys indicate a thin crust on both sides of the trench. Beneath the trench the crust is significantly thicker than on the two sides, the Mohorovićic discontinuity lying at depths of at least 15 and perhaps 20 km.

Bathymetry of Sea Bottom. The Tonga Trench, or rather the northern section of the Tonga-Kermadec Trench, is over most of its length a very slightly arcuate furrow convex to the east. Just southwest of Samoa the northern part of the trench bends very sharply to the northwest, as does the Andesite line. Here the trench loses its identity, ending in a wide, flat-bottomed trough. As in the case of the

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Aleutian Trench, the Acapulco Trench, and others, the trench flank bordering the islands is steeper than the offshore side, and the sea floor immediately east of the trench rises in a broad ridge or swell which may be capped by seamounts.

The depths along the trench axis range from 3000 to 5500 fm over most of the length. The greatest depths occur close to 24°S, where the axial trend changes markedly. Our maximum observed depth was 5440 fm (uncorrected, using sound velocity 4800 ft/sec). The corrected depth has yet to be worked out accurately, but it will be in the neighborhood of 5650 fm, one of the deepest soundings ever made.

South of 17°S the trench is generally V-shaped, although in the deepest portions there is a platform at about 4800 to 4950 fm cut by a deeper, steep-walled inner gorge up to two miles wide. Reflection shooting along this gorge indicates it to be flat-bottomed at about 5500 fm. North of 16° the trench is flat-bottomed and wide in cross-section. The bottom gradually shoals to the northwest.

The Tonga and Kermadec Trenches may be one structure, their apparent separation being due to the presence of a rather superficial seamount constricting the furrow at about 26°S. However, the question whether the trenches are *en echelon* or in line at this point is still undetermined. Further careful soundings are required to answer this important question.

A seamount rising from over 4500 fm to within 200 fm of the sea surface on the east flank of the Tonga Trench at the latitude of Vava'u was investigated in detail by HORIZON. Four attempts to obtain bedrock samples from this seamount were unsuccessful. Such a sample would be extremely valuable. If it consisted of volcanic material it would help determine the position of the Andesite line with regard to the trench axis. If the seamount is capped by a drowned coral reef and the age could be determined from fossil evidence, some minimum age could be assigned to this part of the trench. This statement is based on bathymetric evidence which suggests that the seamount rose after or during the later stages of the trench formation, hence the constriction of the trench just west of the seamount. There is also bathymetric evidence that the seamount is capped with coral pinnacles rising from a platform at about 500 fm to a depth of about 200 fm. If this interpretation is correct, it indicates a slight subsidence. R.L.F., H.W.M., W.H.M., R.W.R., R.R.R.

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PROBLEMS OF DEEP-SEA SEDIMENTS

From the study of sediments deposited in shallow waters and nearshore we may gain greater understanding of the ways in which the sedimentary rocks on land were formed and indeed this is the principal purpose of such studies. Our purposes in studying the sediments of the deep sea are quite different. By comparison of these deposits, which have so many distinctive characteristics, with the nearshore shallow-water sediments, we may learn a good deal about the chemical and physical processes of sedimentation. But our principal objective is to gain information on the geologic history of the ocean. These sediments in many parts of the sea are laid down so extremely slowly that a core a few meters long represents deposition over periods of hundreds of thousands and even millions of years. It thus contains a record which if we could read it aright, would tell us about events in the ocean during the late geologic past.

There are places also where the sediments exposed at the bottom surface or buried beneath a few feet of sediment are Tertiary in age, that is they were deposited 10 to 70 million years ago. The distribution and character of these ancient sediments and the kinds of fossils they contain can give us information on oceanic depths, the temperatures and chemical composition of the waters, and ocean circulation during the Cenozoic era.

Over a longer time scale the sediments of the deep sea may have constituted by far the larger part of all sediments deposited throughout geologic time. Thus the geochemical transformations of the earth's crust during the past three billion years cannot be adequately understood until we have a more complete knowledge of the deep-sea sediments

Geochemical Considerations

These sediments are unique in one most important respect. They are rarely if ever uplifted to form sedimentary rocks on land. No example is known of sedimentary rocks above sea level which are unquestionably of deep-sea origin. We must conclude therefore that the processes of weathering, erosion, and sedimentation have brought about a loss of materials from the continents to the deep-sea floor. The total amount of material thus lost from the continents could be computed if we knew either the average rate of sedimentation on the sea floor throughout geologic time, or the total amount of material which had been weathered and the portion retained on the continents as sedimentary rocks or reincorporated in igneous rocks.

The relative amounts of deep-sea sediments and of continental sediments may be estimated by comparing the average chemical composition of continental sedimentary rocks with that of the igneous rocks from which they are derived. For example, continental sedimentary rocks contain nearly three times as much calcium as the source material. Unless the average composition

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of igneous rocks has changed during geologic time, this must mean that for every gram of continental sedimentary rock nearly 3 grams of igneous rock have been used up, and that the mass of sediments transported to the deep sea is at least twice as great as the mass of continental sediments. From this and similar geochemical computations Kuenen concluded that the total mass of deep-sea sediments deposited throughout the geologic past is about six times the total mass of sediments remaining on the continents, and that the thickness of the deep-sea deposits should be of the order of 3 km.

At the present time, the preponderant type of deposition on the deep-sea floor is of sediments high in calcium, namely globigerina ooze and other calcareous deposits. If the deposition throughout the geologic past had been like that at the present time it would be impossible to arrive at a geochemical balance, because both the deep-sea and continental sediments would be higher in calcium than the igneous rocks from which they are derived. Thus we arrive at another most important conclusion, namely that the character of the deposition on the deep-sea floor has changed radically with time; throughout most of geologic history, deep-sea sediments must have been lower in calcium than the average igneous rocks, whereas the present deposits have an excess of calcium.

Except for calcium and magnesium all the major elements are more abundant in igneous rocks than in continental sedimentary rocks, hence these elements must have become concentrated either in solution in the sea itself, as in the case of sodium, or in the deep-sea sediments. This concentration in the deep sea is particularly striking for manganese, phosphorus, titanium, and iron. The sedimentary rocks of the continents contain only 10 percent as much manganese and 30 percent as much iron, phosphorus, and titanium as igneous rocks. Analyses of deep-sea sediments suggest that many of the minor elements, for example nickel and cobalt, have likewise been concentrated on the sea floor.

Fundamental Problems of Deep-Sea Sediments

Although as shown above, computations based on average chemical analyses have given important clues concerning the geochemical history of the continents and the deep-sea floor, there is little direct information on which to base answers to the following three fundamental questions:

1) What is the total mass of sediments deposited on the floor of the deep sea during the two or three billion years of geologic time?

2) What is the composition of the sediments and the source of the material?

3) How have the composition and rate of deposition of deep-sea sediments varied with time?

Prior to World War II it was generally supposed by geologists and geophysicists that the deep-sea deposits formed a thin and moderately uniform blanket over the sea floor and it could reasonably be hoped that answers to the above geochemical questions might be arrived at by a rather small number of observations.

But information accumulated since the war, particularly by the Swedish Deep-Sea Expedition around the world, the Lamont Geological Observatory – Woods Hole expeditions in the Atlantic, and the Scripps - NEL expeditions in the Pacific, has made it evident that the simple picture of a blanket of sediments spread uniformly on the bottom is far from correct. Both the rates and processes of sedimentation on the deep-sea floor differ widely from place to place and within geologically short intervals of time. Before we can answer the basic geochemical questions posed above it will be necessary to gain a greater understanding of the processes by which the different sediment components are deposited and of the alterations that transform some of them after deposition.

Primary Components of Deep-Sea Sediments

In general there appear to be four major kinds of material: 1) fine particles of clay, iron hydroxide, possibly quartz and other minerals transported from the continents to the sea by wind or running water and dispersed over the sea floor by the ocean waters; 2) the calcareous or siliceous skeletons of small animals and plants that live as plankton in the surface layers of the sea, chiefly diatoms, calcareous algae, Foraminifera, and radiolaria; 3) volcanic glass and mineral crystals ejected from sub-aerial and submarine volcanoes; 4) materials precipitated inorganically from solution in the sea water, perhaps by electrochemical processes involving surface reactions on colloidal particles (for example particles of iron oxide settling through the water may “scavenge” rare elements dissolved in the water and bring about their concentration in the sediments).

Transport and Deposition

These various types of materials settle in a gentle and steady rain which tends to form a mantle of debris spread uniformly over the sea floor. But there are also processes which transport material from one part of the bottom to another. As a result the rate of deposition on the sea floor is widely variable. The agencies of bottom transport always tend to fill up the low places and to strip off topographic highs. In consequence, accumulation of debris may be very slow on highs and in many cases erosion seems to be taking place, so that deposits laid down ten or more million years ago are buried under a few feet of sediment or even exposed at the surface. In other areas, particularly at the foot of large relatively high areas, deposition appears

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to be so rapid that a smooth sedimentary apron slopes gently outward, often for hundreds of miles. Turbidity currents, that is currents which gain their energy from the differences of density that result when bottom materials are thrown into suspension, have been invoked by several workers as an important agent of transport over the sea floor. Although submarine turbidity currents have never been directly observed it is difficult to explain the existence of sands and gravels in deposits far from topographic highs (as for example in CAPRICORN core 9B) by any other means. The strata presumed to be deposited by turbidity currents often exhibit graded bedding, that is the coarsest particles are at the bottom of the stratum and the average grain size decreases rapidly upward. Bedding of this type was observed in CAPRICORN core 5B. It is believed that a foot or more of material may be deposited in a few days from a turbidity current, whereas other processes of sedimentation build up the deposits at rates most conveniently expressed in centimeters per thousand years.

Submarine Weathering

After deposition, chemical changes take place within the sediments. These result in the destruction of some of the original constituents and the development of new minerals. Among the most conspicuous of these new substances formed within the sediments are tiny, beautifully twinned crystals of philippsite, a sodium aluminum silicate belonging to the zeolite group.

Problems Investigated on CAPRICORN

On CAPRICORN, attempts were made to gain information on the following problems of deep-sea sediments:

1) Methods for determining rate of deposition.

2) Topographic control of rate of deposition and character of the sediments.

3) The relative amounts of constituents derived from the continents and from oceanic volcanoes.

4) "Weathering" processes taking place in the sediments.

5) Use of stratification within the deposits to deduce the dates and character of oceanic events during the Pleistocene.

6) Distribution of Tertiary fossils and sediments, and its significance.

7) Average thickness of the sediments.

Rate of Deposition

Many attempts have been made to estimate the rate of deposition of deep-sea sediments. The finding of fossil shark's teeth in dredge hauls led earlier workers to suppose that these deposits were laid down at an almost infinitesimally slow rate, less than a tenth of a millimeter per thousand years. Some recent workers have based their estimates on the occurrence of glacial and post-glacial strata in cores. Assuming that 20,000 years have elapsed since the end of the ice age, and finding an average thickness for the topmost post-glacial layer of about 20 cm, they have concluded that the present rate of deposition is about 1 cm per thousand years. Similar results have been achieved by investigators who have used the decrease in radioactivity (which must come very largely from the uranium, ionium, radium series) with depth in the cores as an index of the time since deposition of different layers. Both of these methods are subject to considerable uncertainty. The first essentially begs the questions of whether the different layers in the sediments can be correlated with Pleistocene glacial and interglacial stages, and whether the oceanic circulation of the tropics synchronized with the retreats and advances of the ice in North America and northern Europe. The second method is questionable because absorption and diffusion of uranium and ionium in different constituents of the sediments may seriously distort the radio-active equilibrium, Moreover, the rates of decay of uranium and ionium are too slow to give the precision needed for accurate dating of late Pleistocene and post-Pleistocene events. The successful use of radio-active carbon as a means of dating carbon-containing materials from a few hundred to several tens of thousands of years old suggests its application to the problem of dating the upper layers of the sediments. Because of the amount of carbon required for the analysis, this method can only be applied to carbonate-rich calcareous oozes. Special large-diameter cores of globigerina ooze were collected near the Equator. It is hoped that these will allow Carbon 14 dating of sediment layers 1 or 2 cm thick with a time resolution of better than a thousand years. Radioberyllium, which has a half life of about half a million years, and is believed to be formed, like Carbon 14, in the upper atmosphere, represents a possible basis for dating more slowly deposited sediments. Large-diameter cores are also needed for this possible method and these were collected in carbonate-poor areas, where radioberyllium maybe enriched sufficiently to allow its use for age determination.

Topographic Control of Deposition

Although absolute rates of deposition are difficult to determine, it is evident from the character of the sediments themselves and from the bottom topography that relative rates of deposition are widely variable. The probable importance of turbidity currents in bringing about extremely rapid intermittent deposition of thick layers showing graded bedding has already been mentioned, as has the evidence for slow deposition or erosion on topographic highs.

Examination of the cores collected on the MID-PACIFIC Expedition and on CAPRICORN indicates that another transportation process may also be significant. Many of these cores contain fossil radiolaria and other organic remains mixed rather uniformly with Recent debris. Evidently there is a relatively continuous dispersion by irregular or oscillating bottom currents of sedimentary particles ranging in size up to fine sand. This process tends to keep topographic highs swept clean of debris and causes topographic lows to become flat over wide areas. Consequently the topography of much of the sea floor is somewhat like that of deserts on land.

We have found marked variations in the character of sediment cores collected comparatively close to each other in regions of topographic irregularity. This emphasizes the need for closely spaced samples collected on a systematic pattern in these regions. Such intensive collecting was not possible on CAPRICORN because of the reconnaissance nature of our work.

Continental and Volcanic Sources

Throughout large areas in the North Pacific the deposits occurring below 2200 fm are light buff colored and consist principally of clay minerals and finely divided quartz. These materials are believed to have been carried out from the continents and spread more or less uniformly in suspension throughout the oceans, whence they slowly settle to the sea floor. Our cores from the South Pacific, on the other hand, between Samoa and the Marquesas, are chocolate brown in color, often contain much volcanic glass and "micronodules" of manganese and iron, and are rich in philippsite. As already stated, the latter is a "new" mineral formed within the sediments themselves. In cores collected at some distance from possible sources of volcanic materials the color remains the same, but the percentage of unweathered volcanic glass and philippsite diminishes. It is believed that comparative study of these very different types of cores from the South and North Pacific will enable development of methods for determining the relative proportion of deep-sea sedimentary materials derived from oceanic volcanoes and from the continents.

Weathering in the Sediments

In order to do this it will be necessary to elucidate the weathering processes within the sediments. To this end we have made careful chemical studies of the interstitial water in the sediments and of the water immediately above the bottom (see Fig.6). The results show that the percentage of silica in the interstitial water is roughly a hundred times greater than in the overlying bottom water, and increases with depth in the core. It is obvious that silica is being dissolved from the original constituents of the sediments but it is not as yet certain whether the source of the silica is volcanic glass, clay minerals, or the siliceous skeletons of organisms. The fact that the percentage of radiolaria decreases gradually below the surface while the content of dissolved silica increases suggests that much of the silica is being supplied by radiolarian skeletons.

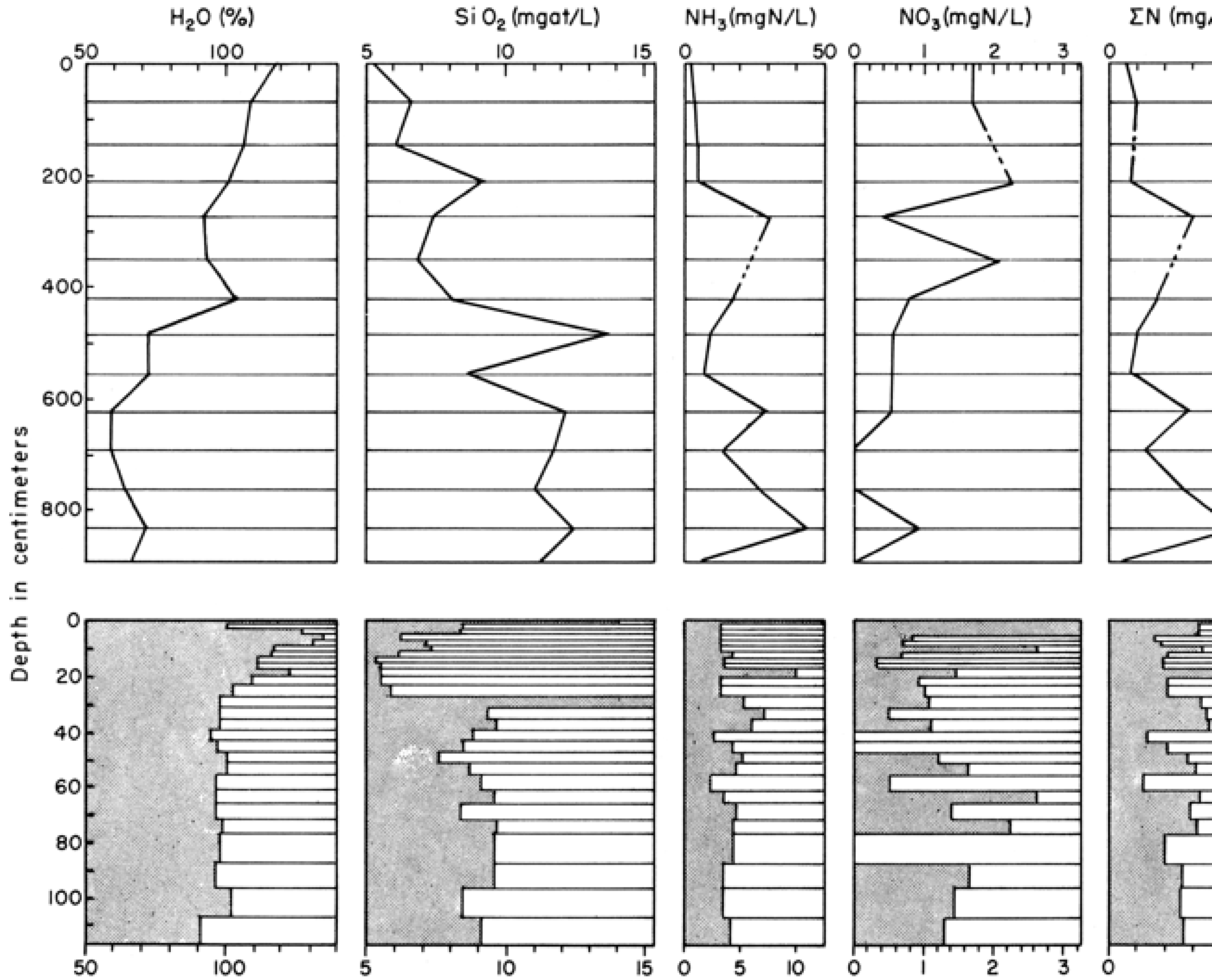

FIGURE 6. Analysis of interstitial water, Cores 38BP and 38BG. Note
nitrate/ammonia ratio decreases with depth in the core, and that silica in

FIGURE 6. Analysis of interstitial water, Cores 38BP and 38BG. Note that water and nitrate/ammonia ratio decreases with depth in the core, and that silica increases.

The ratio of ammonia to nitrate is higher in the cores than in the overlying water and increases with depth below the bottom surface. We have interpreted this to mean that the interstitial waters of the sediments are less oxidizing than the overlying waters and that the state of oxidation decreases with depth below the bottom surface. It is interesting to note that the content of interstitial water decreases rather slowly with depth in the cores despite the fact that the sediments become dry and crumbly in appearence below 5 or 6 m.

Stratification in Cores and its Paleoclimatic Interpretation

In areas of little horizontal transport near the bottom, a core 10 m long penetrates a continuous sequence of sediments laid down over hundreds of thousands and perhaps millions of years. When such a core is examined, marked stratification in the amount and composition of the organic remains is observed – the different strata must reflect variations in conditions of deposition and hence must constitute a record of past oceanic "climate." For example, in the "eupelagic" area of the eastern tropical Pacific, the topmost layer of the cores is usually considerably lower in calcium carbonate and in number of diatoms but contains more shells of certain warm-water species of Foraminifera than the material 10 to 25 cm below the surface. As we go downward in the core we pass through a series of alternating layers. The fluctuations in calcium carbonate content become smaller in amplitude near the bottom of the core.

Similar alternations between layers of high and low calcium carbonate occur in the tropical Atlantic but with the remarkable difference that in many cores the surface layer is higher in calcium carbonate than the layer 25 cm below the surface.

Both these sequences are believed to reflect changes in oceanic circulation and in the character of the surface waters during the glacial and interglacial stages of the Pleistocene. The top layers in both cases may have been deposited since the last retreat of the glacial ice.

Arrhenius has correlated the layers of high calcium carbonate, high diatoms, and low warm-water Foraminifera in the tropical Pacific with the Pleistocene glacial stages. He supposes that during epochs of maximum glaciation the trade winds were narrowed and intensified. The stronger divergence in the wind system near the Equator brought about a corresponding divergence of the surface waters accompanied by marked upward motion of nutrient-rich deeper water. Organic productivity was thus greatly increased, the rate of precipitation of calcium carbonate and silica in the shells of planktonic plants and animals was accelerated, and the quantity of shell material settling through the water was increased. At the same time the

circulation of the deep, cold waters of the ocean may have speeded up during glacial stages; correspondingly the rate at which calcium carbonate was dissolved in these deep waters may have increased. Arrhenius believes that in the Pacific the increased productivity overbalanced the increased rate of solution. Hence the glacial stages were periods of high calcium carbonate deposition. In the Atlantic the intensification of the trade winds and of the vertical water circulation in the equatorial zones was much less pronounced, while the acceleration of the deep-water circulation was greater. Hence glacial stages were times of relatively low calcium carbonate deposition.

This hypothesis differs radically from the explanation proposed by Schott and now widely held. Schott proposed that the surface waters of the tropics were cooled by as much as 10°C during the glacial stages, with the result that organic precipitation of calcium carbonate was greatly reduced. At the same time, because of the relative elevation of the continents, their contribution to the sea floor was perhaps increased. Hence the deposits laid down during glacial periods should be low in calcium carbonate while those of interglacial or post-glacial periods such as the present should have high calcium carbonate content.

Actually the hypotheses of Schott and Arrhenius are not necessarily contradictory. In some regions cooling of the surface waters may have had the predominant effect on tropical pelagic sediments during the glacial period; in others the increased organic productivity brought about by the intensified atmospheric and oceanic circulation may have been most important; elsewhere, the increased circulation of bottom water may have resulted in solution of calcium carbonate before it could be buried, there by determining the character of the sediments.

Arrhenius's hypothesis is based largely on analysis of sediments collected by the Swedish Deep Sea Expedition in the eastern tropical Pacific, mainly north of the Equator. One of the objectives of the CAPRICORN Expedition was to gain additional information on the relationships between productivity in the surface waters and the character of the bottom sediments, and to determine in so far as possible the effect of differences in the productivity over a larger area, particularly south of the Equator. To answer these questions satisfactorily would require detailed studies of the atmospheric circulation, the motion and chemical properties of the sea waters, the populations and rate of production of phytoplankton and of Foraminifera and radiolaria, and the composition and rate of deposition of the different sediment components. Our work was necessarily limited and exploratory, but investigations were conducted along all these lines.

Net hauls for Foraminifera and other zooplankton were made at frequent intervals throughout the entire cruise, and in the eastern Pacific the amount of chlorophyl and other plant pigments in the subsurface waters was determined at intervals of about 50 miles.

The atmospheric circulation was studied by means of radiosondes and captive balloons. Surface current measurements with the GEK may add to our knowledge of the zones of horizontal divergence and convergence in low latitudes. The quantity and composition of the colloidal matter suspended in the water will be determined by laboratory study of particles filtered from water samples collected with special non-metallic bottles, at depths between 500 m below the surface and 1–1/2 m above the bottom. A series of long piston cores ranging up to 9 m in length was collected along a north-south section in the east Pacific from 14°S to 15°N, in addition to a considerably larger number of short gravity cores in which care was taken to preserve the critical layers near the surface.

In the lower part of the long cores the amplitude of percentage variation in calcium carbonate diminishes and the average calcium carbonate content increases. This may indicate that the deep ocean waters were considerably warmer during the Pliocene than they are at present.

Tertiary Deposits

In contrast to the areas of relatively rapid and continuous deposition in the eastern equatorial Pacific is the central Pacific region between the Marshall, Hawaiian, and the Fiji Islands where Tertiary deposits are frequently found at the surface, or buried beneath a layer of Recent sediments only a few meters thick. It may be that the rate of deposition is extremely small in this region, possibly because the bulk of the material settling to the bottom has been carried to other areas. In any case preliminary results indicate that these fossil deposits are higher in calcium carbonate than Recent deposits at the same depth. We may tentatively conclude that during the early Tertiary either the bottom was shallower than at present or the deep Pacific waters were warmer and perhaps nearly stagnant.

Thickness of Sediments

The thickness of the sediments was one of the objects of the seismic refraction and reflection studies. We have already seen that geochemical considerations require a thickness of deep-sea sediments of the order of 3 km. The seismic refraction results indicate that the actual thickness of materials having a velocity of less than about 4 km/sec is nearly everywhere less than 500 m, while over much of the Pacific a layer of velocity 5.2 km/sec is within 200 m of the bottom surface. This velocity is unlikely to represent consolidated sediment, unless it be a crystalline limestone, and it has already been

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pointed out that during earlier geological time the percentage of lime in the deep-sea deposits must have been quite low. We are faced with a dilemma – either the geochemical calculations are wrong or the lower layers of the sediments have somehow disappeared, or have been metamorphosed. At the present rate of deposition of about 1 cm per thousand years, the measured thickness of sediments would represent a total time of deposition of less than 50 million years. Allowing for compaction and for lower rates of deposition prior to the Pleistocene the average thickness of sediments corresponds at most to one or two hundred million years. We are thus almost forced to the conclusion that if deposition of sediments was taking place in the deep sea prior to the late Mesozoic, these earlier deposits are not now present in unmetamorphased form. R.R.R.

CONTRIBUTION TO THE STUDY OF CORAL REEFS

To the mariner as to the scientist coral reefs are one of the most characteristic and important features of the tropical Pacific. Living reefs rising to within a few feet of the sea surface constitute an extreme hazard to navigation, a hazard which is augmented by the difficulty of accurately surveying these complex structures. Passes between the reefs usually form the only nearshore navigable channels, and the lagoons in back of them are the only ports and harbors of refuge.

From the point of view of the geologist, coral reefs are of great interest because they represent accurate and readable tide gauges on which are recorded the changes of sea level that have taken place during the recent geologic past. Moreover the study of living reefs can lead to greater understanding of the fossil reefs and limestones that occur throughout the geologic column and in many areas contain major reservoirs of petroleum. For the biologist and oceanographer, coral reefs represent a fascinating and complex problem in ecology, in the intimate relationships between the organisms which are their builders and the ocean currents and waves which determine their form and structure.

Unanswered Questions About Coral Reefs

Coral reefs have been studied by many scientists and from many different points of view. Yet a surprisingly large number of questions about them remain unanswered. Among these are the following:

1) Though living reefs are very widespread in tropic seas there are places where one would expect their presence but where they are absent or poorly developed. What are the factors that prevent or inhibit reef growth?

2) Above the low tide line, reefs and reef limestones are rapidly eroded. The erosion that takes place above the high tide line can easily be accounted for by the dissolving action of fresh waters, but the most vigorous erosion seems to take place between low and high tide. What are the relative roles of mechanical abrasion and chemical solution? If chemical solution is important how can this occur when the surrounding ocean waters are always saturated or supersaturated with calcium carbonate? Could either mechanical or chemical erosion have been rapid enough to plane off large platforms such as atolls down to the lower sea levels that prevailed during the Pleistocene?

3) Living coral reef areas, while rough in detail, are, on a larger scale, smooth flat regions very close to sea level, in marked contrast to the generally irregular submarine and sub-aerial topography of non-coral areas. Two basically different hypotheses have been advanced to explain these facts. One, first stated by Darwin, is that reefs start to grow around the shores of a land

mass which is initially above the sea but which is subsiding relative to sea level. The living reef grows upward as fast as the foundation subsides and the area between the reef and the shore is kept nearly filled with calcareous debris. Eventually the rocky foundation may be completely submerged and an atoll is born.

The other hypothesis, advocated most recently by Ladd and Hoffmeister, is that coral reefs form a thin cap over broad platforms which have been planed off near sea level or built up to sea level by deposition of sediments. A special form of this "antecedent platform" hypothesis was formulated by Daly, who supposed that broad platforms were cut during the Pleistocene lower stands of sea level, and that reef corals and reef-building algae became established on these platforms and grew upward with the post-glacial rise of the sea to the present level. Drilling under Ladd's supervision on Bikini and Eniwetok has shown the presence of shallow-water calcareous sediments typical of reef lagoons down to 2556 and 4200 ft respectively (basalt was reached at Eniwetok at 4200 ft). Our seismic refraction studies and bottom sampling on the MID-PACIFIC and CAPRICORN Expeditions have demonstrated that on these two atolls and on Kwajalein the calcareous material covers old volcanic masses rising at their shallowest points to between 3000 and 4000 ft subsea. Thus Darwin's hypothesis of great subsidence is definitely established for the Marshall Island atolls. But there are other areas where evidence for subsidence has been lacking. For most of the Pacific east of the Andesite line our information has been completely inadequate. The question still remains, therefore, as to whether an atoll can only form as a result of large scale relative subsidence

4) How did the characteristic features of atolls originate? These include: (a) The encircling reef, broad and flat, roughly planed off at the low tide line; with a precipitous outer edge to leeward and a lesser but still steep slope to windward; varying considerably in width; appearing scalloped in plan, with gentle concave curves separated by sharply jutting points. (b) The low, partly sandy, partly rocky islands capping the reef. (c) The lagoon, varying in maximum depth in different atolls from a few fathoms in small atolls to something over 30 fm in the large atolls of the Marshall Islands, partially filled with reef debris and with skeletons of plants and animals which lived on the lagoon floor. (d) The coral knolls in the lagoon rising to within a few feet of the sea surface, very steep-sided, crowned by a luxurious growth of many species of coral. (e) The passes through the reef, sometimes as deep as the lagoon floor, sometimes at intermediate depth, and frequently, in smaller atolls, only a few feet deep or even non-existent.

Some information was obtained on the CAPRICORN Expedition concerning most of the questions listed above, although of course no complete or final answers can be given.

Rate of Establishment of Reef Corals

That reef corals can quickly establish themselves where conditions are favorable is dramatically illustrated on Falcon Island. This bank lying on the volcanic ridge west of the main Tongan archipelago was a violently active volcano 600 ft above sea level and 2 miles long in 1928. It was again observed to be active in 1936; in 1938 it had shrunk to about 30 ft elevation but was still 1 1/2 miles long. Since that time the island has been completely eroded away by the waves and only a shallow bank remains with pinnacles of volcanic rock projecting to within 3 fm of the sea surface above a gravel-covered plateau 6 to 20 fm deep. Here our divers found many flourishing coral colonies a foot or more in diameter growing at depths of 3 to 5 fm on the rugged surface of a basaltic ridge which extends above the general level of the bank (Fig. 4).

Where the bank was covered with volcanic gravels, no corals were present. Coral colonies on the ridge could not have been more than a few years old because the place where they are now growing was overlain by many feet of volcanic ash during the 1930's when Falcon Island was last above sea level. Did the corals migrate to the island during the last 20 years from the living reefs around Hapai and Tongatabu or were they present around Falcon Island and survived the volcanic activity?

Absence of Large Reefs in the Marquesas

Perhaps equally striking is the absence of large coral reefs in areas that appear superficially to be favorable for their existence. The Marquesas Islands are an outstanding example. Living reef corals are present there only in small fringing reefs around the margins of some of the small bays which indent the islands.

According to Crossland the fauna is restricted to 12 species. There are no elevated reefs. This is in spite of the fact that surface water temperatures average above 26°C even in the coldest months of the year, well above the limit of tolerance for reef corals.

This absence of large coral reefs in the Marquesas has puzzled geologists and biologists for more than a hundred years. Dana suggested that it might be due to rapid subsidence. Agassiz's explanation is that there are apparently no great platforms of erosion around the islands on which reefs might grow. Crossland states that "not only is the fauna restricted beyond all hope of normal reef formation but also half the fauna is but a remnant struggling against adverse conditions." He suggests that an occasional fall in water temperature beyond the normal limit of tolerance may occur with seriously adverse effects on the coral forms. Chubb and Gardiner accept this hypothesis and elaborate on it by supposing that "occasional extensions of the Peruvian current periodically lave the shores of the Marquesas .... so that the present

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absence of coral formations is readily understandable." We may dispose of the hypothesis of Chubb and Gardiner by stating that a 2000-mile westward migration of the Peru current is even more unlikely than an extension of the California current to the Hawaiian Islands. On the other hand we cannot rule out the possibility of sudden chilling due to upwelling brought about by occasional surface divergence in the trade winds. The large variability in rainfall in this area does, according to Palmer, support this point of view.

Our soundings around Ua. Huka, Hiva Oa, and off Nuku Hiva show that neither Dana's hypothesis of rapid subsidence nor Agassiz's supposed absence of a broad shelf can be invoked. The island shelf around these islands is everywhere more than a mile wide, in places more than 2 miles. There is a marked shelf break at about 45 fm and no terraces which would indicate subsidence to greater depths. Our seismic results off Nuku Hiva indicate that the island shelves in the Marquesas are cut in volcanic rock with at most only a thin surface layer of unconsolidated sediments. The depth of the shelf, its wave-cut character, and its gentle outward slope of 1 to 3 percent between the shore and the shelf edge indicate that it was cut during the Pleistocene lower stands of sea level. Its width and the high sea cliffs along the shore indicate that wave erosion was unimpeded by coral reefs during the time of cutting, and hence that reef corals were no more abundant in the Marquesas at that time than at present. It may be that here we have an explanation for the absence of large reefs in these islands. Figure 7 indicates that a very considerable amount of sub-aerial and submarine erosion has taken place around Ua Huka, and field observations suggest that this is true for the other islands of the group. The amount of debris washed out from shore may have been so great that reef corals could not establish themselves on the shifting floor of sediments in transit across the shelf, and could not live in the relatively turbid waters from which fine-grained particles were continually settling. With the rise in sea level at the close of the ice age the shelf became too deep for reef coral growth except right at the shore where continuing marine erosion of the high sea cliffs prevented their extablishing themselves. If large living reefs were present prior to the Pleistocene, no evidence of their presence remains. Corals living here at an earlier time may have been killed by a marked drop in temperature during the Pleistocene and, as suggested above, subsequent sub-aerial and marine erosion may have prevented their re-establishment.

Abortive Reefs

Even where coral reefs have flourished in the recent geologic past they may be killed by a slight change of conditions. We studied two such areas; Alexa Bank, some 500 miles northwest of Viti Levu, and the island shelf north of Tongatabu. We shall call these abortive reefs. Except for the fact that its shallowest depth is more than 10 fm, Alexa Bank has a gross morphology very similar to a living atoll. There is an outer rim 10 to 15 fm above what was formerly the lagoon. In the lagoon itself there are topographic highs

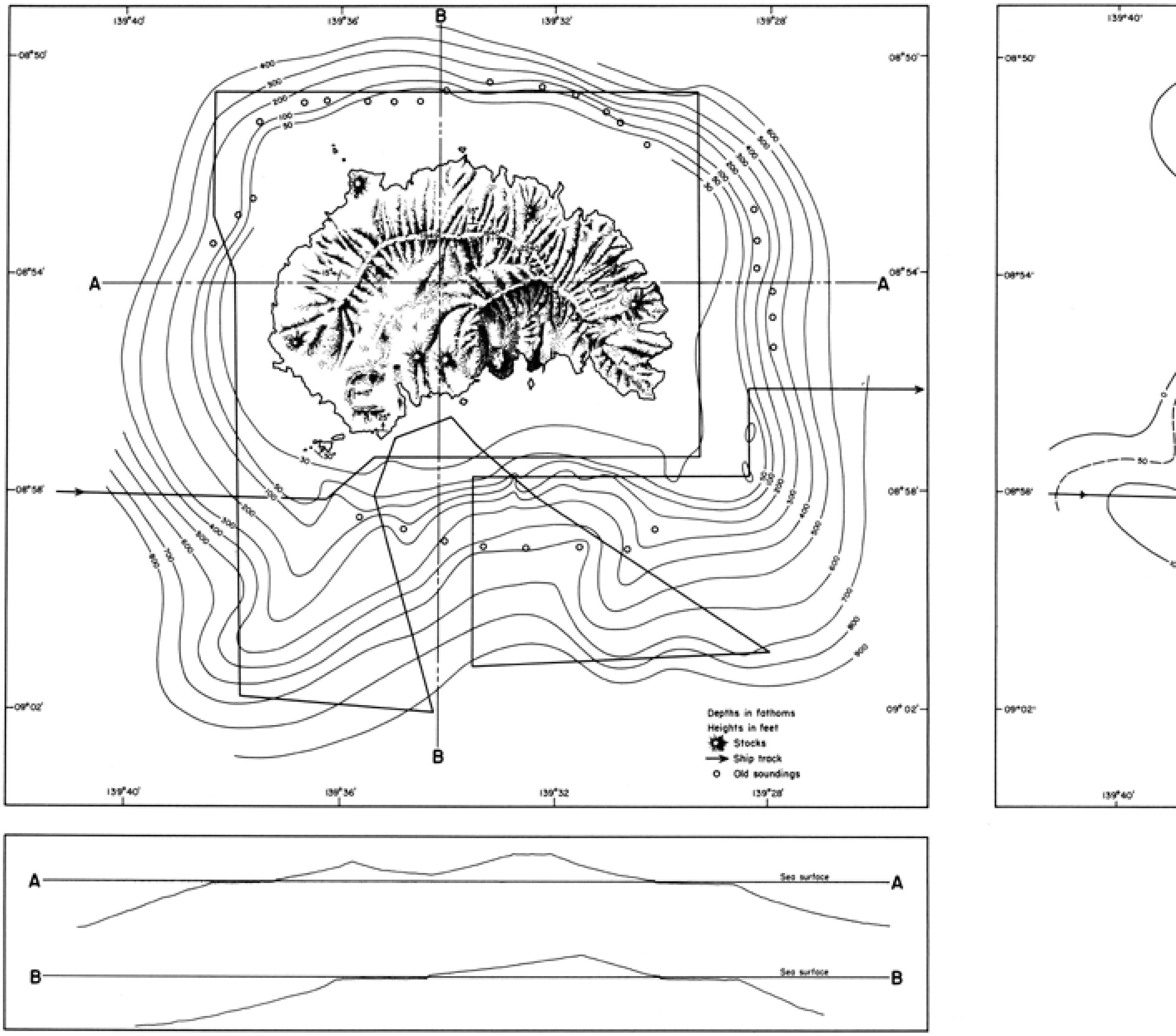

FIGURE 7
Bathymetric and magnetic survey of Ua Huka, a volcanic island of the Marquesas group. Previous soundings are shown by small circles, straight lines show our track. On the island, note two caldera rims, one inside the other; parasitic cones and relatively low angles of dip outside the

rim; absence of coral reefs, broad shelf breaking at about 45 fathoms, and moderate outer submarine slopes.

which must once have been coral knolls; otherwise the bottom is flat and slopes gently toward the center. Outside the rim the slopes are very steep, plunging downward several hundred fathoms at angles of 25° or more. Our seismic refraction survey shows a structure remarkably similar to those at Eniwetok and Bikini with a layer of calcareous material several thousand feet thick. But observations by our aqualung divers show that in detail there are striking differences between this bank and a living atoll (Fig. 3). The surface of Alexa is mantled everywhere by calcareous sands and gravels, largely fragments of the calcareous alga, Halimeda, in which there are abundant patches, arranged in more or less regular patterns, of living and dead lithothamnion. Living corals are relatively rare, most conspicuous being the giant golden cups of *Echinopora lamellosa*. The reef rim instead of being broad and flat has an inverted V-shape cross section, rising steeply from the outer edge to the shallowest point, then sloping more gently downward towards the lagoon. Any evidence of a former lithothamnion ridge or of surge channels has been smoothed over by the mantle of debris. The former coral knolls are larger and much less steep-sided than those of Bikini and Eniwetok.

On the eastern side of the island shelf north of Tongatabu, a drowned barrier reef rises to within 12 fm of the sea surface, more than 20 fm above the general level of the shelf. The eastern side of the barrier has a moderate slope down to 50 fm and below this a very steep slope to 400 fm. Former coral knolls rise above the shelf. Examination by divers, together with bottom photographs, echo sounding profiles, and bottom sampling from shipboard, show all the detailed characteristics described above for Alexa Bank, notably the V-shaped cross-section of the former reef, the scarcity of living coral, the moderate slope of the coral knolls, and the mantle of Halimeda debris masking any previously existing reef structures.

It is easy to believe that with the rise in sea level at the close of the Pleistocene (or perhaps during an earlier interglacial stage) reefs began to grow vigorously upward at Alexa and Tonga. But no obvious explanation as to why the reefs aborted has occurred to us. Perhaps a slight increase in the rate of relative rise of sea level occurred because of local subsidence, and the organisms were unable to keep up. This would be a self-accelerating process because as the water became deeper the organisms would find conditions more and more difficult for growth.

Two Atolls East of the Andesite Line

We made reconnaissance bathymetric and magnetic surveys of two atolls: Palmerston in the Cook group and Takaroa in the Tuamotus. Our objectives were to gain information on the possible depth of calcareous material and to test Fairbridge's hypothesis that the large concavities in the shapes of many atolls are gigantic landslide scars.

Comparison of the steep outer slopes, extending downward several hundred fathoms, of Palmerston and Takaroa with published surveys of Bikini and Eniwetok strongly suggests that these atolls, like those of the Marshall Islands, have a thick layer of calcareous sediments. This is confirmed by the magnetic surveys which show anomalies of roughly the same magnitude as those observed by Alldredge and others at Bikini. Evidence for or against the landslide hypothesis is not very convincing, although the magnetic irregularities observed in the possible landslide areas are suggestive of slumping on a large scale.

Depths of Lagoons as a Function of Lagoon Area and Water Circulation

It is interesting to compare the depths of lagoon and passes in Takaroa and Palmerston with those in Bikini and Eniwetok. At Palmerston, which has a lagoon area of only about 15 square miles, the greatest lagoon depth was said by the natives to be 15 fm and there is only a 6-ft deep boat passage across the reef. At Takaroa, with a lagoon area of more than 50 square miles the maximum depth is 24 fm and the passage through the reef is 11 fm deep. In contrast, the large Marshall Island atolls, with areas of hundreds of square miles, have maximum lagoon depths of 32 to 34 fm.

Emery's studies of the sediments of Bikini and Eniwetok lagoons show that the major portion of the material is debris from the reef while the remainder is principally plates of Halimeda and shells of Foraminifera that lived on the lagoon floor. The deep central portions of the Marshall Island lagoons are evidently too deep at the present time for Halimeda growth and are floored with the shells of Foraminifera.

The shallower depths of Takaroa and Palmerston lagoons as compared with the Marshall Island atolls may be accounted for by their higher ratio of reef circumference to lagoon area, if we postulate that the lagoons of all these atolls were at the same depth, relative to present sea level, of about 35 fm during the Pleistocene, and that the amount of debris contributed to the lagoon by a unit area of reef is relatively constant.

The scarcity of living Halimeda or of Halimeda debris in the deep central portion of Bikini indicates that the rise of sea level has been so rapid that these calcareous algae have been unable to keep up. A possible reason for this may be the low rate at which calcium carbonate and plant nutrients are supplied to the plants by the slow interchange between the lagoon waters and those of the open sea. It is interesting here to consider the relatively shallow present depth of the former lagoon on Alexa Bank, 10 fm below the submerged reef and 24 fm below sea level as compared to 33 fm at Bikini. Circulation of water over Alexa is virtually unimpeded by the drowned reef, and the supply of calcium carbonate and plant nutrients may therefore allow more vigorous upward growth of Halimeda on the lagoon floor. This is continuing at the present time, even though the surrounding rim has long since ceased to support vigorous coral growth.

Evidence for Subsidence West of the Andesite Line

In contrast to the atolls described above, east of the Andesite line, in which there is evidence of very considerable subsidence and no trace of uplift, are the islands and reefs of the Lau and Tonga Archipelagoes. Many of these have been described by Ladd and Hoffmeister. Here Tertiary, nearly flat-lying, shallow-water limestones are found uplifted several hundred feet above the sea. In the Lau group the volcanic cores of some of the islands are exposed above sea level. Most of the islands in this archipelago have broad, living reefs at sea level. In Tonga there are fringing reefs at sea level and broad insular shelves, 30 to 50 fm subsea, which are most probably built up of shallow-water calcareous materials, including reef corals..

That subsidence of the order of 300 fm has taken place in Tonga is indicated by the channels of this depth between the island shelves.

Prior to CAPRICORN only one sounding greater than 100 fm was available for southern Lau. Accordingly we made an echo sounding profile across the Lau ridge, approaching close to Fulanga Island, thence through the passes between Fulanga and Ongea Islands and between Ongea and Thakau Nasokesoke reef and thence down the eastern slope of the ridge. We found that the Lau ridge rises rather gently to depths between 250 and 300 fm. The islands rise steeply from this level to the surface although the average slope above 250 fm is less than that of Palmerston or Takaroa. This steep slope above 250 fm is probably to be explained by upward reef growth during slow subsidence although it could possibly result from outward growth of the reef over its own debris while relative sea level remained nearly constant. In any case we have neither here nor in Tonga evidence of the large rise in relative sea level shown by the atolls east of the Andesite line.

Reef Solution Above the Low Tide Line

One of the striking features of many of the islands, other than atolls, visited by the expedition is a marginal shelf of reef limestone 7 to 12 ft above present sea level. This "10-ft shelf" has been described by many workers and is usually attributed to a higher stand of sea level during the so-called climatic optimum three to five thousand years ago. It is now being eroded, both above the high tide line and in the intertidal zone. The most active erosion seems to be occurring just above low tide, as is shown by the cylindrical indentations or "nips" in the sea cliff at this level. That the erosion process is not very rapid, however, is indicated by the continued existence of the 10-ft shelf. Indeed in some places, as for example around the blowholes on the east side of Tongatabu, deposition of calcium carbonate is taking place at the high tide line as well as erosion at a somewhat lower level.

The important role of chemical solution in the erosion process is well shown in the islands of the Vava'u group of northern Tonga. Here sea level nips are found in protected bays and channels where mechanical abrasion by waves must be virtually non-existent. The rough and pitted surfaces of the upper portions of reef flats also furnish convincing evidence of solution

Careful chemical studies on the MID-PACIFIC Expedition and by other workers have shown that the waters over coral reefs are always at least saturated with calcium carbonate. How then can solution take place? The answer may lie in the existence of "microcells" on the reef surface in which sufficiently acid conditions are produced by organic activity. Some evidence for the existence of such cells was obtained on the reefs off Paiea and Papeete, Tahiti. Shoreward from the lithothamnion ridge, the reef surface is covered with a rich, matted, algal flora. Between the algae are small pools a few inches to a few feet in diameter, the bottoms of which are partially covered with calcareous sand. Samples of water taken from underneath the sand stank of hydrogen sulphide while underneath the algal mat a strong fetid odor was observed. A sample of water collected at daybreak (after plants had been producing carbon dioxide for nearly 12 hours) from a small pool floored by a thick algal mass showed a pH of 6.4, much below the pH of 8.2 exhibited by the water flowing over the reef. Underneath the sand covering of another pool a pH of 8.5 was observed. These observations show that organisms living on the reef surface can markedly affect the acidity of a thin layer of water adjacent to the reef and may easily produce conditions under which solution can take place.

Permeability of Reefs

Finally measurements of temperature (conducted by USGS) and tides in a deep well at Eniwetok may be of interest. In the upper few thousand feet, at least, temperature and tide behave nearly as if the atoll were absent altogether. The measurements put some quantitative limits on the permeability of this atoll. R.R.R.

THE MAGNETOMETER AS A GEOPHYSICAL AND NAVIGATIONAL TOOL

The magnetometer was towed almost continuously, and records of the total magnetic field of the earth obtained, for nearly 7,800 miles between Tongatabu and San Diego; the Tonga Trench was crossed twice and surveys made of Palmerston and Takaroa Atolls, the volcanic island of Ua Huka in the Marquesas, and several seamounts.

Anomalies in the magnetic field represent changes of constitution or structure of the igneous basement, but in general a unique interpretation of such anomalies is not possible. However, the towed magnetometer possesses one very important advantage over the airborne magnetometer for oceanographic investigations: a record of the bathymetry is obtained at the same time.

Taken together, magnetic and bathymetric records provide far more information than either alone, greatly simplifying the problem of interpretation and removing much of the ambiguity of the magnetic results. Thus bathymetric features not matched by anomalies in the magnetic field may be assumed to be confined primarily to the sedimentary layers. On the other hand, if a structure such as the foundation of an atoll can be identified as an igneous formation then, assuming that the composition of the rock remains uniform, it is possible to trace out the contact between the igneous rock and adjacent overlying sediments.

In order to separate out the anomalous field it is necessary to remove from the observed field the normal magnetic field of the earth. This has been done for a representative selection of the more interesting parts of the work, using the Hydrographic Office magnetic chart for 1945. Figure 5 shows the resulting magnetic anomaly and bathymetric section from Samoa to east of the Marquesas and figure 9 the corresponding profiles across the Tonga area. The former line yields a vast amount of information for detailed analysis. Along the Tonga line, the most interesting feature of the magnetic profile is the extensive shallow anomaly on the western flank of the Tonga Trench. Coring operations in the trench show the bottom to be rocky with thin areas of sediment. The magnetic anomaly suggests a thickening of the sediment on the western side of the trench.

The bathymetric and magnetic contours of the area surrounding Palmerston Atoll are shown in figure 10. The magnetic contours are loops roughly encircling the atoll and enclosing a negative anomaly of several hundred gammas, with secondary anomalies, of which the most interesting is the large positive anomaly off the northwest side of the atoll. The geometrical relationship of the total field and the bathymetry points to the existence of a basin in the underlying igneous rock on this side of the atoll. That this basin

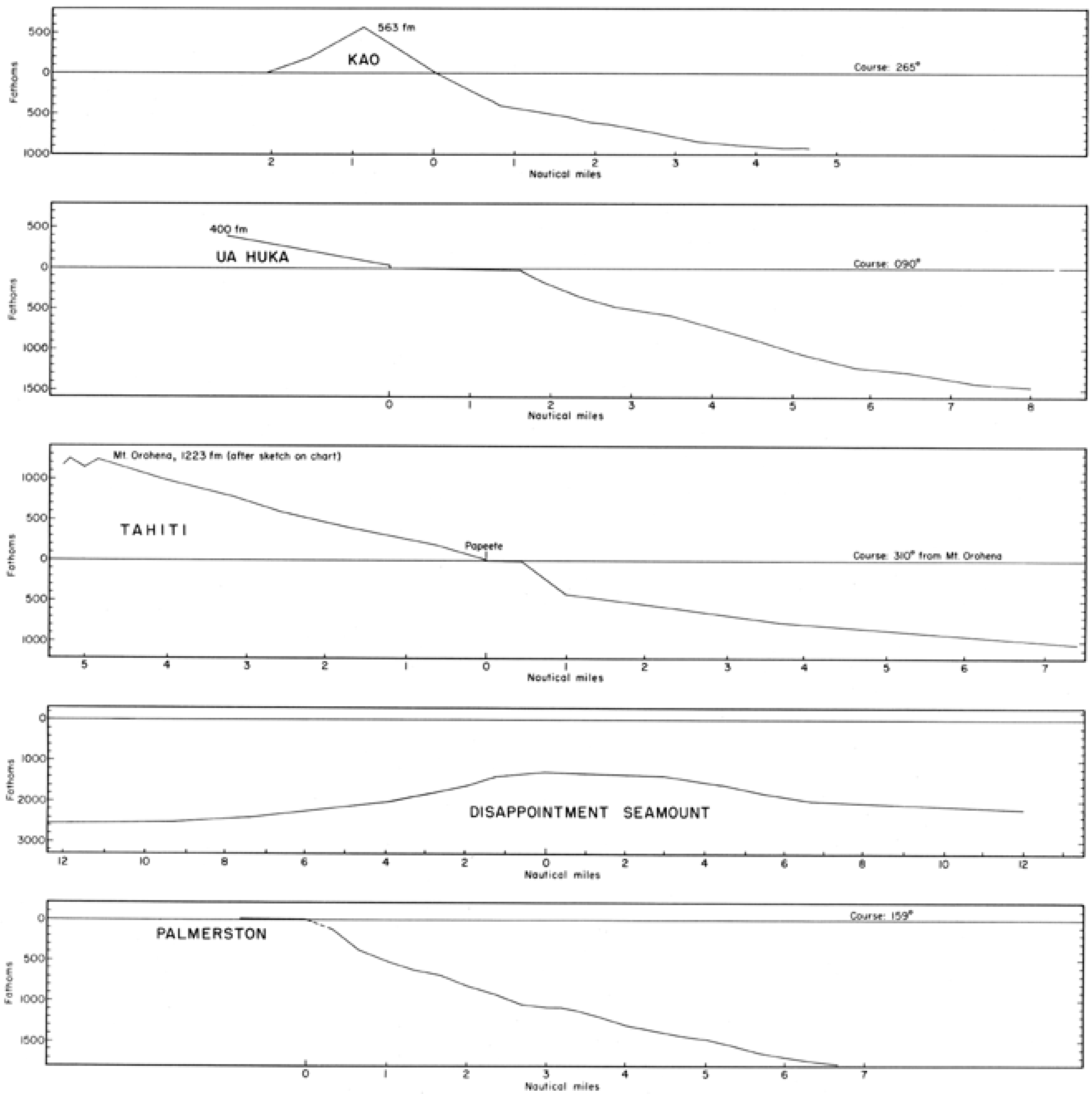

FIGURE 8. Comparative profiles (drawn to natural scale) of volcanoes, seamounts, and coral atolls. Kao Island is a pyroclastic cone of the Tonga group. Volcanic flows are characteristic of Ua Huka and Tahiti. Note steep sub-aerial and submarine slope of Kao compared to the gentler slopes of Ua Huka. Gentler slope of Disappointment Seamount suggests that this is a flow type volcano. Steep underwater slope of Tahiti between 0 and 500 fathoms may in part be due to coral reef upgrowth around a subsiding island. Steep underwater slope of Palmerston atoll is typical of coral atolls.

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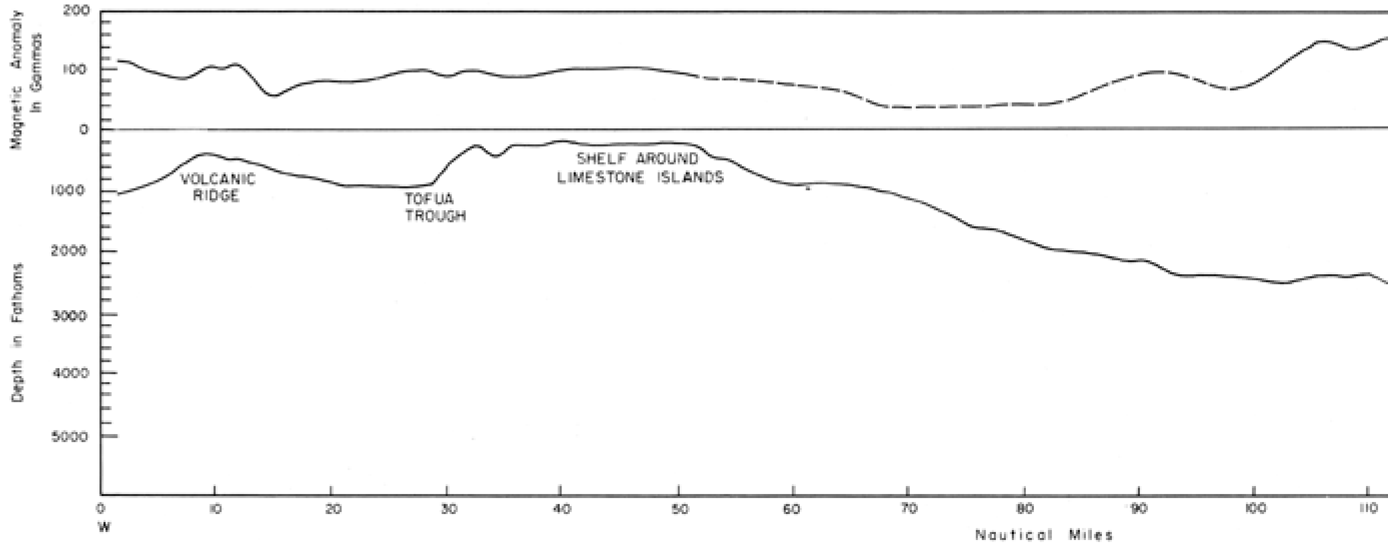


FIGURE 9. Bathymetric and magnetic section across the Tonga

FIGURE 9. Bathymetric and magnetic section across the Tonga area.

is not indicated by the bathymetry lends support to the theory that the concavity of the atoll on the northwest side is the result of submarine slipping, the debris being assumed to have filled the basin.

An extensive survey was carried out around Ua Huka, the remnants of a volcano whose southern part is now missing. The bathymetric and magnetic contours are shown in figure 7. Two caldera rims, one inside the other, run around the western, northern, and eastern sides of the island, while several parasitic cones and volcanic plugs are to be seen on the southern side. The magnetic survey revealed a highly disturbed area off the southern side of the island with at least three areas of negative anomaly. These are highly suggestive of submerged volcanic plugs and it is possible that the island represents less than half the area of the original volcano.

The survey of Helen Seamount is typical of the several surveys carried out over seamounts. Figure 11 shows the bathymetric and magnetic contours. The top of the seamount is about 800 fm beneath the surface and the associated magnetic anomaly about -300 gammas. More interesting however is the fact that, as a result of the relationship of the topography of the seamount to the direction of the earth's field, while the bathymetric contours are ellipses with major axes north-south, the magnetic contours are ellipses with major axes east-west. The two sets of contours thus tend to intersect at large angles so that values of depth and magnetic field are more or less unique at any given point. This fact has been made use of in the calculation of the ship's drift during the course of the survey.

The dead reckoning plot of the ship's course is shown in figure 12a For the few minutes on either side of each of the four apparent points of intersection the depth has been plotted against magnetic field at one-minute intervals for each of the two intersecting tracks. The point where the two curves intersect gives the actual times at which the two tracks crossed. The method is illustrated in figure 12b. These points have then been joined on the dead reckoning plot in the usual way to obtain the direction and velocity of the ship's drift at each of the four points. At the two more southerly intersections the current points towards the center of the seamount while at the two more northerly intersections the current is deflected slightly in the direction of the contours. Whether or not this represents a real deflection of the current by the seamount can only be determined after a careful statistical appraisal of the results and further work on other seamounts.

The principle used in the determination of drift, the identification of a point through its depth and magnetic intensity, suggests a possible method of navigation, since the method could be extended to any area with strong

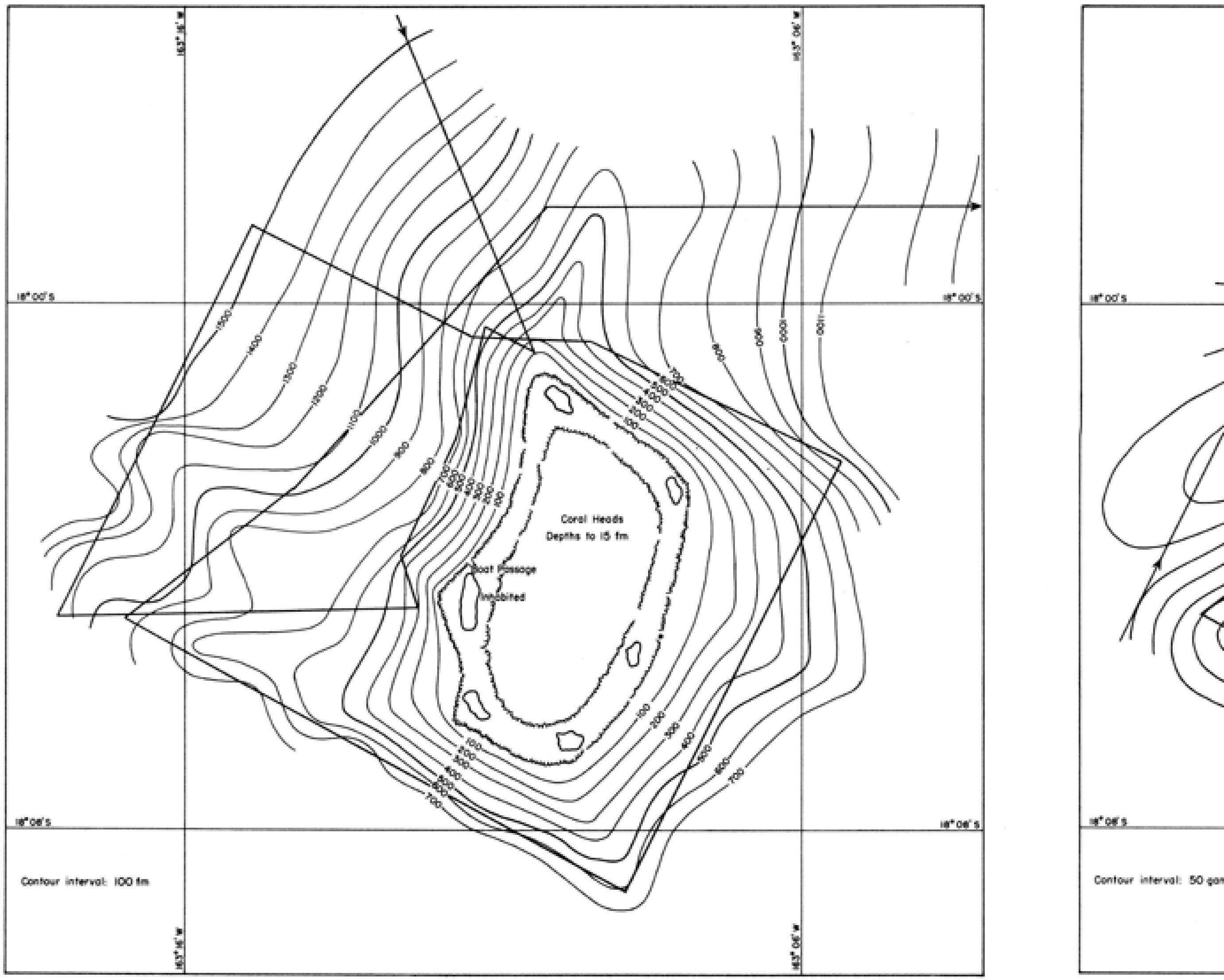
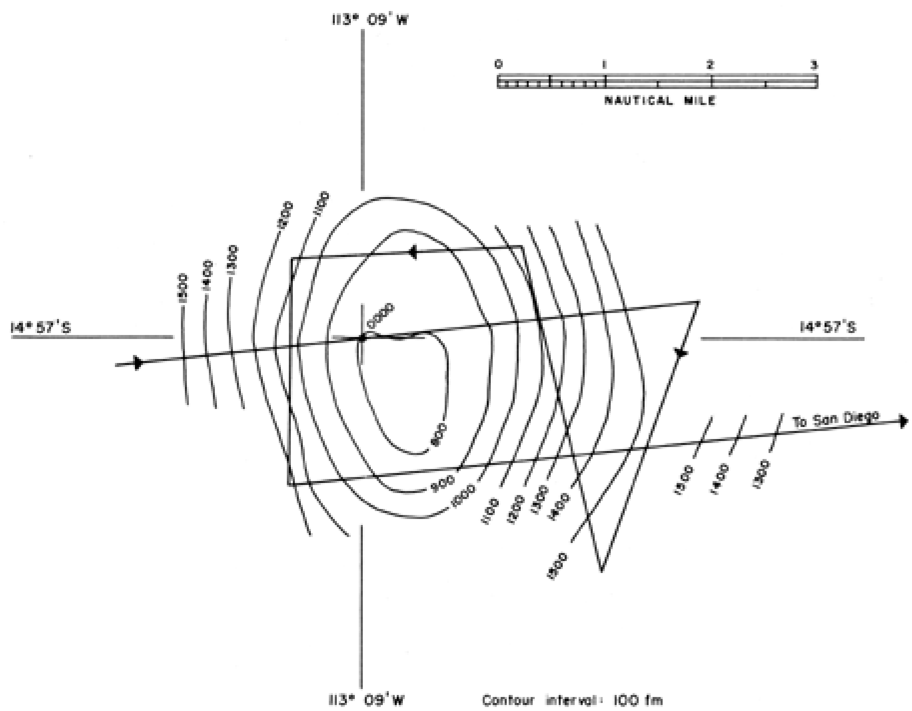


FIGURE 10
Bathymetric and magnetic contours of area surrounding Palmerston Atoll. Contour intervals, 100 fathoms and 50 gammas. Comparison with H.O. Chart 1980 will show that Palmerston Atoll is nearly two miles longer than indicated on the published chart. The magnetic contours probably

reflect the relief of the volcanic basement (but note that a large positive anomaly corresponds to a low in the basement).



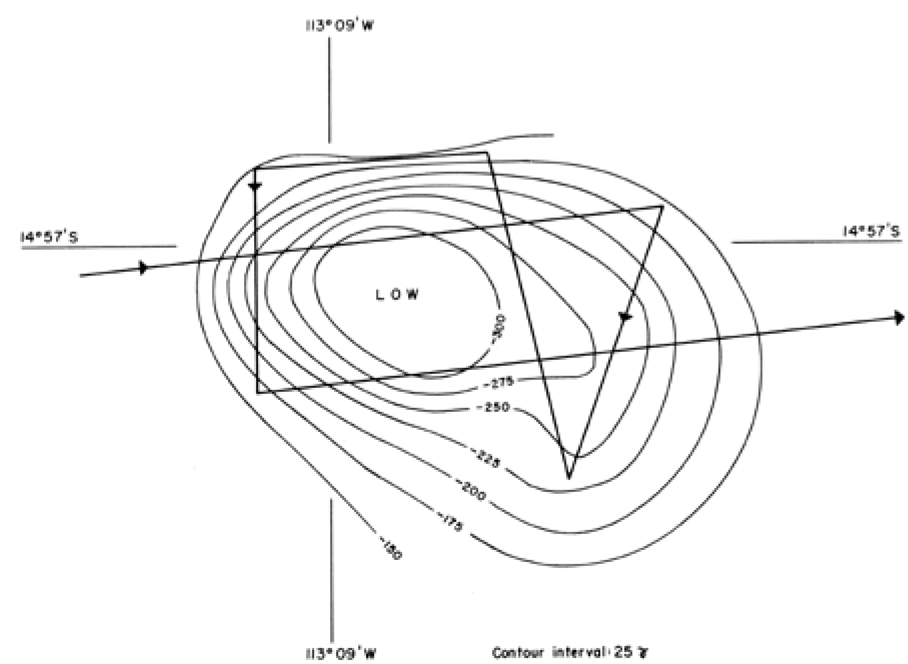


FIGURE 11. Bathymetric and magnetic survey of Helen Seamount. The contour intervals are 100 fathoms and 25 gammas. Note that the top of this submarine volcano coincides with a low in the magnetic field and that the bathymetric and magnetic contours tend to

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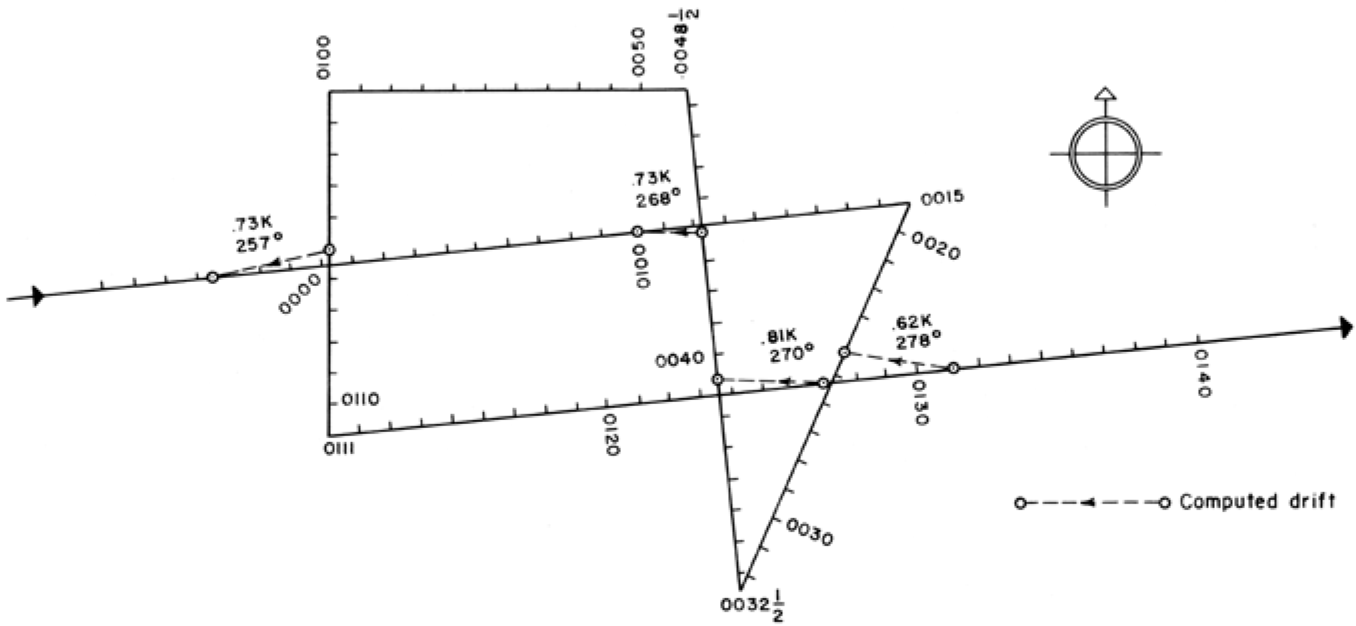
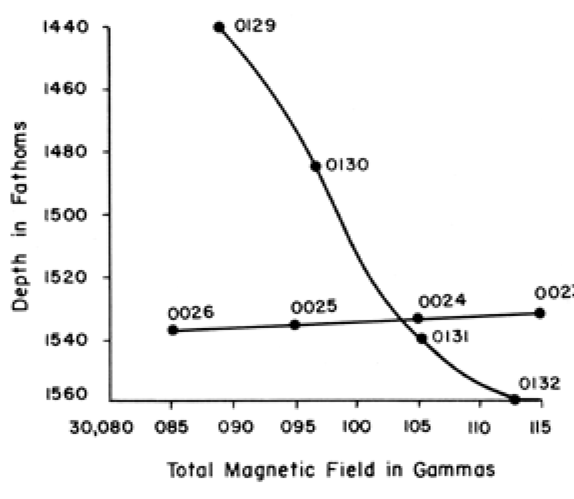


(a)



(b)

FIGURE 12a. Dead reckoning track and computed drift. 12b. Method of finding drift.

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bathymetric and magnetic relief. Depth and magnetic field are not, of course, unique for any given point but the changes of depth and magnetic field along the course give a great deal of information. Navigation by such means would require the preparation of detailed magnetic charts, at least of "landmarks" on the sea floor. R.G.M.

THE BIOLOGICAL PROGRAM

Only a small part of the program time was alloted to marine biology and Johnson was the only biologist included on the scientific staff.

Over 200 biological collections were made at widely distributed locations. These collections include 58 vertical hauls with No. 20-mesh plankton net for microplankton; 35 oblique hauls with one-meter net for macroplankton from depths of 150 and 450 m; 2 midwater trawl hauls from 2000 m; 28 night collecting stations with dip net and light; and about 80 miscellaneous collections. Many of the last are from various coral reefs on Bikini, Eniwetok, and Majuro Atoll, Marshall Islands; Ocean Island; Alexa Bank; Viti Levu, Fiji; Tongatabu and Lifuka, Tonga; Tutuila, American Samoa; Tahiti, Society Islands; and Nuku Hiva, Marquesas.

On both the eastern and western crossings of the Equatorial Current system, there was a noticable increase in the surface zooplankton, particularly on the eastern crossing. This probably results from upwelling in this current system, which in turn brings about enrichment of plant nutrients in the upper layers.

The deep midwater trawl yielded a good variety of abyssal invertebrates and several families of deep-sea fishes. Both invertebrates and fishes, while not identified specifically, give further evidence of the widespread distribution of the types of life so characteristic of abyssal depths.

The plankton catches with the meter net were generally small and consisted dominantly of copepods and chaetognaths.

Night collecting was usually poor in the open ocean. However 24 widely distributed stations yielded specimens of the marine insect *Halobates*. The regularity with which this strange insect was found suggests that it is everywhere present both in the open tropical Pacific and in harbors of this region. Numerous squid were encountered from the Easter Island Rise to about 5°N.

Many hours were spent in bird and mammal watch. On Bikini Atoll the fairy and noddy terns were abundant. The former was actively nesting in October; both eggs and newly hatched young were present.

In the remainder of the tropical areas covered, birds were not numerous. Near the Equator just north of Ocean Island several flocks of shearwaters and terns were observed fishing, and in the same general region several Wilson's petrel, considered rare in the area, were seen. Two flocks of birds were seen fishing over the Tonga Trench south of Tongatabu. Between the Tonga Islands and American Samoa, three small flocks of fishing birds were seen. Near Tutuila

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Island the flocks included gannets and tropic birds. Between Tutuila and Tahiti, two consecutive days were passed without seeing any birds whatever, but upon approaching Tahiti, fishing birds were present including mostly terns and gannets. Between Tahiti, the Tuamotu Archipelago and the Marquesas, only occasional shearwaters, terns, and petrels were seen. At the entrance to Taio Hae Bay, Nuku Hiva, more gannets were observed than elsewhere on the whole cruise. This was also true for the frigate birds which were especially common in nearby Taipi Bay.

Just south of the island of Hiva Oa a flock of shearwaters, fairy terns, and a few tropic birds was fishing. Further south on our course the birds were again absent for several days.

In the region of the Easter Island Rise and northward to about 15° N, shearwaters and petrels were especially common. Four or five gannets and seven to eight tropic birds were also seen. Flocks of fishing birds were, however, not seen, although flying fish were especially numerous in this area.

Very few mammals were seen. Porpoises were observed near Ocean Island; Viti Levu, Fiji; Nuku Hiva and Tahu Ata, Marquesas. One whale was seen south of Ocean Island and two just south of Tahu Ata Island. Two whales were seen at 8°00'N, 124°11'W.

MARINE BIOLOGY OF ALEXA BANK

Conspicuous among plants brought to the surface is the calcareous green alga *Halimeda*. Live *Lithothamnion*-like encrustations were found on much of the exposed coral rubble, but nowhere were extensive, massive growths of this reef builder in evidence. On the basis of visual observations and photographs by the divers, it is clear that the concentration of attached plants is not uniform. Dominant among these is a small non-calcareous green alga of a type often found inside lagoons in the northern Marshalls. The local diversity in abundance of this plant doubtless represents a corresponding diversity of coral or algal rubble large enough to provide stable attachment by holdfasts. Inside the "lagoon" there are extensive areas of *Halimeda* sand which are barren of these plants, though living *Halimeda* was present having holdfasts in the sand.

Collections made by the divers indicate that in general the bottom fauna is quite meager, with no obvious differences in the types of organisms occurring in the various areas surveyed. A good variety of reef-building corals was brought to the surface in small quantities. Apparently the most conspicuous corals are two species forming large (up to 6 ft in diameter) flaring "vases." These vases are scattered at random (about 1–2 per 1000 sq. ft.) and grow more luxuriously on the outer portion of the encircling rim of the bank. Some branched corals were present but these were not very delicate and not over about 18 in, in height.

Animal encrustations occurring on the exposed rubble included liberal quantities of compound tunicates, sponges, and some bryozoa and hydroids. Tube building worms were not abundant.

Coral-destroying organisms such as boring worms, mollusks, and sponges were only moderately abundant compared with those of most intertidal reefs.

The gastropods and bivalves, especially the larger species, were noticably scarce.

Among the macroscopic crustacea there were about a dozen types of small brachynuran crabs, a few small prawns, and the snapping shrimp *Synalpheus*. (Considerable shrimp crackle was heard over the hydrophones.)

Small enchinoidea were not uncommon and one large holothurian was collected.

The sparse display of animal life on Alexa Bank doubtless reflects the condition of the oceanic waters that flow at speeds up to several knots over the bank. A plankton haul taken with a No. 20-mesh net from the bottom to the surface just inside the eastern rim of the bank revealed a sparse plankton population comparable with surface waters of the open ocean. There may, however, be some daytime concentration of copepods in the deeper part of the "lagoon" where the bottom prevents deeper daytime descents of these crustacea. This is suggested by an increased abundance of flying fish observed within the lagoon compared with the more open ocean. A deep plankton haul with a one-meter net lowered to 450 m just outside the bank yielded a moderate catch of copepod plankton.

BIOLOGICAL SAMPLING RELATED TO THE PROBLEM OF SEDIMENTATION

Because of their close relationship to the study of the bottom sediments, two special aspects of the biological work should be emphasized:

1) Vertical hauls between the surface and 50 m were taken whenever HORIZON stopped. Using a No. 20-mesh, these hauls collected microplankton, including pelagic Foraminifera. It is hoped that the sampling of this relatively thin surface layer will give information useful in the interpretation of the sediments. Altogether 58 vertical and 35 oblique hauls were made.

2) The concentration of chlorophyl between the surface and 100 m was investigated by Rotschi. A known amount of water was passed through a membrane filter, and the filter was dissolved in acetone for chlorophyl and carotenoid analysis. The concentration of chlorophyl is approximately proportional to the standing crop of phytoplankton, which in turn may be related to the size of the zooplankton population, including the radiolaria and pelagic Foraminifera.
M.W.J.

METEOROLOGY AND ATMOSPHERIC ELECTRICITY

AEROLOGY OF THE SOUTH PACIFIC

The following observations were taken aboard HORIZON by Hilleary, Nicholson, and Ruttenberg under the general direction of Palmer, as part of the Tropical Pacific Project of the Air Force Cambridge Research Center. The observations will be used in a first step towards an indirect aerology of the South Pacific, and the study of the general circulation of the tropics.

Radiosondes

Using 145-contact radiosondes, altogether 182 soundings were taken. Most of the soundings went to a 20-mb elevation, but many reached as high as 5 to 10 mb. Measurements in the dry zone were emphasized. Except for the vicinity of Suva, very few previous soundings have been taken in the area covered by the expedition.

Soundings in the Marine Layer

A "kytoon" was towed behind HORIZON at elevations up to 1000 ft. Attached to the "kytoon" was a ventilated and radiation-shielded meteorograph which recorded temperature and pressure against time on a smoked glass slide. The instrument was also used for detailed vertical soundings up to 4000 ft. The purpose of these soundings was to study in detail meteorological conditions in the so-called marine layer, with emphasis on the physics of marine clouds. This information may be useful in the study of radar ducts in the marine layer.

Standard Surface Observations

These included wind speed and direction, temperature, humidity, barometric pressure, clouds, precipitation, etc.

Collection of Rain Samples

Collections of rain samples were made for condensation nuclei analysis and other studies.

Micrometeorological Study

A qualitative survey of the wind system in Nukualofa lagoon was made from a skiff using a hand anemometer. The reversal of the wind directly in the lee of an island gave evidence of the presence of an eddy. This bears out the usual contention that the placement of an anemometer on cocoanut palm islands can be critical.

Moving Pictures

Moving pictures of shipboard meteorological methods were taken for use in a military training film.

Cloud Photography

This is to be used for a cloud atlas, and for teaching purposes. Special emphasis was placed on doldrum and trade type cumulus, and on orographic clouds. About 700 colored 35 mm stills were taken, including panorama views, and 7500 ft of 16 mm colored movies, including some time-lapse studies.

FIXED NITROGEN IN THE ATMOSPHERE

This work was done by Arrhenius, who was assisted by Folsom and Munk. Very little is known about the fixed nitrogen cycle in the atmosphere. It is not even known whether the sea is a sink or source of ammonia, and what the state of aggregation of fixed nitrogen in the atmosphere is. In support of a broad attack on this problem under the general direction of Professor C.-G. Rossby, air samples were collected for laboratory determination of fixed nitrogen.

Air was sucked in through plastic tubes at the levels of the masthead (49 ft above sea level) and boat deck (16 ft) of BAIRD and bubbled through a mixture of nitric acid and hydrogen peroxide, using equipment furnished by the College of Agri culture, University of Upsala, Sweden. Altogether eight pairs of samples were taken, all in excess of 1000 liters. The samples are to be sent to Sweden for analysis.

AEROSOL COLLECTION

Using equipment furnished by Dr. Christian Junge of the Air Force. Cambridge Research Center, Arrhenius and Folsom made aerosol collections on BAIRD. The instrument consists essentially of an air pump blowing the air at high speed through thin slots, and collecting the particles on plastic disks oriented at right angles to the slots. The analysis of the disks is to be made by Junge.

ATMOSPHERIC ELECTRICITY

Ruttenberg was in charge of observations of atmospheric electricity. These represent part of a general project dealing with atmospheric electricity under Professor R.E. Holzer at the University of California, Los Angeles.

Equipment

The two principal instruments are 1) a potential gradient meter (generating mill type) and 2) a modified Gerdean type conductivity apparatus. Subsidiary equipment consists of an electronically recording potential gradient meter of the radioactive probe type, and an experimental direct-reading air-earth current meter with one hour time constant.

Diurnal Variation

From continuous records, monthly averages of the variation of potential gradient will be computed.

Global Variations

The daily records are to be compared with the records of similar instruments at UCLA, Mt. Palomar, and White Mountain.

Suitability of Shipboard Observations

This includes an evaluation of the effects of salt spray, stack smoke, and of relative wind (as observed during course changes). Measurements ashore were made at Bikini, Kwajalein, Ocean Island, and Samoa. A comparison of the measurements at Bikini and Samoa with simultaneous measurements aboard HORIZON also served for calibration purposes.

Visual Observations of Evening Thunderstorms

The observations include information concerning period of strokes, cell life time and type of stroke, such as single or multiple, cloud to cloud, or cloud to sea.

SOFAR CHANNEL TESTS

The following items were undertaken at the request of the U.S. Navy Electronics Laboratory:

1) *SOFAR bomb test drops.* Under Silverman's direction, 96 SOFAR bombs, Mark 22 (bottle-cap type) were dropped, starting 300 miles west of Tahiti and ending just north of the Equator. The bombs were set for detonation at 2000 ft.

2) *Determination of sound channel depth.* Two hydrographic casts were made using an array of Nansen bottles specially designed for accurate determination of the sound channel depth. The remaining 24 casts will also give useful information on channel depths.

PERSONNEL

Roger R. Revelle, Expedition Leader

SPENCER F. BAIRD

- Lawrence E. Davis, Captain
- Arthur L. Bergen, Radio Operator
- Harold W. Brown, Boatswain
- Albert E. Chapman, Oiler
- John H. Colton, Communications Officer
- Kenneth Conger, Cook (from Kwajalein)
- Cleveland H. Davis, Second Mate
- Edward J. Dennager, Oiler
- Donald E. Derringer, Oiler
- Robert B. Haines, First Mate
- James A. Hayden, Second Engineer
- Donaldson W. Heller, Seaman
- William C. King, Jr., First Engineer
- Vincent E. Lilly, Seaman
- Franklin E. Newberry, Messman
- Richard J. O'Brien, Chief Engineer
- Edmond J. Proulx, Electrician
- Richard R. Rathbun, Seaman
- William B. Sawday, Messman
- Joseph O. Traverso, Cook (to Kwajalein)

HORIZON

- Noel L. Ferris, Captain
- Charles V. Bryant, Seaman
- Floyd Bussman, Seaman (to Kwajalein)
- Willis T. Carey, Jr., Seaman
- Madison E. Carroll, Oiler
- Aloysius A. Cartisser, Oiler
- Lloyd E. Chandler, First Mate (from Pago-Pago)
- Earl F. Daniels, Chief Engineer
- Terrel R. Eddy, First Engineer

- George M. Fenton, Oiler
- Frank J. Friel, Electronics Technician
- Marvin F. Hopkins, Second Mate
- Samuel J. Hough, Marine Electrician
- Peter E. Jeffreys, Cook's Helper
- Frank Miller, First Mate (to Suva)
- Donald A. Noland, Seaman
- Thomas J. O'Callaghan, Cook
- Stanley W. O'Neill, Seaman
- Henry G. Patstone, Second Engineer
- Richard J. Smith, Radio Technician
- Robert C. Swanson, Seaman (Cook's helper)
- Jack L. Wood, Electronics Technician

SCIENTIFIC PARTY

SD (San Diego); E (Eniwetok); K (Kwajalein)

- Gustaf Arrhenius, Suva to SD
- Edward Barr, SD to Suva
- Willard Bascom, E to SD
- Warren W. Beckwith, SD to E
- Richard Blumberg, K to SD
- M.N. Bramlette, E to Suva
- Bernard Darsey, SD to E
- Robert F. Dill, (U.S. Navy Electronics Laboratory) K to SD
- Rhodes Fairbridge, (University of Western Australia) Suva to Tahiti
- Robert L. Fisher, K to SD
- Theodore R. Folsom, E to SD

- Daniel K. Gibson, SD to E
- Edwin Lee Hamilton, (U.S. Navy Electronics Laboratory) SD to E
- C.N.G. Hendrix, (ONR Liaison Officer) E to K
- Don T. Hilleary, (University of California, Institute of Geophysics) K to SD
- Norman J. Holter, (Holter Research Foundation, Helena, Montana) SD to E
- Winter D. Horton, SD to E, Suva to SD
- John D. Isaacs, E to Tonga
- Philip E. Jackson, K to SD
- Martin W. Johnson, E to SD
- Alan C. Jones, SD to SD
- John A. Knauss, E to K
- Wayne H. Larimore, SD to SD
- Robert B. Livington, (University of California, Los Angeles, Medical School) K to SD

- John B. Mac Fall, SD to SD
- Ronald G. Mason, Suva to SD
- Arthur E. Maxwell, SD to SD
- Henry W. Menard, (U.S. Navy Electronics Laboratory) K to SD
- Walter H. Munk, E to SD
- J. R. Nicholson, (University of California, Institute of Geophysics) K to SD
- Willard C. North, E to SD
- Clarence Palmer, (University of California, Institute of Geophysics) SD to E
- Miles M. Payne, SD to SD
- Arthur D. Raff, SD to K
- Helen Raitt, Tonga to SD
- Russell W. Raitt, E to SD
- Roger R. Revelle, K to SD
- William R. Riedel, K to SD
- Henri Rotschi, (France, Department de Recherche Outre Mer) K to SD
- Stanley Ruttenberg, (University of California, Institute of Geophysics) SD to SD
- Samuel Scripps, Suva to Samoa
- Maxwell Silverman, (U.S. Navy Electronics Laboratory) SD to SD
- Harris B. Stewart, Jr., K to SD
- Edward J. Taylor, K to SD
- Richard P. Von Herzen, SD to SD

SOME EXPEDITION STATISTICS

Length of track (nautical miles):	BAIRD	HORIZON
San Diego to Eniwetok	4,655	4,657
Eniwetok to Kwajalein	788	2,573
Kwajalein to San Diego	*11,970*	*15,041*
	17,413	22,271

Seismic work:

- 25 stations, covering 2,542 miles
- 2,133 shots with 25 (1.1%) duds[*]
- 41,409 lb of explosive, enough to heat the Pacific Ocean by 10^{-14}°C

SOFAR Program:

- 96 SOFAR bombs dropped

Fathometer records:

- About 3/4 mile of records, covering about 39,000 miles of sea bottom

Magnetometer survey (nautical miles):

- 7800

Cores:

- 20 piston cores, totalling 90 meters
- 93 gravity cores, totalling 87 meters (estimated)

Dredge hauls:

- 12

Temperature gradients in sediments:

- 9, out of a total of 21 measurements made to date in all oceans

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Hydrographic Stations:

- 26 standard casts; 6 midwater casts with plastic water samplers; 13 bottom casts with plastic water samplers.

Jog-log (GEK) current measurements:

- 126, out of which 24 were simultaneous measurements

Bathythermograms:

- 1170

Plankton hauls:

- 58 vertical hauls; 35 oblique hauls; 2 midwater trawl hauls;
- 7 phytoplankton series, 0–100 meters

Radiosonde balloon releases:

- 182

Diving:

- 20 diving days, consisting of 75 man-hours of actual diving

FOOTNOTES

1. A complete list of CAPRICORN personnel appears later in this report.

2. The Andesite line is drawn between the regions of more acid rocks on the "continental" side and more basic rocks on the "oceanic" side of the Pacific basin.

3. One half of the duds occurred during the last two days of shooting, when a new type of lighter was used.