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RADIOACTIVITY BACKGROUND AND OCEANOGRAPHIC CONDITIONS IN THE PACIFIC PROVING GROUNDS AT THE START OF OPERATION REDWING

(A field report based on data collected 5 April - 5 May 1956 on the M/V HORIZON and LCU 1135)

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Credit is due the crews of the M. V. HORIZON and LCU [illegible] for the excellent cooperation and assistance given both scientific parties.

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ABSTRACT

Background radioactivity and oceanographic conditions in the Pacific Proving Ground are of significance; in evaluating the contaminating effects of REDWING events, in the understanding of the fallout problem at sea and extrapolation to land fallout patterns. Thus, as a part of Project 2.62, a month-long study has been made of radioactivity in water, organisms, and bottom sediments, and of currents and physical character of the water over a 140,000 square mile area around Bikini Atoll.

The waters are slightly radioactive, with values of 150 to 1500 gamma counts per minute per liter (cpm/l), whereas the natural radioactive background, due to potassium-40, is about 94 cpm/l.[1] A field of maximum activity (800 to 1500 cpm/l) exists at 800 to 1200 meters depth at locations to the west of Bikini Atoll, within 150 miles of it, and between $10\frac{1}{2}^{\circ}$ and $13\frac{1}{2}^{\circ}$ N. Radioactivity is associated with particulate matter (possibly organic) at the surface only; at all other depths it is mostly in solution. Organisms collected from the upper layers and deep sea fauna captured in a trawl as deep as 2500 meters depth are about equally radioactive; the level of activity in these marine creatures is about 30 to 50 times as much per unit weight as that in equivalent weight of water. Lagoon waters and surface waters in the open sea around the lagoons are slightly more radioactive than other areas (1100 to 2100 cpm/l).

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1. All values of radioactivity given in this report are gamma rays emitted per minute.

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The highest ~~amount~~ level of radioactivity in the area studied is on the ocean & lagoon floor in the region of CASTLE fallout. The top of one deep sea core taken 10 miles northwest of Bikini Lagoon tested 29,500 cpm/gram; sediment from the northwest end of the lagoon emitted 45,000 cpm/g. Presumably both were from BRAVO event at CASTLE. Elsewhere in the lagoon, the bottom sediment generally emitted from 1500 to 4000 cpm/g compared with a usual 1000 to 3000 cpm/g in the fallout area outside the lagoon.

Sampling of bottom living organisms outside the lagoon is, so far, unsuccessful. Bottom dwelling organisms in Ailinginae and Bikini Lagoons (particularly the latter) were quite radio-active. Other lagoons were not studied. The molluscs displayed the highest activity and this was outstandingly concentrated in the livers and kidneys (52,000 to 84,000 gamma cpm/g).

In the open sea area, measurements of currents verified the general circulation obtained at CROSSROADS and by Japanese cruises, but more explicit information was obtained. Meanderings and eddies dominate the flow in the latitude of Bikini; the main flow westward is located at the north side of the PPG. A large, counterclockwise-revolving eddy at Bikini is found down to depths of at least 500 meters. The current at the surface attains 0.6 to 0.7 knot speed and averages 0.3 to 0.4 knot; thence it decreases to a maximum of 0.3 knot and average of 0.15 knot at 500 meters depth.

The thickness of the wind stirred layer above the thermocline, where temperature decreases rapidly, varies from 40 meters near Bikini to 170 meters in the northwestern part of the area. The waters are most stratified (i.e., density gradients are greatest) at depths of 50 to 175 meters, being shoalest in the southeastern part of the area, deepest in the northwestern portion, and of intermediate depth at Bikini. Water masses in the area are primarily Equatorial Pacific, North Pacific Intermediate, and West North Pacific Central.

Underwater sound propagation conditions at depths above the thermocline are good, but will become less favorable as summer progresses. Propagation in the deep water is bottom limited where depths are less than 1000 fathoms. The axis of the deep sound channel is found at 800 to 1200 meters (1.3 to 1.5 times as deep as off the U. S. West Coast).

The physical hydrography of Bikini Lagoon is similar to that obtained at CROSSROADS. Surface waters move downwind, and deep waters flow in the opposite direction to complete a cellular circulation. At the upwind end the deep waters are diverted both north and south into two secondary horizontal cells. During moderate to strong trades, water flows into the lagoon along the windward reefs and flows out through Enyu channel and at the leeward reefs and channels. With southerly and southeasterly winds most of the inflow occurs through Enyu channel.

Speed of the surface current was measured to be about 1.6% of the wind speed instead of 3% as previously found. The deep flow was apparently more variable in direction and of considerably less speed than that obtained during previous investigations. As the trade winds materially decrease, the surface current essentially stops immediately, but the deep flow continues for some time.

It is calculated that when the east northeast trades are prevailing, water in the lagoon is completely exchanged on the average every 40 days. At times of light southerly or southeasterly winds an estimated 60 to 100 days are required. No conditions were observed during the field work in which very rapid flushing of the lagoon occurred.

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1. INTRODUCTION

The several purposes of studying the radioactivity background and oceanographic conditions of the Pacific Proving Ground are:

(1) To evaluate effects of REDWING events on the radioactivity content in water, marine organisms, and bottom sediments.

(2) To facilitate accurate reconstruction of the equivalent land fallout pattern from measurements by ships and aircraft and enable future fallout surveys to be made with less effort.

(3) To understand the fallout problem at sea, per se, and to provide oceanographic assistance to the Task Force.

Previous oceanographic data in the PPG are primarily from collections made during the period March to August, 1946, in connection with CROSSROADS and from Japanese hydrographic investigations during 1933-1941. These are mostly measurements of density and thermal structure and of some chemical constituents. Although the data are many, they are neither closely spaced nor synoptic. The Japanese made several crossings in the area with a research vessel during June 1954 to procure information in support of a claim of damage to their tuna fishery.

In analyzing the CASTLE fallout results, the need was evident for more explicit data on currents, rates of vertical penetration and horizontal mixing to properly interpret fallout measurements in the open sea.

Studies of these physical aspects, as well as measurements of the background of radioactivity, were conducted aboard the Scripps vessel M. V. HORIZON during 5 April - 5 May 1956 in a rectangular area reaching 100 miles to the south, 200 miles to the west and north, and 250 miles to the east of Bikini Atoll (Fig. 1A).[2] Particular attention was given to background radioactivity and currents near Bikini and the most probable fallout areas (Fig. 1B), background in and rate of eflux of water from Bikini Lagoon, and fallout particles on the deep ocean bottom from the CASTLE events. Background radioactivity was studied in Ailinginae Lagoon.

As used in this report, radioactivity background is the total amount due to the combination of naturally occurring radioactive elements and the radioactivity remaining from previous nuclear weapons tests.

This report was prepared in the field during and immediately following the data collections; it is for use by Program 2 specifically and the Task Force in general. Wind produced waves and tides have been excluded from the discussion because such information is being provided by the J-3, Hq., JTF-SEVEN Oceanographer.

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2. All figures are at the end of the report.

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2. RADIOACTIVITY BACKGROUND IN THE OPEN SEA AND LAGOONS OF THE PACIFIC PROVING GROUNDS AREA

by

DeCourcey Martin, Jr. and Robert L. Wisner

The M. V. HORIZON is equipped with a small radiochemical laboratory, radiation detection and assay equipment, and sampling devices. Assay of the radioactive contamination in the Pacific Proving Ground Area was done in conjunction with the preliminary oceanographic studies.

A study was made of the radioactivity of the waters in the open ocean. Samples of the lagoons and ocean floor were obtained with a coring device and dredge. Plankton samples were taken in the open ocean and phytoplankton and colloidal matter were filtered from lagoon waters. Other marine organisms were obtained by trawling, line fishing and skin-diving. Several samples were taken of the air over the sea surface.

2.1 ASSAY EQUIPMENT

The samples were measured for both beta and gamma radiation. Those samples which were sufficiently active were analyzed to determine the isotopes producing the radiation by means of gamma ray, differential pulse height analysis. The samples were obtained, identified, and prepared for counting.

An end-window Geiger-Muller tube, with a mica window of 1.4 mg/cm^2 thickness, was used to count the beta particles. The counting tube was shielded by two inches of lead to reduce the background of cosmic and external instrument radiation to 25 cpm. The sample planchet was mounted in a plastic and aluminum shield to reduce scattering and bremsstrahlung.

Gamma radiation was detected and counted with a lead shielded RCA 5819 photomultiplier tube and a 1½ inch diameter sodium iodide scintillation crystal. Both beta and gamma counters were connected to a decade scaler. Gamma energy spectrum studies were made with a well type scintillation counter, single channel pulse height analyzer, and a decade scaler.

2.2 SAMPLE PREPARATION AND COUNTING

The samples to be counted for radioactivity were weighed, dessicated, dried at 110°C, in some cases ashed, and counted on aluminum planchets. The self-absorption variation due to differences in mass and density of the various types of samples caused some difficulty in comparing their absolute beta activities. Since gamma rays are not significantly affected by self absorption in samples of these thicknesses, gamma radiation is used in this report as an indication of the amount of radioactive elements present. The ratio of gamma rays to beta particles has not been accurately determined but appears to be roughly 1 to 1.

The activity of the samples was compared with the activity of calibrated standard sources. The instrument background was subtracted and the counts corrected to agree with the standard source. The values are reported as gamma rays emitted per minute per unit mass or volume of sample abbreviated, cpm/g or cpm/ℓ. The probable error in each counting rate was difficult to maintain at a constant level. In the case of the water and plankton observations where the counting rate was very small, the probable error was usually greater than 8%, often as much as 50% and occasionally over 100%.

2.3 RADIOACTIVITY IN OCEAN WATER

Samples of sea water taken at various depths at ten of the hydrographic stations were used in this study. A 150 ml. volume of the water from each sample was evaporated to dryness and the resulting salt assayed for radioactivity. Table 1-A shows the gamma radioactivity, corrected to 1 liter, at each station. The salinity values are listed only for station 29. (Locations of stations are shown in Figures 1A, 1B.) There appears to be no detectable relationship between the variations in activity with the slight variation that exists in salinity.

Surface samples of the water at several stations were filtered through a 0.5 micron millipore filter in order to determine if activity were present in the upper layers as dissolved substances or as particulate matter greater than 0.5 micron diameter. Most of the activity was found to be in the dissolved phase. For example, at station 14, at 0 meters, the water emitted 45 cmp/150 ml., or 600 cpm/2 liters. The suspended particulate and colloidal matter in the 2 liters was 89 cpm, or 15%. For subsurface water at station 27, the total activity in 6 liters of water taken as a vertical column from depths between 50 and 1500 meters was 2050 cpm/6 liters, while the particulate matter was only 20.2 cpm/6 liters, or 1%. If the surface particulate matter is largely composed of living organisms, then the radioactivity within dead organisms settling downward must rapidly become dissolved. 15

TABLE 1-A

RADIOACTIVITY OF PPG OPEN SEA AREA WATERS

Gamma Rays Emitted per Minute per Liter (cpm/l) of Sea Water

Approx Depth in meters	Stations 6	7	8	9	12	14	25	27	26	29	Salinity for Sta. 29 (‰)
Surface 0	413	474	267	210	293	300	340	60	180	460	34.56 ‰
50			260		350			280		180	34.58
100			435	-45*	≦0*	130	110	120	≦0	120	35.01
125			≦0								35.25
150								340		470	35.12
200			340	210	300	400			≦0	410	34.58
250	250						≦0			350	34.43
300										374	34.41
400				90	390	280		390		410	34.60
500	340						350		314	≦0	34.58
600						490				340	34.59
800	855	740	[illegible]	220	470			500		835	34.58
1,000		1480	870	460	90		650		370	520	34.59
1,200	1240					410				390	34.60
1,400	535	580	120		90		535	435	400	520	34.63
2,000	280	580	120								
3,000	410	314	300								
4,000		330	375								
Bottom Depth (meters)	3560	4300	4600	4200	5200	5100	4300	3400	4800	1440	

TABLE 1-B

RADIOACTIVITY OF LAGOON WATERS

Station	Depth	cpm/l	Probable Error
Bikini Atoll, Enyu Island	Surface	1,150	27 %
" " Namu "	Surface	1,620	20 %
" " Namu "	Near shore, midpoint of 1meter depth	2,130	15 %
Bikini Atoll, Mid-lagoon	Surface	1,290	23 %
Ailinginae	Surface	1,070	30 %
Eniwetok Atoll, Parry Island	Surface	400	42 %

*Note: The above values have been corrected to account for a 12% efficiency and a 41% geometry of the scintillation counter. The average background due to noise and cosmic rays has been subtracted from the reported values. This has caused the negative and zero values. The natural K-40 background of 94 cpm/l has not been subtracted and is included in the above figures.

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The main naturally-occurring radioisotope in the ocean is potassium-40 with a half life of 1.2×10^9 yrs, which should remain constant throughout the ocean. One liter of sea water emits 94 K^{40} gamma rays per minute. Any additional gamma radiation shown in Table 1 is due to contamination.

Throughout the PPG area the radioactivity of the sea water is fairly constant with the exception of one layer of water between 800 and 1200 meters found northwest of Bikini Atoll at stations 6, 7, 8, and 29. This area is on the edge of a large eddy current found around Bikini, hereinafter referred to as the "Bikini eddy" system (Figures 6A-6E).

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2.4 RADIOBIOLOGICAL ASSAY OF NEAR-SURFACE AND DEEP SEA FAUNA

In general, the following is based on samples of ZOO-plankton taken during the M. V. HORISON's cruise. These samples were collected with a standard one meter diameter plankton net towing obliquely from 280 meters depth to the surface in 15 minutes time while the vessel proceeded at about 2 knots. The net mesh is of nylon "Nitex" cloth, 60 meshes to the inch. Its cod-end is of the same material, 90 meshes per inch. The net is designed to sample all forms larger than phytoplankton and crustacean larvae.

Samples were assayed for radioactivity without sorting into like kinds of organisms. In most cases the bulk of the "sample" was small crustaceans. Large, individual animals were removed for individual assay. Table 2 lists the results of the radiological assay. Station positions are given in Figs. 1A, 1B.

As is shown in Table 1 the levels of activity in the water are quite low throughout the total area studied. However, it is significant that the greater activity is to be found within the influence of the eddy system around Bikini, Ailinginae and Rongelap Atolls (Figs. 6A to 6E). It is probable that within this area the supply of radioactivity in the ocean is being constantly renewed by tidal flow from Bikini and neighboring atolls to the east. Swept into the eddy where it does not escape for some extended period of time crop after crop of the short lived plankton become contaminated. As will be shown

 [redacted]

TABLE 2

RADIOACTIVITY ASSAY OF PLANKTON SAMPLES FROM THE PPG AREA

Station	Wet Weight (grams)	Gamma Rays Emitted per min/gram
5	6	0
7	9	99
9	8.7	50
11	10.2	16
12	8.0	17.8
13	5	0
14	11	7.7
15	10.2	0
16	9.1	26.9
19	8	36.3
21	9.1	22.2
24	7.8	0
25	13	27.3
26	11	20.6
28	3.2	11.1
29	13	15.0
30	11	1.9

later in the report the lagoons of Bikini and Ailinginae are still markedly contaminated. No studies were made of other atolls. ---

Three samples of the deep-sea fauna were obtained in the area, using the 10 ft. Isaacs-Kidd Midwater Trawl as the sampling device. The depths sampled ranged from 730 to 2560 meters. But only one sample, that from the shallowest depth, has so far been studied in detail. The activity levels were, in most instances, quite similar to those of the zooplankton from the upper water levels. Fishes and planktonic forms from the remaining two depths, 1300 and 2560 meters, were very similar in levels of activity to those of the 730 meter depth. Therefore, the results from the 730 meter depth only are listed, Table 3. Because the trawl continues to fish constantly during the two hours required for lowering and retrieving, it is not possible to state with certainty at what depth any individual form was captured. However, as the trawl remained at the 730 meter level for more than 9 hours it is reasonable to assume the majority of the sample was taken at that depth.

TABLE 3

RADIOACTIVITY ANALYSIS OF SOME DEEP-SEA FAUNA NEAR NEAR BIKINI ATOLL. DEPTH OF CAPTURE 0 to 730 METERS

Sample Item	Gamma CPM Per Item	Gamma CPM/Gram (Wet Weight)
Hatchet fish (entire)	144	18
Angle-mouth fish	35.6	3.6
Lantern fish (6 young)	111	12.4
Shrimp (Mysidae)	266	35.6
Colonial Tunicate	77.8	11.1
Siphonophore bracts	3.5	10.0
Portugese man-o-war (small)	1.0	.3
Jellyfish (small)	166	83.4
Pteropods (3 small)	71	-----
Jelly fish (large)	1,750	234
Octopus and squid (combined)	193	2.6

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At present the activity in the lower levels differs little from that of the upper. The resulting gamma activities for the deep fishes are therefore, very similar to those for plankton of the upper layers. It should be noted that the foregoing study was made within the influence of the Bikini Eddy System and may be representative of that area only.

2.5 RADIOACTIVITY BACKGROUND OF THE OCEAN FLOOR

A series of 16 samples of the ocean floor were taken around Bikini Atoll. These were obtained with a coring device and a bottom dredge. They consisted of small bits of coral, basalt, manganese nodules, coarse coral sand and fine globigerina ooze (fossils of minute organisms of the order Foraminifera). Portions of such material were weighed, dried at 110° C. in aluminum planchets, and counted for gamma radioactivity. Several of the cores were lost due to the inability of the core barrel to penetrate, and the core-catcher to retain the coarse sand found in some of these areas. Of these, only a few grains were saved and were insufficient for accurate assay. The water trapped over the core top was filtered and evaporated for counting. The suspended sediment thus removed was also counted and was found to be considerably more active than the water. The top layer of each core, and portions of the dredge samples were assayed. The results are shown in Figure 2. in which the activity of the gamma radiation per gram of ocean floor surface is plotted at locations sampled. In general, the most radioactive samples consisted of globigerina ooze (Fig. 2.core C-2, C-4, C-10A). Manganese nodules 22 weighing from 0.05 to 30 gms., which contained no loose mud or sand on the surface, also showed considerable activity (C-1, C-8, C-10). Small coral bits were only slightly radioactive (C-1, C-6, C-7, C-9, C-12). The most active sample consisted of fine sand and globigerina ooze found at 1460 meters depth at core C-10A. The coarser sand was found to emit 8,200 cpm/g whereas the ooze emitted 29,500 gamma rays per minute per gram. A gamma energy spectrum showed the presence of Zinc-65 and one other gamma-emitting isotope which has not been identified. This sample was found in the area where the sea water at 1000 meters showed a high peak of radioactivity.

A cross section of core C-4 is illustrated in Figure 3. The water trapped over the top surface of the core was filtered through a 0.5 micron Millipore filter. The suspended sediment thusly removed as well as the filtered water was counted. The core which consisted essentially of calcareous globigerina ooze and fine coral sand was frozen and sliced into 3mm sections. The outer perifphery of the core was cut away and discarded to reduce contamination which may have been transferred from slice to slice by the barrel of the core as it penetrated the bottom. The slices were assayed, giving the results shown on the core slices in Figure 3. The activity of the core is highest in the top 3mm layer, and then decreases to the 18mm depth where a sharp increase occurs. This peak then diminishes at a rate similar to the surface peak. At the bottom of this 46 cm core only a 3.3 cpm/g trace of activity is found, which closely agrees with the values calculated from the concentration of radium in sediments as given in The Oceans (Sverdrup, Johnson, and Fleming, 1942, pp 1035). A similar core, C-2, showed high surface activity which dropped off with depth but did not exhibit any peak below the surface.

2.6 RADIOBIOLOGICAL ASSAY OF CERTAIN FAUNA OF BIKINI AND AILINGINAE LAGOONS

Collections of molluscs and fish from both lagoons were analyzed for gamma radiation activity. As was expected, contamination was found in the Bikini specimens. Also a rather marked difference exists between collections from the two Bikini areas, e.g., the southeastern and northwestern portions of the lagoon. Most collections in the latter area were made at "Baker" (Bokonejein) Island. Table 4 lists the activity levels found for specimens from each area.

Of the various specimens collected the molluscs proved to be the most radioactive. The activity was found to be most pronounced in the liver which was markedly more active than other portions of the body (Table 4).

There is ample indication that the major portion of the activity presently encountered in the area is in the form of particulate matter on the lagoon floor, Fig. 4). Evidence in support of this is found in the giant clam, genus Tridacna, frequently called "Killer" clam, and a large snail, the liver and kidney of which respectively furnished the highest gamma counts of the area. The principal radioactive isotope in the Tridacna liver was found to be zinc-65. Also the liver of a

TABLE 4

Radioactivity Levels of Certain Fauna from Bikini Lagoon

--- -Southeastern Area-

Sample Item	Gamma CPM per item	Gamma CPM/Gram (Wet weight)
Tridachna Clam		
Liver	1,510,000	83,900
Gills (both sides)	6,300	790
1/8 of stomach	15,200	1,520
1/8 of mantle	4,100	413
1/2 adductor muscle	3,800	384
Gastropod Snail		
Liver	1,530	1,390
1/4 of foot muscle	2,550	850
Gills (both sides)	39,000	13,000
Kidney (entire)	66,000	52,000
Stomach	44,400	5,500
Opercular valve	955	-----
Siphon	120	-----
Small Bivalve Clam		
Entire body	11,100	4,440
1/2 of shell	1,400	700
Polychaete Worms	0	
Larval fish	1,755	1,750
3 tiny sea urchins	4,688	2,340
Northwestern Area of Bikini Lagoon		
Algae	8,400	1,120
Hermit crab (small, entire)	19,700	10,090
Jellyfish (small)	2,200	1,760
Cowrie shell (empty)	2,630	329
Red coral (dead)	48,700	3,745
Calcareous seaweed	118,000	15,730
Fish (Plectropomus sp.)		
Flesh	4,720	780
Tail fin, unscraped	14,500	7,250
Gills (one side)	3,210	1,600
1/8 of epidermis	5,900	4,210
1/4 stomach contents	8,100	2,480
1/5 of vertebrae	160,000	15,000

bottom feeding fish, Plectonomus sp., was found to be notably higher in gamma activity than the liver of the other fishes studied, (Table 4).

Coring and dredging results clearly indicate the presence of a considerable amount of contaminants on the sea floor in an arc extending northwest to northeastward from Bikini. This coincides to a large extent with the CASTLE fallout pattern; in addition the Bikini eddy may have permitted the water to remain in approximately the same area until the additional settling of particulate matter occurred.

Ailinginae Atoll, southeast of Bikini, was also found to be contaminated. Table 5 lists the levels of activity for the specimens collected there. Part of the activity may have come from outside waters as it washed over the reef and entered the lagoon. Roughly, the activity of organisms tested from Ailinginae Lagoon was about one-half the activity of those from Bikini. As at Bikini, the clams and bottom feeding organisms show the greatest radioactivity, indicating the major contamination to be on the lagoon floor.

2.7 LAGOON WATER SAMPLES

A limited number of water samples were obtained from Bikini and Ailinginae lagoons. After evaporation to dryness, the salt of 150 milliliters from each station was counted and is shown in Table 1-B, to emitt from 1000 to 2000 gamma rays per minute per liter of water. These values are somewhat greater than the 150 to 1500 cpm/l found in the open ocean surrounding the atolls. The water in the western side of

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TABLE 5

RADIOACTIVITY LEVELS OF CERTAIN FAUNA

FROM AILINGINAE LAGOON-WESTERN SECTION

Sample Item	Gamma cpm per Organ	Gamma cpm/gram (wet weight)
Tridacna Clams		
Liver of 4 in. clam	4,300	2,200
Liver of 8 in. clam	57,800	5,050
½ of adductor muscle	2,690	900
Portion of connective tissue	355	20
Portion of mantle	55	10
Liver of 8 in. clam #2	36,440	5,200
Bear-Claw Clam (Hippopus)		
Stomach contents and wall	155	40
¼ adductor muscle	155	50
Liver	11,380	3,700
Fishes		
Mullet viscera (4 fish)	670	
Mullet, 4 in. (in toto)	6,140	
Perrot fish		
gills from right side	755	270
liver	9,800	3,270
kidney	1,580	1,050
testes	1,820	460
½ stomach contents	2,090	290
Tail fin, unscraped	3,600	1,800
Snapper		
¼ gills	670	---
Liver	12,700	1,060
1/5 stomach and contents	2,870	320
1/10 of vertebrae	690	60
Flesh, portion of.	600	40
Spleen	220	2,200
Gall bladder	70	440
Kidney	170	100
Tail fin, unscraped	1,070	200
Sample of scales	90	60
Portion of clam from fish's stomach	440	70

Bikini lagoon is more active than the eastern side. The most active sample was taken from water at 1 meter depth on the lagoon side of the reef between Namu and Bokonejien Islands. This sample was taken near the surf and was filtered to remove the particulate matter. The activity of the samples of surface water from Ailinginae Lagoon was similar to the water from the eastern Bikini lagoon. Only one sample was obtained at [illegible]. That was about one-half as radioactive as the water from the other two lagoons and was similar to the water of the open sea.

The values reported in Table 2-A and 2-B are the gamma counts per minute per liter of water after the background due to instrument noise has been subtracted and after the efficiency and geometry of the instrument has been considered. The probable error of the counting rate is given in the right-hand column for Table 2-A. This error is large since the activity was small, although the samples were counted for [illegible] minutes each.

2.8 LAGOON BOTTOM [illegible]

A number of samples from the surface of the Bikini lagoon floor were assayed. These are shown in Figure 4, which presents the gamma counts per minute per gram of bottom sand. High points were associated with a living calcareous algae (Halimeda). The west and northwest sections of the lagoon showed the greatest radioactivity. In general, with the exception of living calcareous algae, the activity was inversely proportional to the size of the sand grains in a given weight of sample.

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One bottom sample which was obtained from Ailinginae lagoon gave a count of 904 cpm/g which is about one-half the activity found in the east end on Bikini lagoon.

2.9 LAGOON PHYTOPLANKTON SAMPLES

Several phytoplankton net hauls were taken in Bikini and Ailinginae lagoons with a standard #20 phytoplankton net. The amounts captured were very small. No identification of the contents was attempted and no means were available to separate inorganic debris from living organisms. The diluted sample was filtered through a millipore filter, which was counted for gamma and beta activity. The samples from Ailinginae showed a count of 21 gamma cpm and 26 beta cpm for the entire haul, whereas a sample taken from the open ocean at station #4 showed no detectable activity. One very small sample at the east end of Bikini lagoon gave 398 cpm gamma and 429 cpm beta while the greatest activity was found in the northwest area of Bikini with 8,500 gamma cpm in a very small sample.

2.10 MISCELLANEOUS SURVEY

Several spot checks were made on the plant life from "NAN" (Enyu) in Bikini Atoll and from the western end of Ailinginae Atoll. The meat of three green coconuts from NAN averaged 146 cpm/g while the milk from the same nuts was 184 cpm/g. A ripe coconut obtained from Ailinginae indicated 116 cpm/g. A green coconut from the same area gave 62 cpm/g for the meat and 129 cpm/g for the milk. A kernel from the pandanus fruit from Ailinginae emitted 64 cpm/g.

DRAFT [redacted]

2.11 AIR SAMPLING

Equipment has been set up for collecting airborne particulate matter aboard the Horizon. Ten liters of air per minute are drawn through a type AA millipore filter for a period of 60 minutes. During the preliminary survey, no airborne radioactivity was detected.

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 [redacted]

3. OCEANOGRAPHIC CONDITIONS IN THE PPG OPEN SEA AREA
by Paul L. Horrer

3.1 CURRENTS, GENERAL INFORMATION

The dominant feature of ocean geography in the PPG is the trade wind driven, westerly-flowing North Equatorial Current. Transporting about 2000 times as much water as the Mississippi River, this current is mostly contained within the upper 350 meters of depth. Its position is farthest north in summer, shifts southward in winter by several degrees of latitude, but on the average stretches from about 8° N to 20° N latitude. Its maximum flow is about 1.0 knot at the surface, but much of the water within this wide, flat ribbon moves at speeds of more nearly ½ knot.

Direction of flow in the North Equatorial Current varies due to meandering, like a river in lowlands, and to formation of great, revolving, horizontal eddies. One such eddy appears in the Marshall Islands area, and is believed due to the vorticity produced as water turns northward to flow round the closely grouped atolls to the east. Contaminated waters from fallout that occurs within 100 miles of Bikini Atoll moves in rotary fashion and remains in the area for an extended length of time.

Both the CROSSROADS and Japanese surveys suggested a narrow band (50-75 miles wide) of easterly flowing current at about 17° N. Found also at 15° N near Hawaii on U. S. Fish and Wildlife cruises, this feature is probably due to a narrow east-west band of weaker winds or a marked horizontal shear in

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the winds at that latitude. Wind data are inadequately detailed to provide statistical proof of the existence of the phenomenon. However, the Japanese survey in June 1954 revealed an easterly extending tongue of contaminated water originating at about 17° N. At 174° E (500 miles east of Bikini, or 200-300 miles east of the CASTLE fallout area) the tongue was 50 to 100 miles wide with an activity of 300 counts per minute per liter.

On the 5 April - 5 May 1956 HORIZON cruise, surface currents were determined at 65 positions by using an instrument to measure potential due to the water movement through the earth's magnetic field (Fig. 5). Currents at subsurface depths were computed from the distribution of water density measured at 15 to 24 depths at each 21 locations. A total of 36 drogues (freely-drifting, submerged sea anchors connected to a surface float by small wire) were released at various depths at 7 locations and tracked to obtain direct measurements for corroborating the above data (departures of the drogues were measured relative to an anchored buoy). The several methods gave satisfactory agreement, and all data from them were utilized to prepare flow charts for five levels, as discussed in the following section.

Winds during most of the cruise were from the east-northeast at speeds of 16 to 22 knots.

3.2 CURRENTS AT VARIOUS LEVELS

Surface. At the surface (Fig. 6A) water moves westward into the area around Taongi Atoll at 0.2 to 0.3 knot; then it curves southwest until almost reaching the longitude of Bikini

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where it again turns west and passes north of Bikini and Eniwetok Atolls at speeds of 0.5 to 0.6 knot. Another stream enters the southeastern part of the area studied and moves past Rongerik, Rongelap, and Ailinginae Atolls to form the counterclockwise rotating vortex about Bikini Atoll. Other smaller, meandering, or rotating streams of water appear in the southwest and northwest parts of the area. Current speed is only 0.05 to 0.10 knot in the east central part of the area, and it is negligible at the centers of the Bikini eddy and the meander, or eddy, at Eniwetok. The total range of speed is 0.0 to 0.6 knot; speed averages 0.3 to 0.4 knot for the whole area studied.

<u>At 75 Meters Depth</u>. Flow at 75 meters depth (Fig. 6B) is very similar to that at the surface with speeds varying from 0.0 to 0.7 knot. Direction of flow north of Bikini within the eddy is more toward the west-southwest than toward the west as it is at the surface. The meander, or eddy, at Eniwetok is almost non-existent at this depth.

<u>At 150 Meters Depth</u>. The two main streams entering the area on the southeast and northeast corners meander more at this depth (Fig. 6C) than at levels above it. Magnitude of motion is very similar to that at 75 meters depth. The Bikini eddy is more elongated in north-south directions than at shoaler levels, and it is larger, possibly due to broadening of the atoll groups with depth. No eddies or meanders exist near Eniwetok. Because the eddy-like feature there is rather superficial, it is probably temporary.

At 250 [illegible]rs Depth. At this depth [illegible]re is much less total flow through the area (Fig. 6D). The eddy around Bikini is still maintained with velocities nearly as great as at shallower levels. The other main features of the surface circulation are maintained but are much less intense and have changed somewhat in direction. In the east and southeast, the circulation has become weak and meandering. Current speeds range from 0.0 to 0.5 knot with a general average for the chart of 0.25 knot.

At 500 Meters Depth. Little, if any, North Equatorial Current remains at this depth. Nearly all flow is meridional (north-south) and speeds range from 0.0 to 0.3 knot with an average of about 0.15 knot for the whole area (Fig. 6E). The dominant feature is still the Bikini eddy, located in the same position and having similar orientation as at the 150 and 250 meters depths. Other apparent eddies at this depth are weak, and their existence may be questionable.

At Depths Greater than 500 Meters. A drogue at 1000 meters depth launched at one location revealed 0.03 knot current. As discussed earlier in the report, the highest concentration of radioactivity found in waters was at 800 to 1200 meters depth on the periphery of the Bikini eddy. Some radioactivity probably reached these levels initially by dissolving into the water from heavy particle fallout on the bottom areas that flank the atolls and seamounts, especially Bikini and Sylvania, at these depths. Some small amount may have been contributed by marine organisms during vertical migrations and by decayed dead bodies and excreta that reach this level. Whereas more heavily contaminated

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waters nearer the surface, where currents are stronger, would be swept out of the area in 2 years time, waters at these depths would not have been renewed because of the feebleness of flow there. Also the eddy may be present at 800 to 1200 meters with water in it moving at a speed of only a few hundredths of one knot; it would further delay exchange of water in the area at these depths. Some information that suggests the presence of the eddy in this range of depth is inferred from water mass studies, discussed later in the report.

3.3 TEMPERATURE AND DENSITY

Surface water temperatures in the Bikini area are relatively high and uniform. They vary from 25.9°C on the northwest side of the area studied to 27.5°C on the southwest side (Fig. 7). The most abrupt change is at the 26.8 and 27.0°C isotherms which mark the southern boundary of the main branch of the North Equatorial Current in the area. Surface waters which are light and warm move very slowly toward the north side of the current; this produces a more pronounced change in temperature there. This crossdrift is so slow it cannot usually be detected by current measurements.

As the surface waters move across the equatorial current toward its right hand boundary they become piled up, causing warmer temperature to extend deeper than at the south side. This process is of sufficient importance to overcome the greater solar radiation received at the lower latitudes in spring. This is illustrated by the average temperature in the upper

250 meters ..h (Fig. 8). Even though ..rface waters are warmer on the south than on the north side, the average for this layer is 1 to 3°C less on the south.

Vertical distribution of temperature is characterized by a shallow, wind-stirred layer usually 50 to 125 meters deep and nearly constant in temperature; below this the temperature decreases abruptly down to about 250 to 300 meters depth; thence it decreases ever more slowly to 1.4° C at 4000 meters depth (See example in Fig. 9). The zone of rapid decrease in temperature is the main thermocline; here the density also increases rapidly (Fig. 9). In general, the thermocline thickens toward the north in the area studied. In World War II, submarines found the thermocline to be a highly useful structure; they were able to escape detection by stopping all engines and balancing on the thermocline. This is analogous to lighter-than-air ships bouncing on a layer of cool air at a temperature inversion during descent.

The CASTLE results show that radioactivity that is soluble or finely particulate has a strong tendency to remain in the upper isothermal layer. Mixing across the thermocline requires a great deal more energy than vertical mixing in this near-surface, turbulent layer. Thus the depth to the top of the thermocline is, as a first approximation, a measure of the depth to which activity in solution or as fine particulates will diffuse in the first few days after detonation.

Based on 125 bathythermograph lowerings made during the HORIZON's cruise, a chart was prepared of depth to the top of the thermocline (Fig. 10). Over the entire area this depth ranges from to 170 meters. It is le , in an area to the north of Bikini and to the east of Rongelap Atolls, forming a tongue like distribution. The tongue coincides with the north boundary of the stream of water that enters the area on the southeast corner and moves into the Bikini eddy. Another locale of shallow thermocline depths exists in the north central part of the area studied. Areas of deep thermoclines are found where water enters the northeast corner and where it leaves the northwest corner. A band of intermediate depths extends east-west across the chart on the north boundary of the main branch of the North Equatorial Current. One stem of this band reaches southwestward toward Bikini Atoll in the anticipated fallout area. Fallout that mixes to 75 or 80 meters depth in this area may, with the water it is in, be squeezed from below into a thinner layer as it moves westward in the eddy where the top of the thermocline rises to 40-60 meters depth. Dissolved radioactivity will probably reach its greatest depth in the area as the current carries it westward to the longitude of Eniwetok.

3.4 MIXING PROCESSES AND STABILITY

Horizontal spreading and dilution of contaminated water in large areas of fallout from a megaton weapon is accomplished not only by horizontal but also vertical variation in currents. In some portions of the area the current in the lower part of the layer above the thermocline differs from the upper part by a few tens of degrees in direction and by 0.1 to 0.2 knot in speed. As the two zones shear apart the upper portion of the contaminated water moves over relatively clean water and clean water flows in above the lower contaminated portion. Simultaneously, vertical turbulence acts to homogenize the entire layer above the thermocline, thereby diluting the contaminated water.

For fallout over a small area from a nominal kiloton weapon the primary mixing process is the latter effect discussed above, the vertical shear. Horizontal shear in the currents over a small area is generally, although not always, relatively small. The horizontal molecular diffusion is also minor. Off the California coast, measurements of horizontal dispersion due to both horizontal shear and diffusion gave an average rate of one foot per minute for areas up to 10 miles across. In the North Equatorial Current region where current speeds are stronger than off California, this rate would probably be two or three times as great; nevertheless, the effect of the process would be of a second order. For both small and large contaminated oceanic areas the rates of vertical mixing are essentially equal.

Large, heavy particles in the fallout (e.g., coral) must sink fairly rapidly and account for radioactivity found on the deep ocean bottom in the PPG. But much of the fallout radioactivity is on smaller coral particles, or ash material and is dissolved into the water above the thermocline. Coral particles that are 100 microns in diameter would sink at the rate of 30 to 100 meters per hour; these would reach the thermocline in 2 or 3 hours time on the average and may lose much of their radioactivity. Both the measurements made at CASTLE and by the Japanese one to two months after CASTLE showed much greater concentration of activity above the thermocline than anywhere else in the water column.

Vertical mixing is inhibited at the thermocline due to the stability associated with the rapid increase in density with depth. Vertical mixing requires the vertical movement of parcels of water. Where vertical density gradients are great, as they are in the thermocline, these movements involve relatively large amounts of energy and are therefore less probable. Mixing, therefore, is less.[3] In the WIGWAM operation (deep underwater atomic detonation off California) radioactivity was materially concentrated in thin stratified layers of high stability. These sheets of radioactive water had horizontal dimensions measured in miles and tens of miles with vertical thickness of only a few meters (except above the thermocline). Contamination existed in the depth of the thermocline and below it at WIGWAM because it was introduced at these levels. This is contrasted with fallout which is spread on the surface and remains mostly above the thermocline, but WIGWAM is the best known example to illustrate the degree of stratification of waters at layers of high stability.

Computations of stability have been made for the data taken on the HORIZON's cruise in the PPG area. Fig. 11 shows the average stability of the most stable 25 meter layer, and Fig. 12 gives the depth of the layer. The stability values

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3. Since the downward penetration of radioactivity in solution in the water is very slow at the thermocline, submarines may generally avoid water with high activity by diving into the middle of the thermocline. Surface vessels may obtain relatively clean water for their evaporators by pumping water from within the thermocline depth zone. With a depressor on the end of a water line the latter might be accomplished at normal speed. (At early times or during fallout, clean water undoubtedly exists in a ship's wake; therefore, a ship probably may obtain clean water for wash-down by traveling in a wide circle, or by following another vessel at some distance. - Isaacs.)

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given are proportional to the acceleration a mass of water would have if it were displaced vertically a distance of one meter. The greatest stability in the entire area is just southwest of Bikini at depths of 75 to 125 meters. A spot just west of Eniwetok Atoll and another southwest of Taongi Atoll have nearly as great maximum stability values. The stability values appear nearly constant (2500 to 3000) over the areas of the main streams of Equatorial Current water.

Shoaler on the south than on the north side of the area studied, the depth of the 25 meter layer of highest stability varies from 50 to 100 meters to 150 to 175 meters. Its depth, at many places, is just below the top of the thermocline, but in other places, where temperature decreases with depth slowly at first, it is nearer the middle of the thermocline. In the latter case, radioactivity may be expected to reach this depth after some period of time (probably within a few days to a few weeks).

Fig. 13 shows the average stability for the upper 250 meter layer. Time for penetration of dissolved radioactivity to 250 meters depth is a function of this quantity. Small values at the northwest corner of the area reflect the deep thermocline there. In general, the magnitude of this average stability increases from north to south.

In the very deep water the stability remains positive, but it decreases slowly to very near zero (Fig. 9).

3.5 WATER MASSES IN THE AREA

Oceanographers use characteristics of the water to define specific water types as the aerologist does with the atmosphere. The natural mixing of a number of specific water types results in a mass of water that can be recognized by its characteristic temperature and salinity relation. Water masses are named after oceanic regions where they are formed or are found. Further mixing between two or more water masses may occur. By comparing the horizontal continuity of water masses present in the area studied, movement of water into the area may be estimated.

The water masses in the Pacific were named, described, and located on the basis of the relatively sparse data taken in this ocean before about 1940. Hence, the descriptions and boundaries are somewhat arbitrary, and the characteristics of a water mass are accepted as varying within only moderately well defined limits. The boundary regions contain waters of intermediate types.

The water masses to be dealt with here are given below. Except for the last one listed, they are found in the upper layers, within the geographical limits specified.

(1) Pacific Equatorial Water, extending from about 2° S to 8° N in these longitudes.

(2) Western North Pacific Central Water, from 160° W to the western boundary of the ocean, and from about 8° N to 40° N.

(3) North Pacific Intermediate Water, occurring at depths from 400 to 1200 meters over most of the North Pacific.

Water in the wind-stirred layer and downward to about the middle of the thermocline has features representative of the local area. Due to the action of surface mechanisms (solar radiation, evaporation, precipitation, etc.) the characteristics of this water are in between that of the Pacific Equatorial mass and that of the Western North Pacific Central water. South of the latitude of Bikini, this water mass is present between the surface and depths of 150-200 meters; it appears between the surface and depths of 200-265 meters elsewhere in the area studied, except on the northern boundary where it extends to 420 meters depth (Depths of water masses at each location sampled are shown in Fig. 14).

Beneath the upper water mass a layer of Western North Pacific Central water appears at nearly every location sampled. This layer is only 10 to 50 meters thick and occurs at 155 to 245 meters depth near Bikini and south of Bikini's latitude. From there it submerges with northward travel to depths of 265-400 meters and becomes 80 to 150 meters thick. This is consistent with the fact that the lighter, and usually warmer, surface waters move to the right of the current. Piling up on the north side of the area they cause a downward displacement of water already present as revealed by lines that delineate their characteristics.

North Pacific Intermediate water is found at every position where sampling was done. On the north side of the area studied it is 300 to 800 meters thick and occurs at depths of 400 to 1200 meters. It thins to about 125 meters thickness in the latitude of Bikini and appears at 220 to 400 meters depth. On the south side of the area studied, the layer becomes about 300 meters thick and is found between 165 and 600 meters depth. Eddying and meandering of the current at these depths in the latitude of Bikini (Ref. Figs. 6D and 6E) apparently causes water to be welled upward from within this layer. Thus the layer becomes thinner there than farther south.

Below the widespread North Pacific Intermediate water there are spotty appearances of Western North Pacific Central water interspersed between layers of Pacific Equatorial water. Locations where Western North Pacific Central water was found are north of Likiep Atoll, north of Rongerik Atoll, and 90 to 130 miles northwest of Bikini Atoll. (It may appear at other locations at greater depth than was sampled). All three are in a northwest-southeast line and apparently represent a former influx of deep water from the northwest central Pacific. This tongue appears pinched to the north of Ailinginae Atoll by inflow of the Pacific Equatorial water mass of particularly high salinity from south of Rongelap Atoll to about 120 miles north of Ailinginae Atoll. The latter flow is within the eastern part of the Bikini eddy as shown in Fig. 6E.

Pacific Equatorial water is also found at all other locations where samples were taken. It appears at all depths below about 350 to 400 meters in the latitude of Bikini, below 415 to 600 meters depth on the south side of the area studied and below 700 to 1200 meters depth on the north boundary of the area. By continuity, it is shoalest in the latitude of Bikini where it moves upward to replace North Pacific Intermediate water that wells toward the surface within the great, horizontal, slowly revolving eddy there.

3.6 UNDERWATER SOUND PROPAGATION

At five locations on the HORIZON's cruise, temperature and salinity were measured to depths of as great as 2500 meters to more than 4000 meters. For these stations computations were made of the speed of underwater sound. At all locations the sound speed profiles from top to bottom were very similar except in the depth range of the thermocline. Thus, sound speed data are shown plotted only for one station as an example (Fig. 9).

At all locations the speed of underwater sound is nearly constant above the thermocline. In general, conditions are now relatively good for near-surface propagation of underwater sound in the PPG. As summer progresses and the trade wind weakens the surface will be warmed. Then sound speed will be greater near the surface than elsewhere below it and more sound energy will refract downward and be lost from the layer above the thermocline. Thus, sound propagation conditions in upper waters will become less favorable.

Commencing at the top of the thermocline, sound speed decreases rapidly with decreasing temperature (Fig. 9). It reaches a minimum, generally at 1000 to 1200 meters, except at one location where it was least, at 800 meters. This minimum is the axis of the deep SOFAR channel. For comparison, off the west coast of the United States this minimum is found at 600 to 800 meters depth.

Below the minimum the sound speed increases with depth. The increase is very slow down to below 2000 meters. Thus any part of the area less than about 1000 fathoms water depth is bottom limited for deep water sound propagation. Where depths are 2000 fathoms or greater the deep water propagation is fairly good. It is not as good, however, as off the west coast of the United States where the speed near the bottom is more nearly equal to that at the surface.

DRAFT [redacted]

4. CIRCULATION IN BIKINI LAGOON

by

Donald W. Pritchard

Previous studies of Bikini Lagoon, notibly those by Von Arx (1954) and Munk, Ewing and Revelle (1949), have established the characteristic circulation patterns and, to a lesser extent, the diffusion rates in the Lagoon. Because of the predominance of the ENE tradewinds during winter and spring these studies deal primarily with the circulation pattern associated with moderate ENE winds. Conditions in the lagoon during periods of light winds or of winds from the southerly quarter are less well understood.

Field studies of the hydrography of Bikini Lagoon were initiated early in April in support of present [illegible] program. These studies support, in the main, results from previous studies. Some notable differences were found, and these will be reported in the body of this report. Evidence of the changes in the circulation pattern which occurs during periods of light winds are also presented. Unfortunately during this initial field study there were no periods of more than a few hours duration in which the wind had a southerly component, and so the circulation pattern under conditions of a SE to S wind could not be studied.

4.1 GENERAL DISCUSSION OF WATER MOVEMENTS IN BIKINI LAGOON

Four factors contribute to the circulation of the waters in Bikini Lagoon. These are: (1) direct wind induced currents; (2) Currents associated with the flow of water over the windward reefs as a result of the breaking of waves on reefs; (3) Tidal currents; and (4) Currents flowing through Enyu channel.

The primary parameter controlling the circulation pattern in the Lagoon is the wind. With the ENE trade wind a cellular circulation pattern is established with surface waters flowing across the Lagoon from the east toward the west, and the deeper waters flowing in the opposite direction. Waves breaking on the windward reefs produce an influx of water into the Lagoon. The wave energy actually produces a water level over the reefs which is about 1½ feet above that prevailing in the Lagoon. This head of water produces a flow into the Lagoon along the windward reefs which has been estimated by Von Arx to consist of about 665 million cubic meters per day. This is about [illegible]% of the Lagoon volume, and constitutes nearly 1/3 of the volume of the new water [illegible] to the Lagoon each day.

Some of the westward flowing water is exhausted across the leeward reefs, and through the leeward passes during the ebbing tidal flow. A major portion of the surface flow can not be so exhausted, and so subsidence occurs in the western end of the Lagoon and these waters return towards the east in the subsurface layers. Most of this return flow upwells along the eastern [illegible] of the Lagoon and returns westward along the surface. A portion of the deeper flow is diverted, both north and south, into [illegible] secondary horizontal cells, producing a counter-clockwise flow in the northern section of the Lagoon and a clockwise flow in the southern section of the Lagoon.

Water from the open ocean enters the Lagoon through Enyu Channel in a westerly flowing current. This flow augments the westerly surface flow along the wide mouth of Enyu Channel and [illegible]

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large portion of the mixture escapes to sea at the western end of the channel.

During periods of southerly or south-easterly winds the flow across the eastern and north-eastern reefs is greatly reduced. The major inflow is then through Enyu Channel. Any prolonged period of such winds probably establishes a cellular circulation pattern oriented along a northwest-southeast axis. In the central portion of the Lagoon a return flow directed toward the southeast would exist in the deeper layers. Secondary horizontal cells are also likely to exist.

4.2 RESULTS OF PRESENT FIELD STUDIES

Currents in Bikini Lagoon have been studied by measurements made from an anchored vessel and by tracking drift drogues. Fig. 15 shows observations taken at the surface and at a depth of 10 meters (33 ft.), and represents the flow in the westward moving surface layer. Fig. 16 shows observations taken in the deeper layers at depths of 30 meters (98 ft.) and 40 meters (131 ft.).

Previous investigators have reported that the wind induced surface flow in the Lagoon is directed with the wind at a velocity equal to about 3% of the wind velocity. These previous studies depended to a large extent on drift poles which are directly influenced by the wind. The present measurements indicate that the 3% figure is too high. Our direct observations from an anchored vessel show that the surface current (actually the flow in the upper three feet of the water column) is directed at about 22° to the right of the wind direction and at a speed equal to 1.6% of the wind speed, (using an anemometer level of 30 ft.).

At five meters (16 ft.) the average deviation to the right increases to 26° and the average speed decreases to 1.3% of the wind speed. During the period of observation (early April through early May) the average wind velocity was 19.5 knots from 063°T. The average surface current was then 0.31 knots towards 265°T and at 5 meters (16 ft.) the current velocity averaged 0.21 knots towards 269°T.

The easterly flowing current in the deeper layers was observed to be much slower and more variable both in speed and direction than the surface flow. The direct measurements from an anchored vessel gave speeds of from 0.06 to 0.15 knots.

These speeds are somewhat higher than those given by drift drogue observations.

The results from a series of current measurements taken over a five hour period at a location near the center of the Lagoon are presented here to indicate the characteristic distribution of currents with depth, and their relationship to the wind. In Fig. 17 the currents at the surface, 10 meters, 15 meters, 20 meters, 30 meters, 40 meters and 50 meters are shown as vectors. In addition a vector equal to 1/100 of the average wind velocity during the period of observation is shown for comparison.

In addition to the measurements made from an anchored vessel, several drift drogues were released near the center of the Lagoon, and currents at the surface and at 30 meters determined from the observed drifts. The surface drogues, which give velocities representative of the upper ten feet of the water column, compare very favorably with the direct measurements made from the anchored ship.

The average velocity as determined from the drift of the surface drogues was directed 27° to the right of the wind direction with a speed equal to 3.5% of the wind speed.

Fig. 18 gives the current vectors as determined from three drift drogues set at 30 meters (98 ft) near GOOA in the center of the Lagoon. The observation made on 24 April was during a period of very light winds and will be discussed below. The observations on the 3rd through 7th of May were taken during normal ENE trade wind conditions, and show the characteristic easterly movement of the deeper waters. The speed of movement of the deeper waters would appear from these observations to be of the order of 0.05 knots-- considerably lower than indicated by the direct measurements from the anchored ship.

4.3 CONDITIONS DURING PERIODS OF LIGHT WINDS

During the two day period 23-24 April the ENE trade winds decreased markedly in the Bikini area, and for several hours were approximately 5 knots. Drift drogue observations made on the morning of 24 April showed virtually no motion of the surface, and apparently the relationship between wind velocity and surface current no longer holds at these low wind velocities. The drogue at 30 meters indicated a very low current velocity (less than 0.01 knots) in a westerly direction (see Fig 18). With wind velocities of 5 knots or less the circulation in the central portion of the lagoon apparently ceases, with the deeper layers exhibiting a weak return oscillation which produces currents directed opposite to the normal flow direction. Renewal of lagoon water through inflow across the windward reefs and outflow across the leeward reefs must be greatly reduced, and the primary exchange of water with the open ocean must take place as a result of flow through Enyu Channel and tidal exchange through the southern and southwestern passes.

4.4 THE RENEWAL OF WATER IN BIKINI LAGOON

Von Arx has estimated that under normal trade wind conditions the various process of exchange of water with the open ocean—i.e., the inflow across the windward reefs and the outflow across the leeward reefs, the flow through Enyu Channel and the tidal exchange at the passes will lead to an exchange of the water in Bikini Lagoon in approximately 40 days. Our observations at stations located along the windward reefs indicate that the inflow across these reefs is greatly affected by tidal height. During spring tides exchange of water by this mechanism is probably significantly higher than during neap or mean tides. Since approximately 1/3 of the new water brought into the lagoon each day comes in across the reefs, significant variations in this volume of inflow will markedly affect the exchange time for the lagoon.

During periods of light winds, when the main cellular circulation in the lagoon ceases, the exchange of water in the lagoon becomes very slow. Such a condition would also tend to reduce the vertical exchange and since most of the inflow and outflow occurs in the upper 10-20 meters, the rate of renewal of the deeper waters of the lagoon would become almost negligible.

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 [redacted]

With southerly and southeasterly winds most of the inflow occurs through Enyu Channel--the inflow across the windward reefs becoming negligible. The rate of renewal of Lagoon water in this case will depend on the wind velocity, and will be limited by the amount of water which can escape across the northern and northwestern reefs. The exchange time for southern or southeastern winds is estimated at between 60 and 100 days.

Table 6 gives estimates of flow into and out of Bikini Lagoon, for normal trade wind conditions. The major influx and outflow of waters into and out of the Lagoon takes place through the south and southwestern passes and channels. However, this flow is primarily tidal in nature, and the majority of new sea water carried into the Lagoon through these passes and channels on the flooding tide is withdrawn from the Lagoon on the succeeding ebb flow. As a result, the major source of new water for the flushing of the Lagoon is the flow across the windward reefs.

DRAFT [redacted]

TABLE 6

Estimate of Flow Into and Out of Bikini Lagoon

For the Trade Wind Season

(+ = Inflow; − = Outflow)

Location	Volume in millions of m^3 (During designated stage of the tide) Ebb ([illegible] hrs)	Volume in millions of m^3 (During designated stage of the tide) Flood ([illegible] hrs)	Net Transport (millions of m^3/day)
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible] Channel	[illegible]	[illegible]	[illegible]
[illegible] Pass	[illegible]	[illegible]	[illegible]
Southwest Channels	[illegible]	[illegible]	[illegible]

DRAFT [redacted]

MOVEMENT AND FLUSHING OF RADIOACTIVE CONTAMINATED WATER IN THE LAGOON

The initial short-range distribution of residual radiation which will exist following the test shot cannot be predicted with certainty. In order to indicate the likely effects of the circulation pattern on the time changes in the pattern of water-borne radioactivity in the lagoon, use is made of certain generalized features of assumed initial patterns of distribution.

HIGH AIR BURST

The initial pattern of radioactive contamination in the lagoon waters is assumed to be a relatively uniform, low-level and wide-spread distribution in the surface waters of the lagoon. The highest concentrations are assumed to occur in the [illegible] quarter of the lagoon.

Under normal trade wind conditions the surface currents will carry the radioactive contaminated water in a [illegible] direction. At the same time the contamination will rapidly be mixed vertically, and become distributed throughout the water column in approximately [illegible] hours.

The speed of drift of the contaminated surface waters would be about 0.5 knots, directed towards the [illegible] under conditions of the normal trade winds. Thus, contamination originating just inside the lagoon at a point off [illegible] ([illegible]) would reach the western reefs in approximately 27 hours. About 10% of the contaminated surface waters will be discharged over the western reefs at this time. The remainder will enter the return flow in the sub-surface layers and be carried eastward, towards [illegible] ([illegible]) and [illegible]

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(Bikini), at a speed of about 0.07 knots. During the [illegible] to [illegible] days of travel required to carry the contaminated water from the area of subsidence in the western end of the Lagoon to the area of upwelling in the eastern end of the Lagoon, vertical mixing will continue to return a portion of the contaminated water into the westward flowing surface layer, from which a portion will be continuously discharged from the Lagoon over the western reefs and through the southwestern passes.

The leading edge of the subsurface, eastward moving mass of contaminated water will continually be moving under [illegible] surface water, and the vertical mixing of the contamination into the westward moving surface layer will effectively erode away the leading edge, so that the progress of the radioactive material toward the eastern end of the Lagoon will be materially less than the actual eastward drift of the subsurface waters. By the time the contaminated water mass reached the eastern end of the Lagoon, the concentration of radioactivity will be quite low.

[illegible] SHOT ([illegible])

It is here assumed that ZUNI shot will result in the formation of a crater some 2100 feet in radius and 150 feet deep. Such a crater will break through the reef at the western end of TARE (Eninman) on three sides--that is, on the Lagoon side, the ocean side, and towards the channel between TARE and UNCLE (Eneirikku). The sill depths on the Lagoon and ocean sides of the crater will be approximately 50 ft below sea level. The shot will thus create a new channel between the open sea and the Lagoon.

Tidal currents, upon which will be added a net outflow from the wind drift within the Lagoon, will occur in the new channel. Flood velocities of approximately 0.3 knots, and ebb velocities of about 0.6 knot will result. During periods of large tidal ranges (0-6 ft.) these current velocities may be expected to about double in magnitude. The influence of the tidal currents should be felt for a distance of about 3000 yards inside the Lagoon. Within this distance the predominant westerly current, which flows parallel to the reefs along TARE and UNCLE, will be bowed in and out by flood and ebb of the tide. The ebb current will set toward the SW, and the flood current toward the NW.

It is assumed that the ZUNI test will produce highly radioactive contaminated water in a large segment of the South-central portion of the Lagoon. Here the probable drift and spread of the very highly contaminated water contained initially within a one mile radius of point zero is considered. For convenience we will designate this volume of radioactive water as "volume A".

The drift of this mass of contaminated water will depend to a large extent on the stage of the tide at the time of the shot. If the shot occurs between high tide and high tide plus three hours, the prevailing Southwest currents will carry out of the Lagoon about 80% of "volume A".

With the turn of the tide to flood just after low tide occurs, the remaining contaminated mass of water will be carried into the lagoon. Very little of the radioactive contamination which escaped

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~~49~~

from the Lagoon on the ebbing tide will return on the succeeding flood.

The 20% of the original highly contaminated mass which remained in the Lagoon will be swept WNW along the Southern side of the Lagoon at a speed of about 0.2 knot, arriving in the vicinity of Rukoji channel in approximately 18 hours. Here about 50% of this remaining segment of "volume A" will be swept out of the Lagoon through Rukoji channel by the prevailing ebb flow. Thus only 10% of "volume A" remains in the lagoon after 24 hours subsequent to shot time.

This remaining segment will be carried northward and then eastward in the subsurface return flow. The vertical mixing, coupled with the vertical shear in the horizontal currents, will result in a spread of the area of contamination at a rate roughly proportional to the first power of time, and a consequent decrease in concentration inversely proportional to the first power of time. This relationship will no longer hold when the size of the contaminated area becomes a significant fraction of the size of the lagoon, since the lateral boundaries will then become important.

The subsurface flow of about 0.07 knot directed toward the east will carry the remaining contamination of "volume A" to the region of upwelling along the NAN-HOW section of the eastern reefs in about ten days. After this time the contamination will be relatively uniform throughout the lagoon.

If the test should occur at low tide, or in the four hour period just after low tide, the majority of the contaminated water of "volume A" will be carried into the Lagoon with the flooding current. This will be true, particularly, if the test occurs during a period of large tidal ranges. Because of the westerly set to the currents in the lagoon along the TARE-UNCLE (Eininman-Enirikku) boundary, much of this contaminated water will be moved westward and will not be available to be carried out to sea on the subsequent ebb tide. After the first eight hours approximately 65% of the initial "volume A" will be within the Lagoon. About 40% of this remaining segment of "volume A" will be discharged from the Lagoon at Rukoji channel, the remaining 39% of the original "volume A" being carried slowly northwestward and then eastward by the subsurface current. Subsequent movements would parallel those described above for the case of a shot time close to the time of high tide.

This discussion has been concerned with the movement of the very highly contaminated volume which initially would occur within a one mile radius of point zero. A much larger area in the south-central section of the lagoon will be highly contaminated. Because of the location of the shot the initial flushing rates associated with the removal of this contamination from the Lagoon will be much higher than indicated by the renewal times for the Lagoon, provided the ENE trade winds prevail.

Assuming the moderate ENE trade winds occur during and for some weeks after the test, it is estimated that 20% of the initial contaminated waters in the lagoon will be flushed from the Lagoon in the first 24 hours. During the next full day 20% of the remaining contamination will be discharged from the Lagoon, and for the following three days it is estimated the flushing rate would be 10% per day. From the sixth to the 10th day after the test approximately 5% per day of the remaining contamination will be flushed from the Lagoon, and subsequent to the tenth day the flushing rate is estimated at 2½% per day.

Under these conditions 50% of the initial contamination carried by the waters in the Lagoon will be flushed out of the Lagoon by the fifth day following the blast. By the tenth day only 30% of the contamination will still be in the lagoon waters. These figures involve only the natural flushing of the contaminated waters. Radioactive decay rates have not been included here.

Should the prevailing winds just after the shot be from the SE, the flushing of the contaminated water from the Lagoon would be at a much slower rate than indicated above. The maximum concentrations of weapon debris in the upwelling waters of the NAN (Enyu) anchorage area would occur about five to seven days after the shot, and be an order of magnitude higher than would prevail under ENE trade wind conditions.

BARGE SHOTS

The location of the proposed barge shots, in the area south of FOX (Romurikku), is not conducive to rapid flushing of the water born radioactive contamination. The currents in the surface layers will require about three days to carry the contaminated water from the vicinity of the blast to the leeward reefs and

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southeastern passes. During this period vertical mixing will introduce significant amounts of activity into the deeper layers which are flowing eastward. The upwelling water in the vicinity of HOW (Bikini) will contain radioactive contamination about five days after the shot, and this contamination would reach the NAN (Enyu) anchorage area about six days after the shot. By this time the contamination will be distributed over a wide area, and no local spots of high activity should be found.

UNFAVORABLE WIND CONDITIONS

Should the wind blow with a westerly component, immediately subsequent to either ZUNI or one of the large shots, highly contaminated water could be carried by the easterly setting surface currents to the eastern end of the Lagoon. High activity could be expected to occur in the waters of the NAN (Enyu) anchorage for an extended period should the westerly winds prevail. Moderate to strong westerlies seldom occur in Bikini Lagoon, and would most likely be associated with a typhoon passing to the north of the Atoll.

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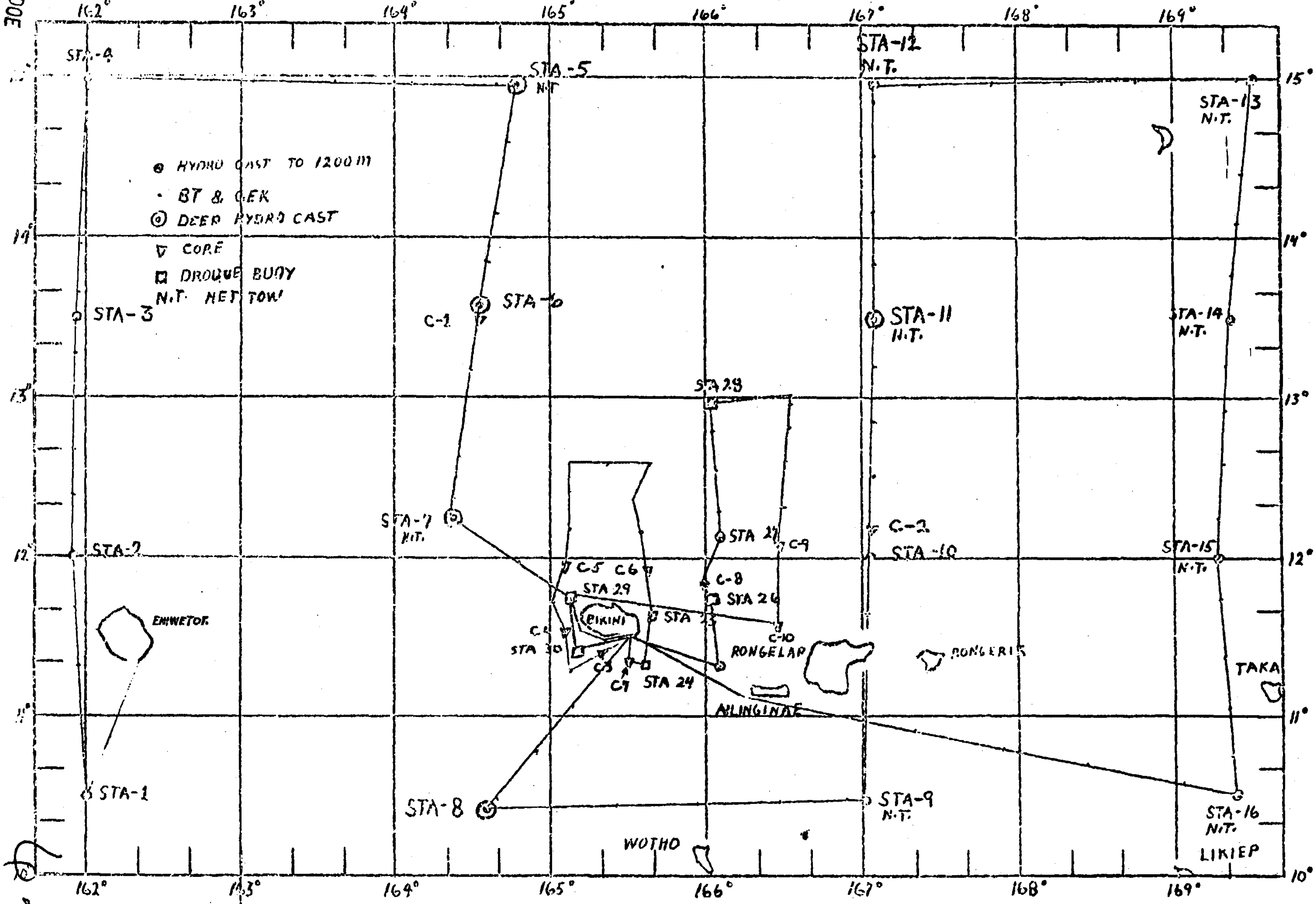

POSITION OF OBSERVATIONS

F.. 1A

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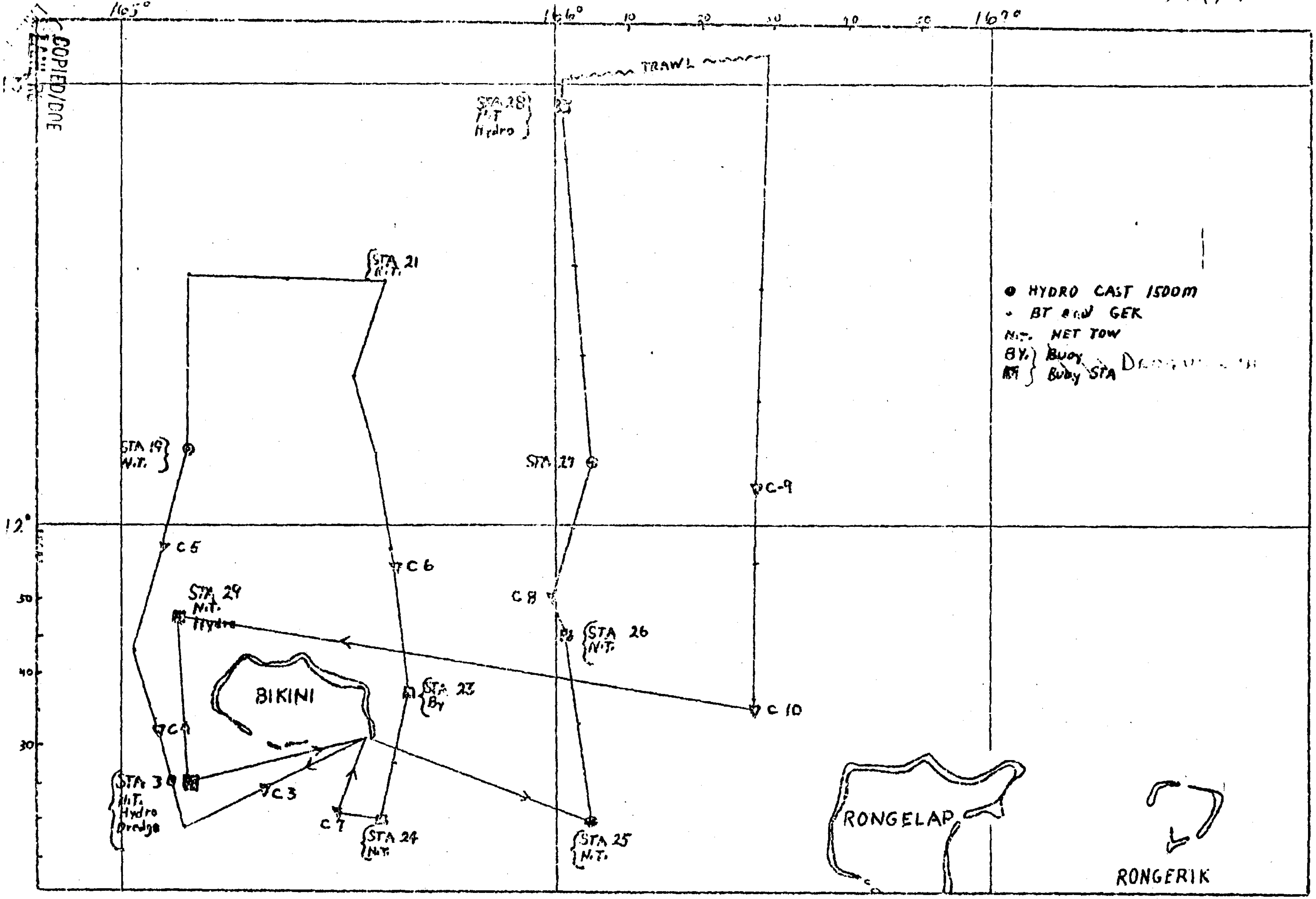

POSITION OF OBSERVATIONS
Fig. 1B.

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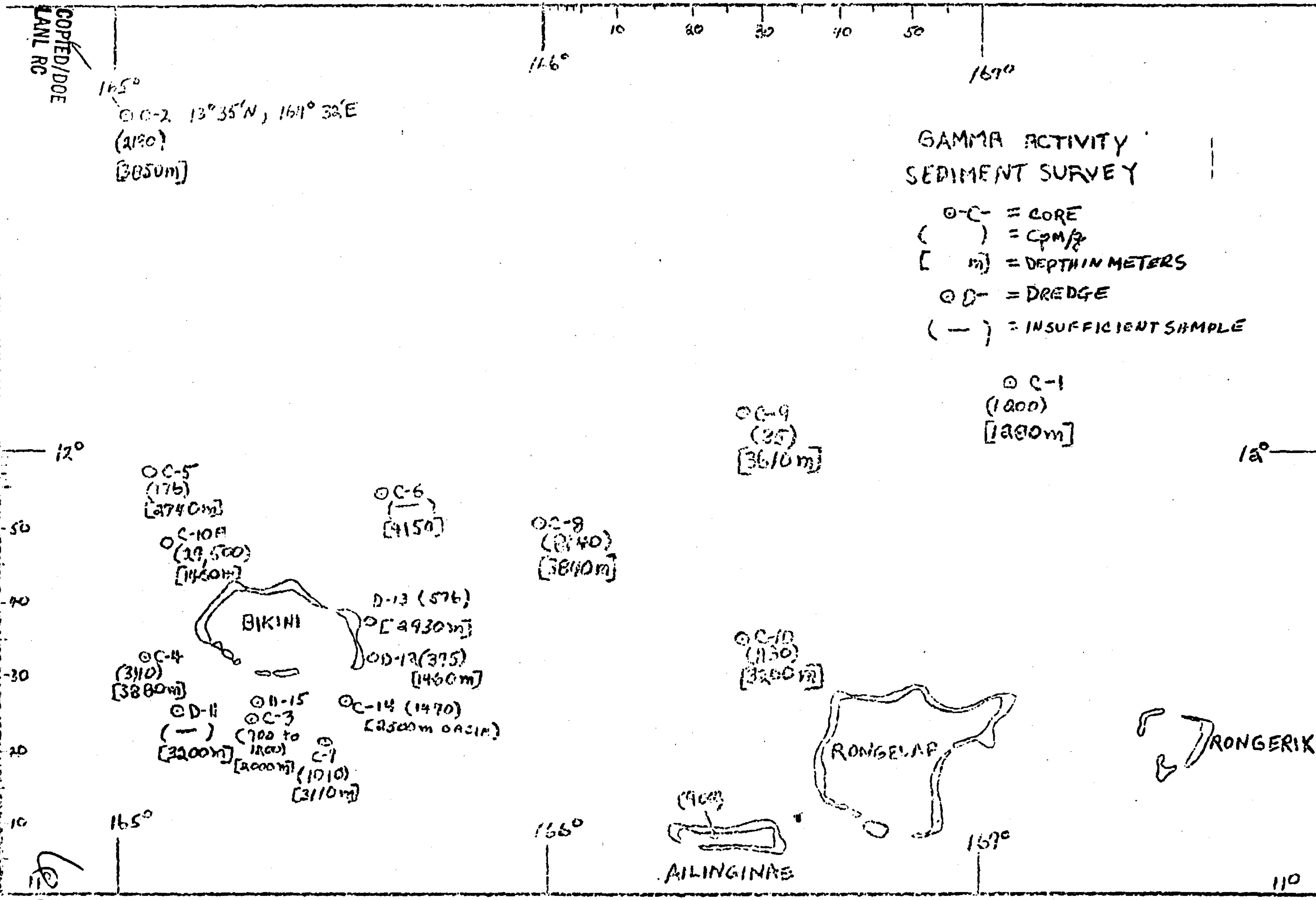

Fig 2

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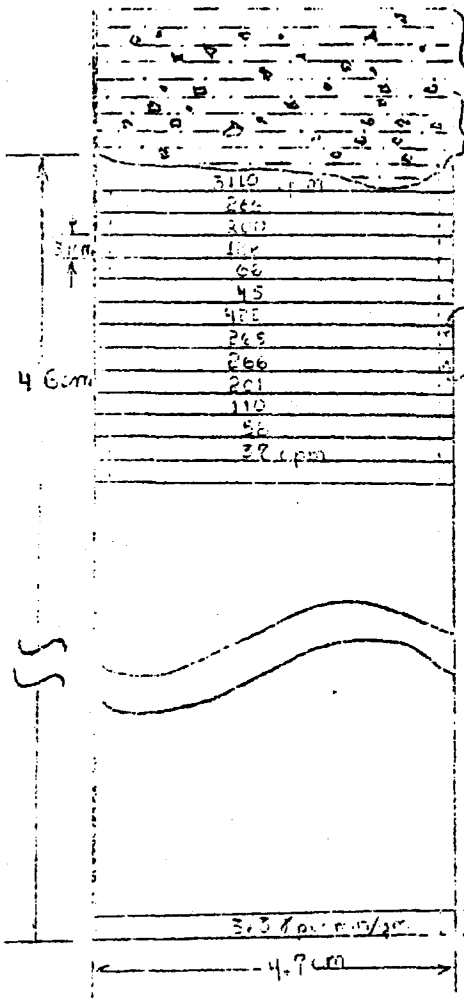
Levels of Radioactivity Found in a Sediment Core Taken in the Pacific Proving Grounds
13° 35' N. 164° 32' E.
11 April 1956



Suspended Sediment filtered from 1 liter of water over core :: 915 cpm

100 mls of filtered water over core :: 7.1 cpm

Gamma rays emitted per minute per gram of sediment taken from a 3 mm slice.

Discarded portion

Yellow - grey Globigerina ooze and fine coral sand with some stratification visable.

3 mm bottom section :: 3.3 gammas per min. per gram

NOT

Fig. 43

[redacted]

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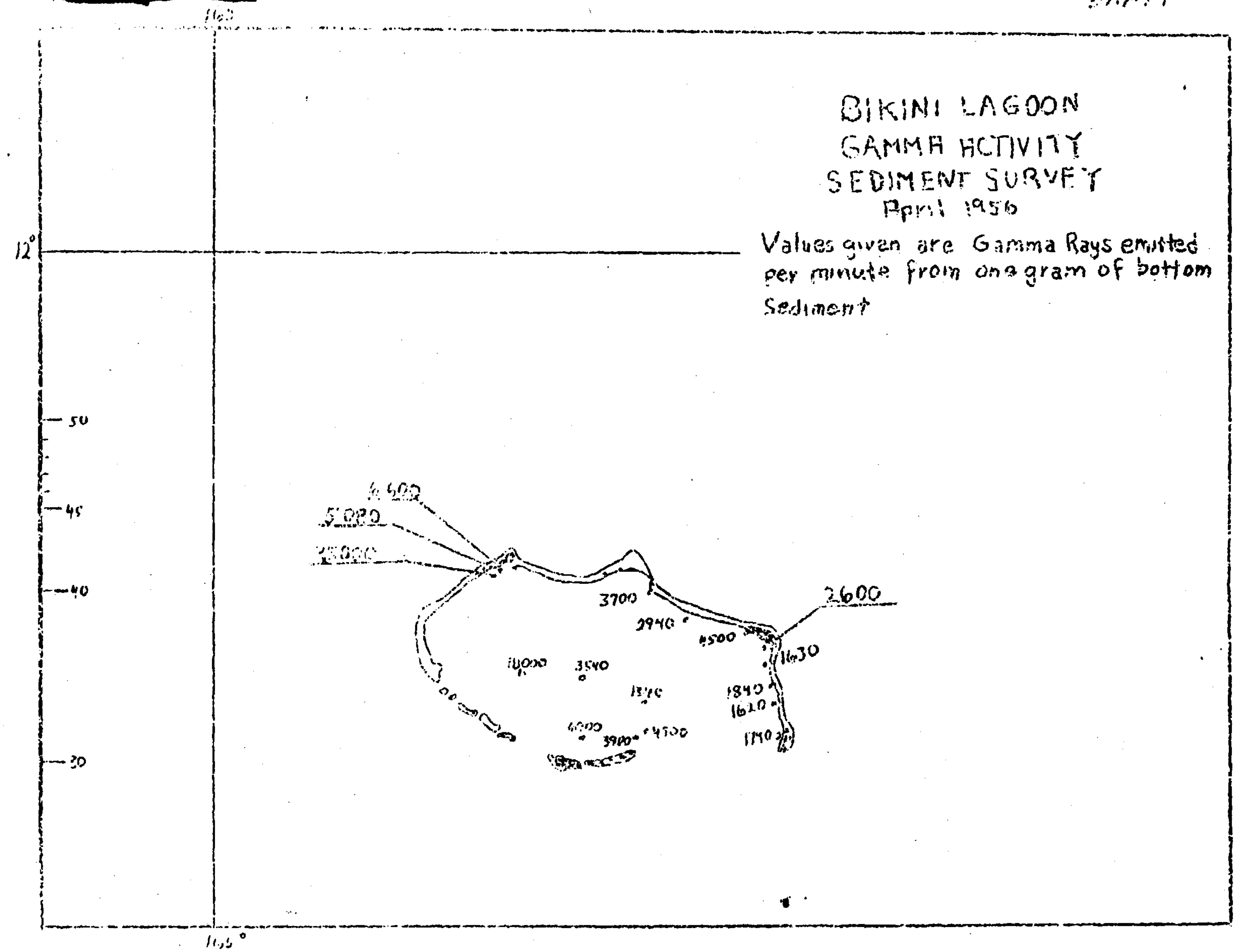

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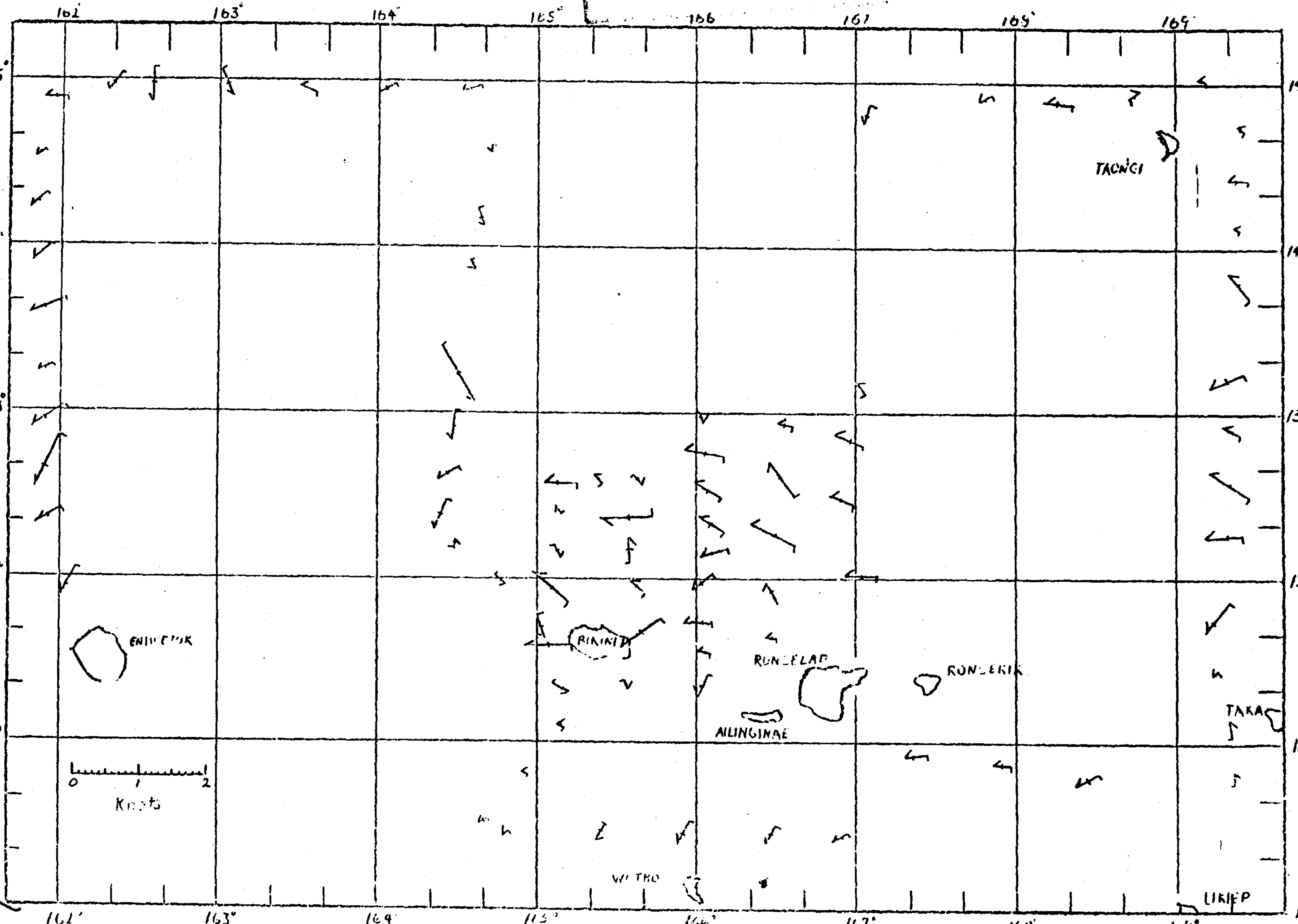

SURFACE CURRENTS from GEK.

Fig. 5

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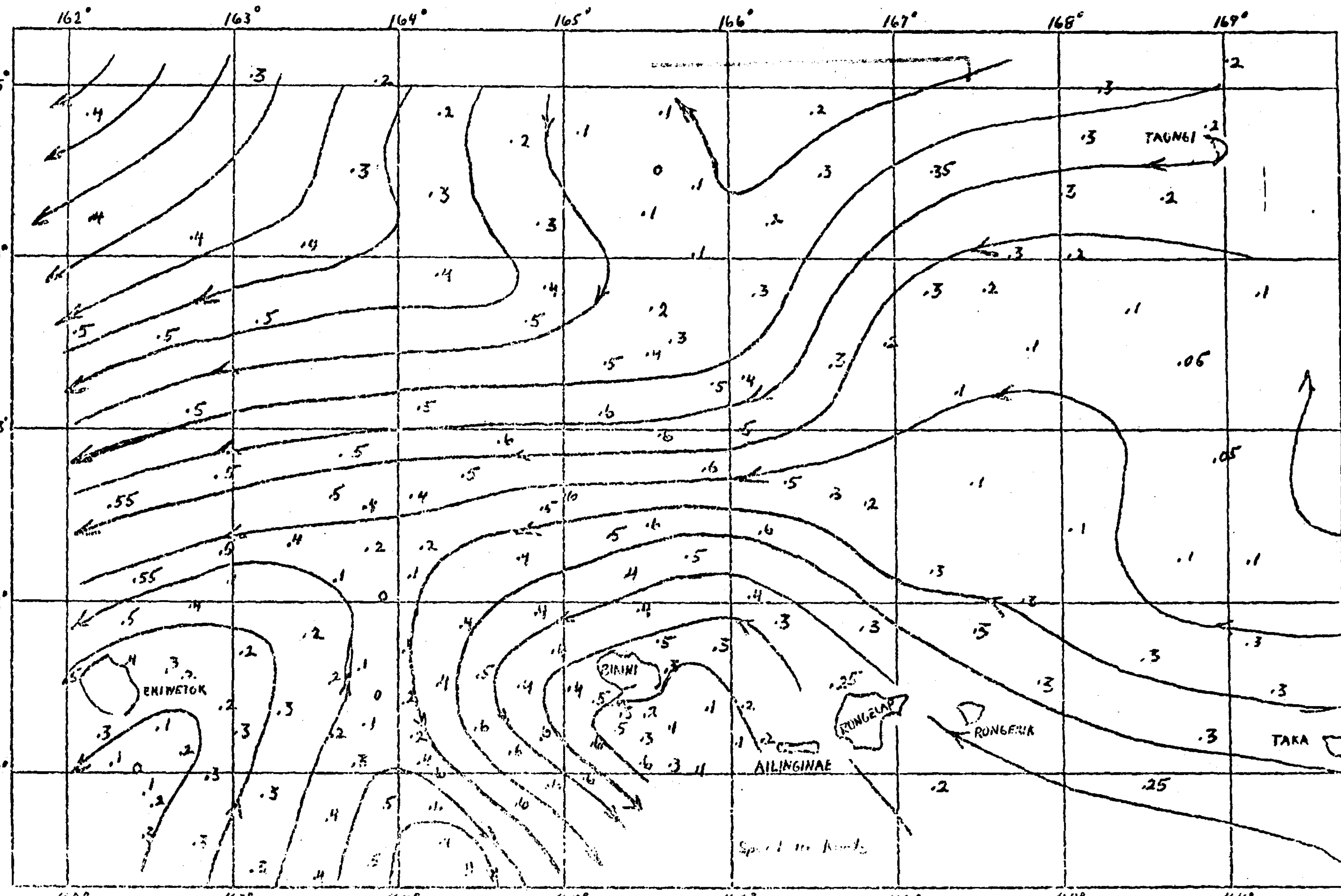

DIRECTION AND SPEED OF SURFACE CURRENTS

Fig. 6A

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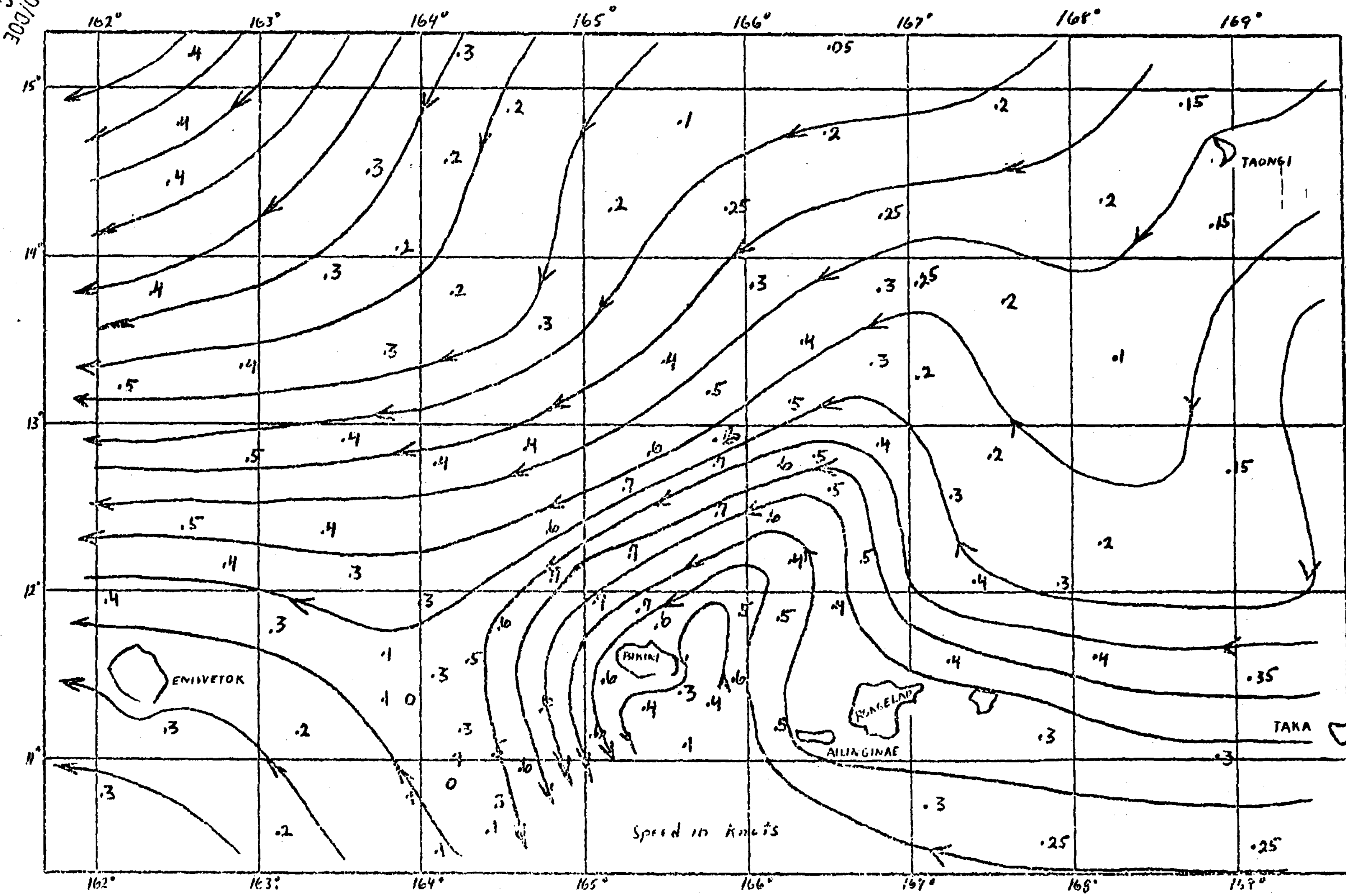

DIRECTION AND SPEED OF CURRENTS AT 75 METERS DEPTH

Fig. 6B

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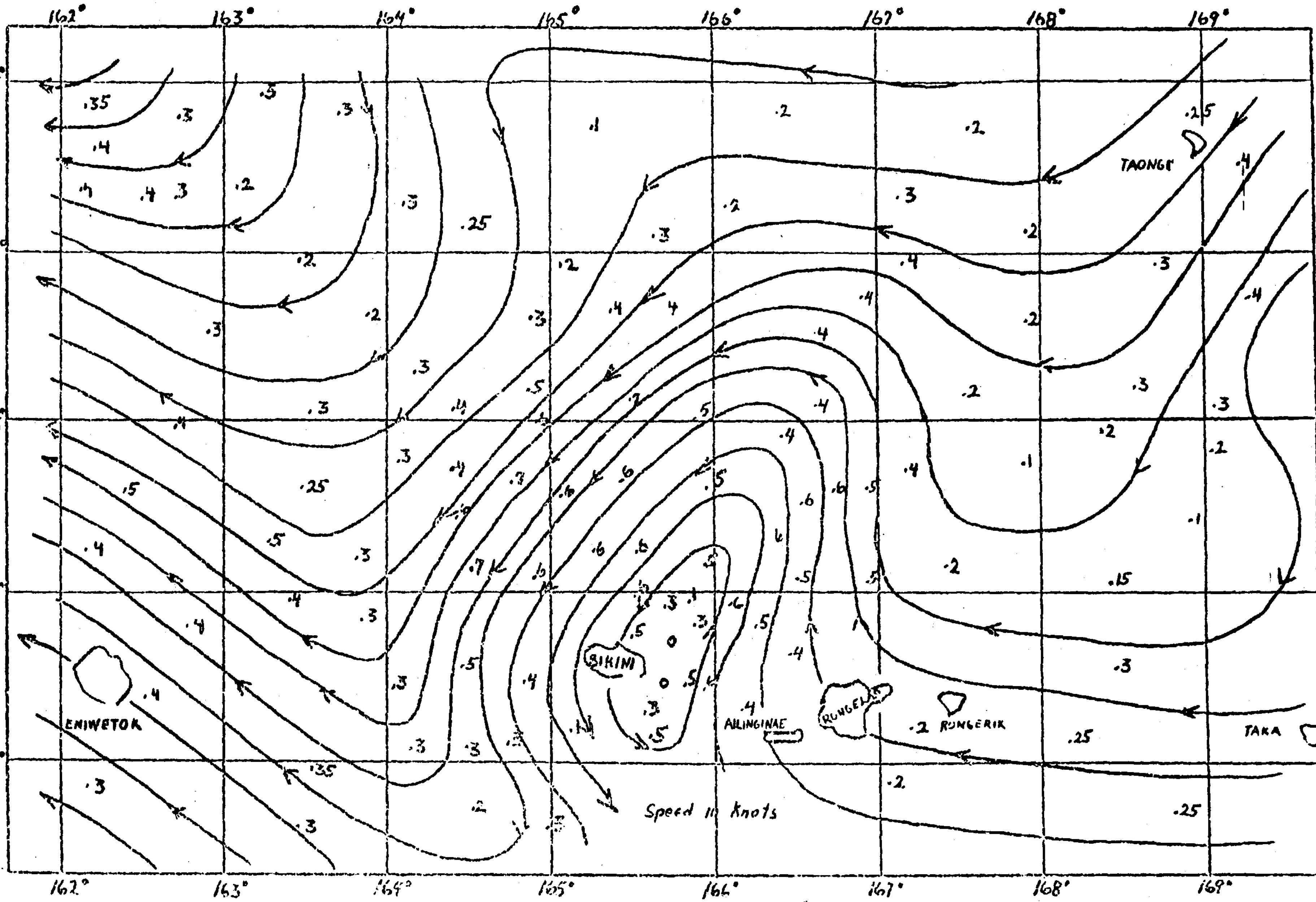

DIRECTION AND SPEED OF CURRENTS AT 150 METERS DEPTH

Fig. 6C

[redacted]

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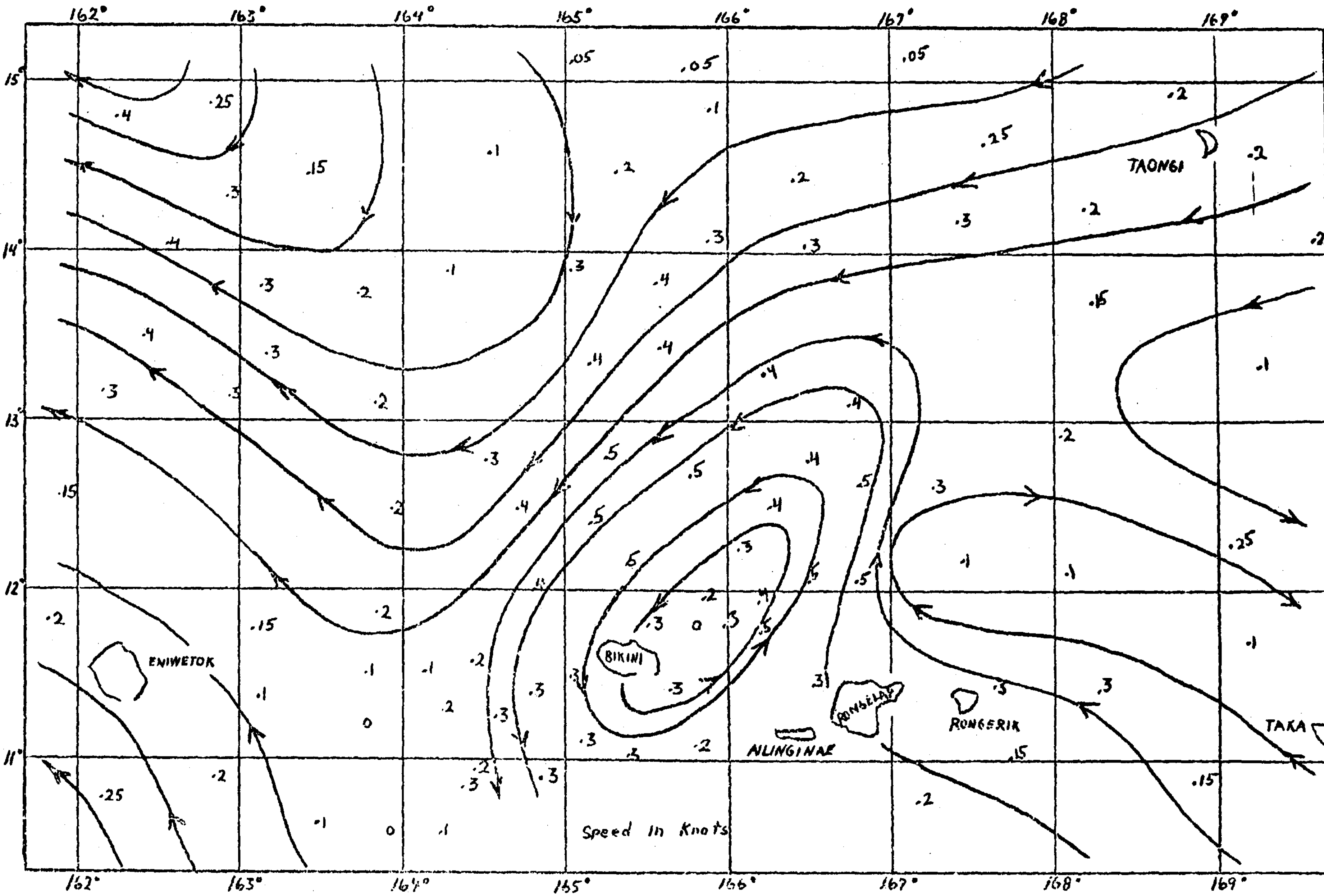

DIRECTION AND SPEED OF CURRENTS AT 250 METERS DEPTH
Fig. 6D

[redacted]

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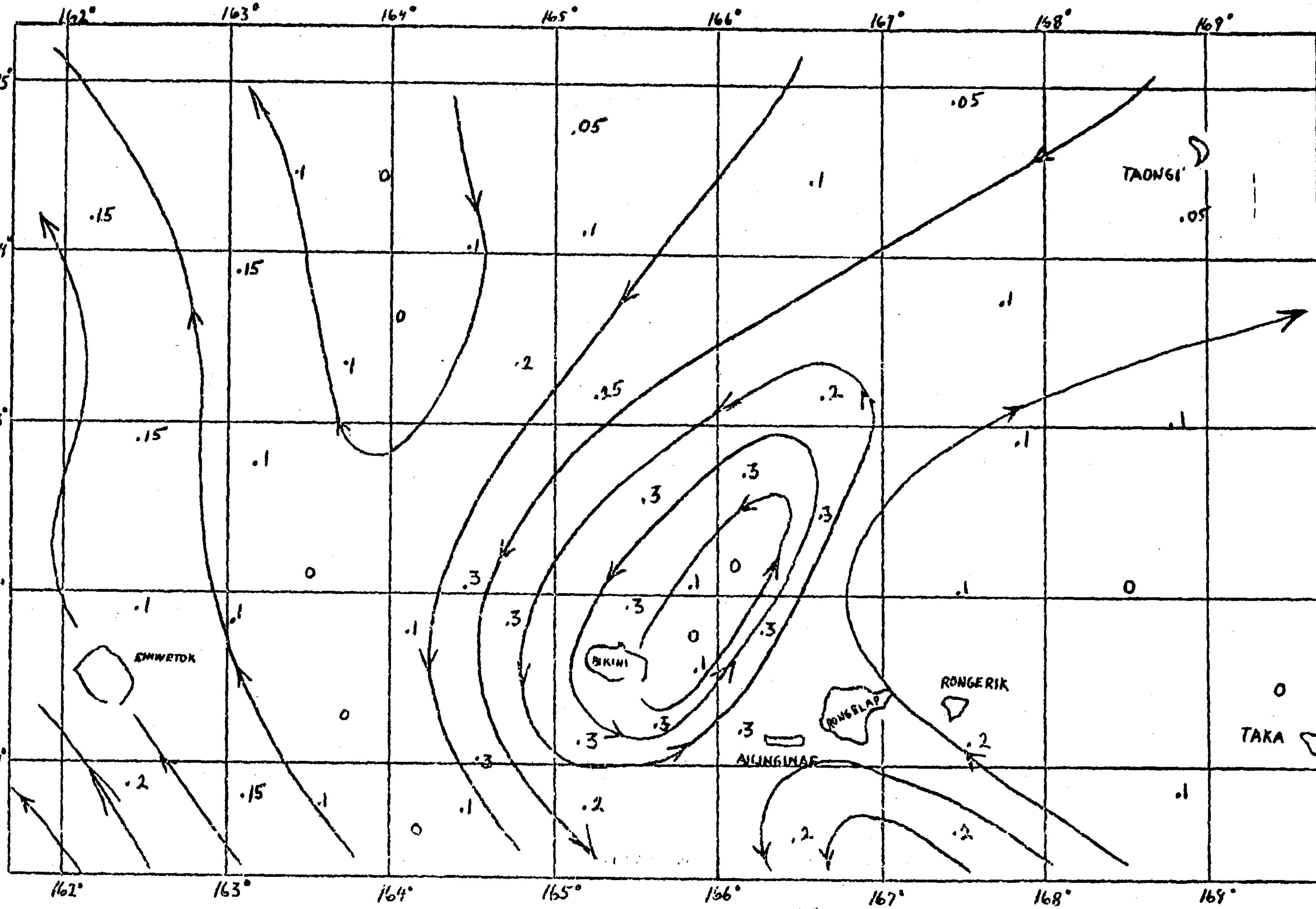

DIRECTION AND SPEED OF CURRENTS AT 500 METERS DEPTH

Fig. 6E

[redacted]

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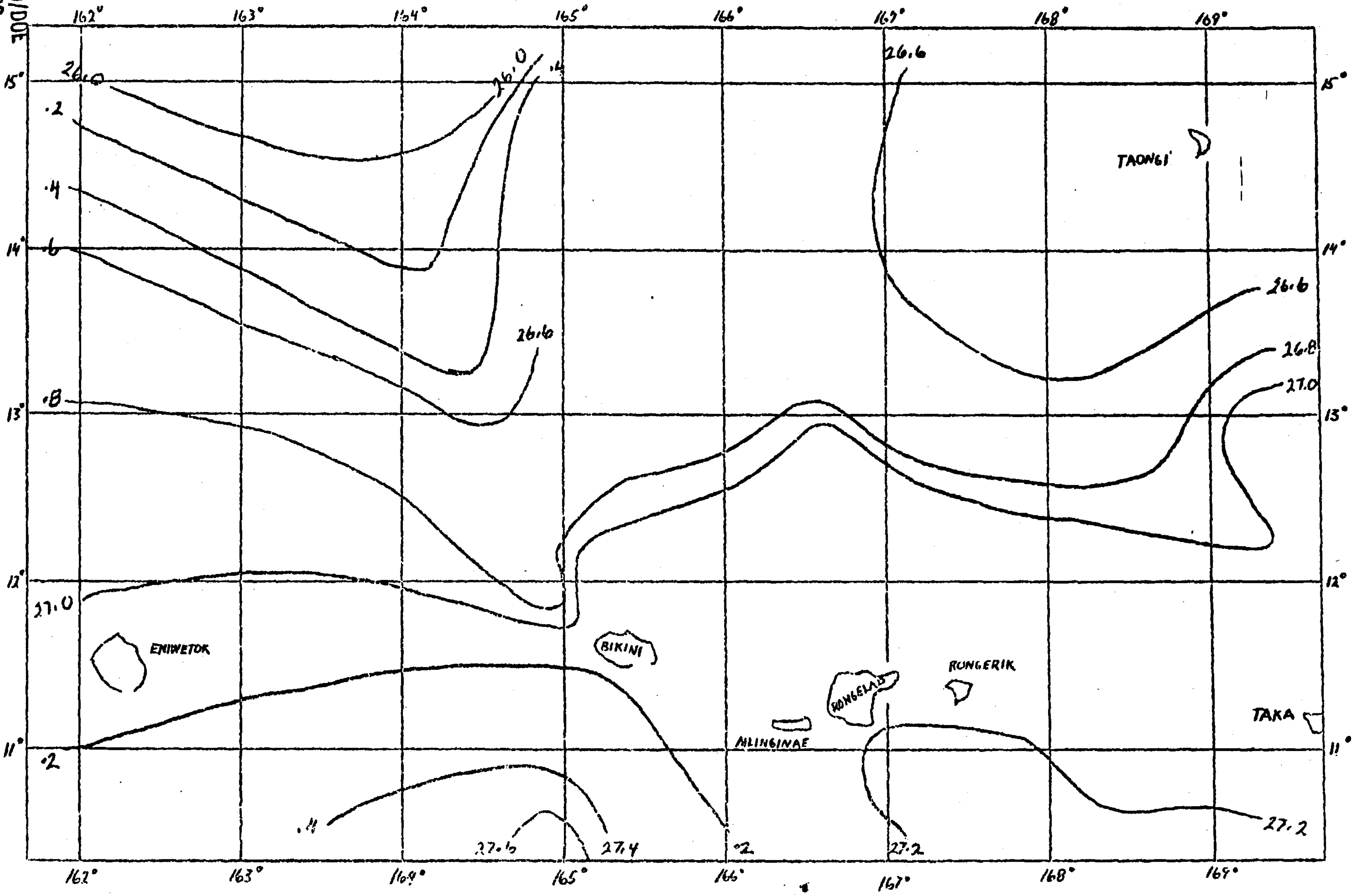

SURFACE TEMPERATURE
Fig. 7

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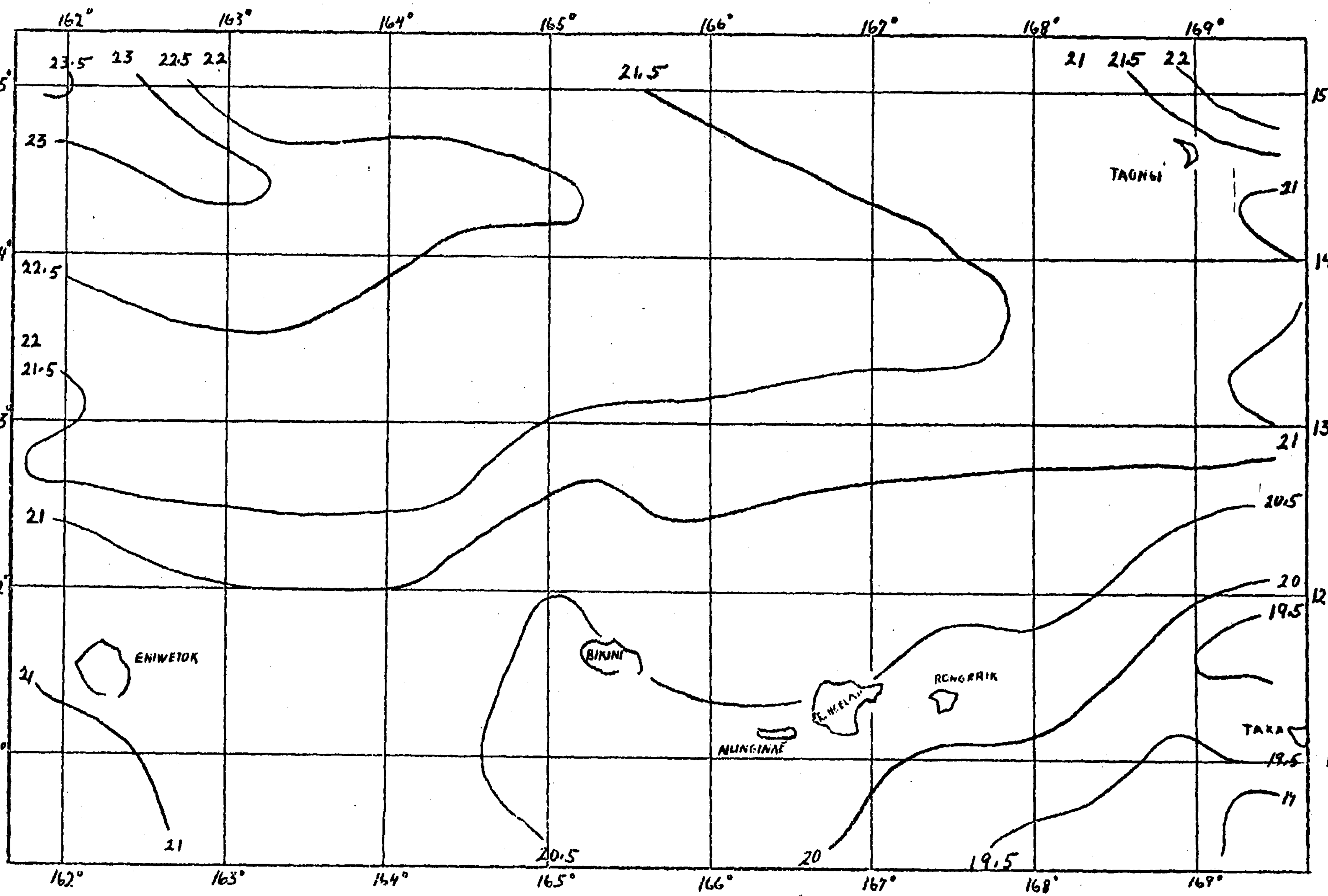

AVERAGE TEMPERATURE IN UPPER 200 METERS DEPTH

Fig. 8

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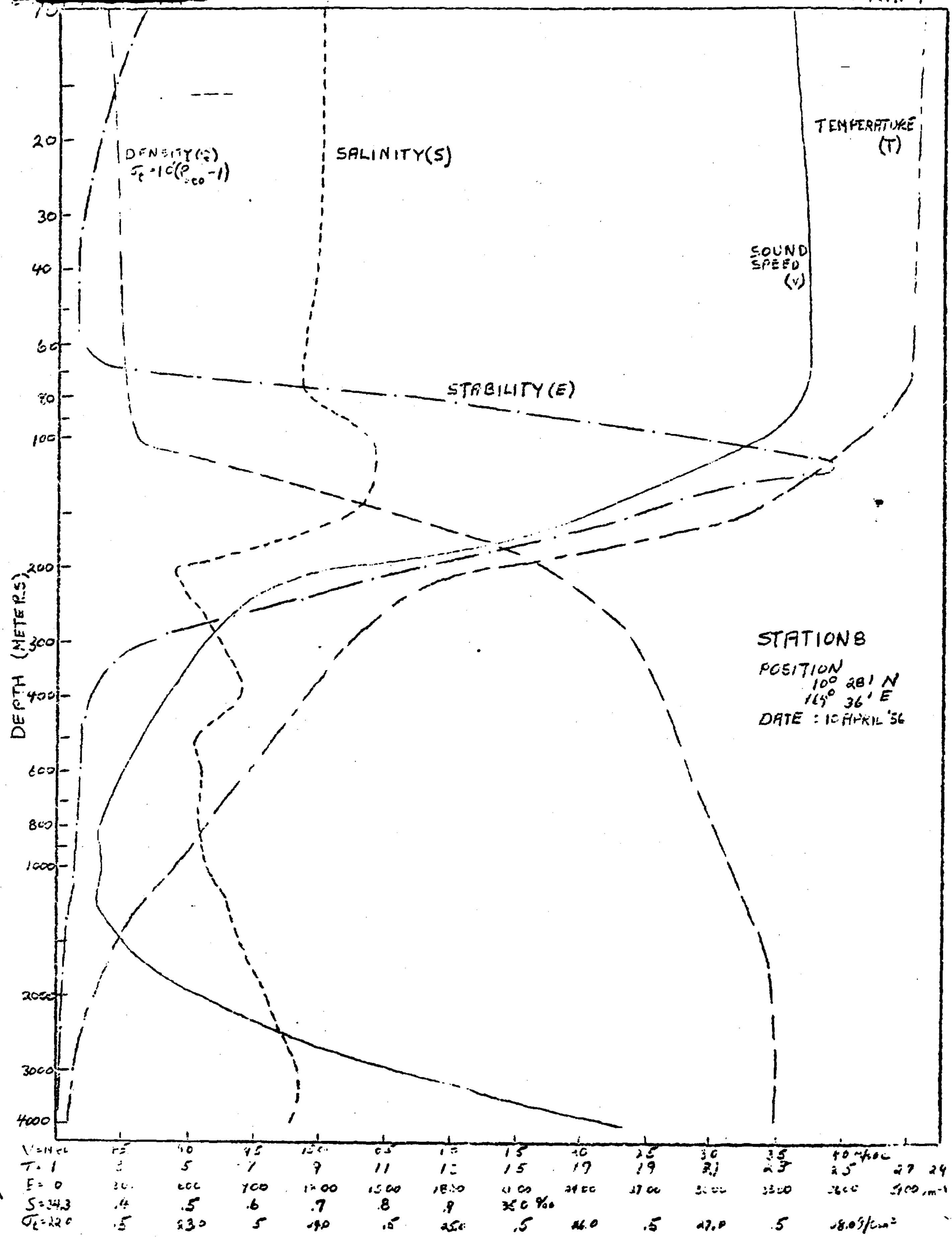

EXAMPLE VERTICAL DISTRIBUTION OF PHYSICAL DATA

Fig.

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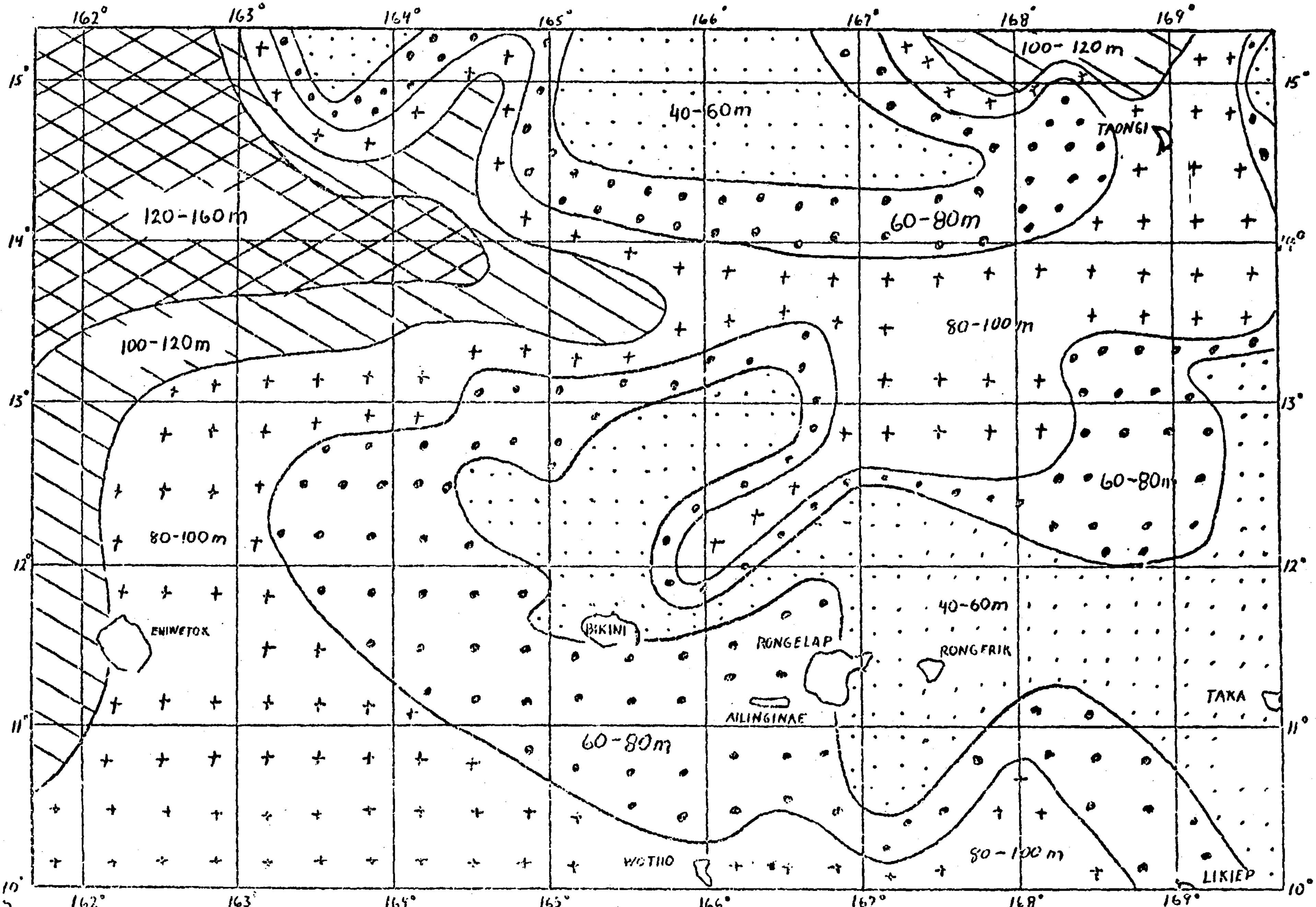

DEPTH of THERMOCLINE

Fig. 10

[redacted]

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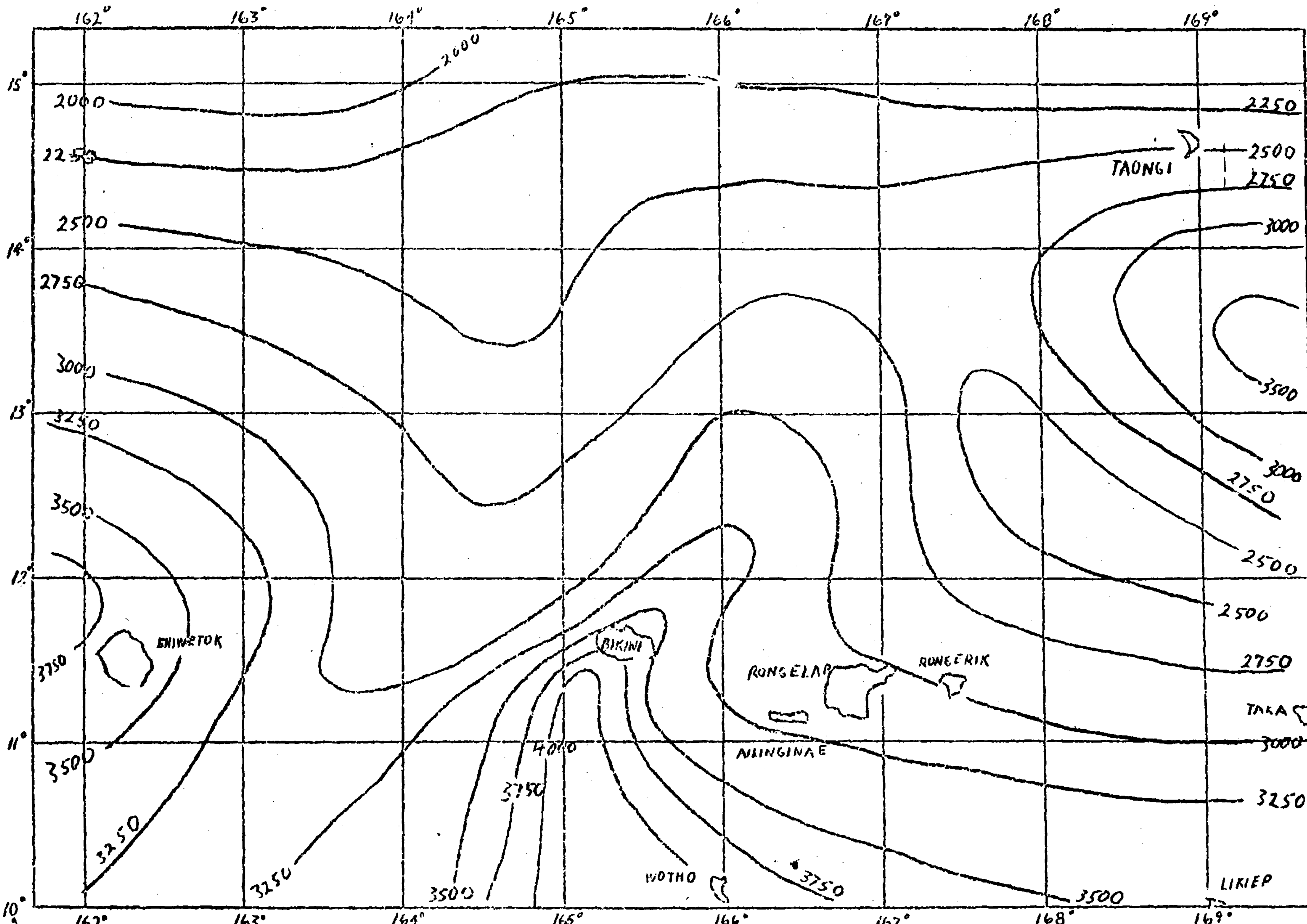

STABILITY OF MOST STABLE 25 METER LAYER

Fig. 11

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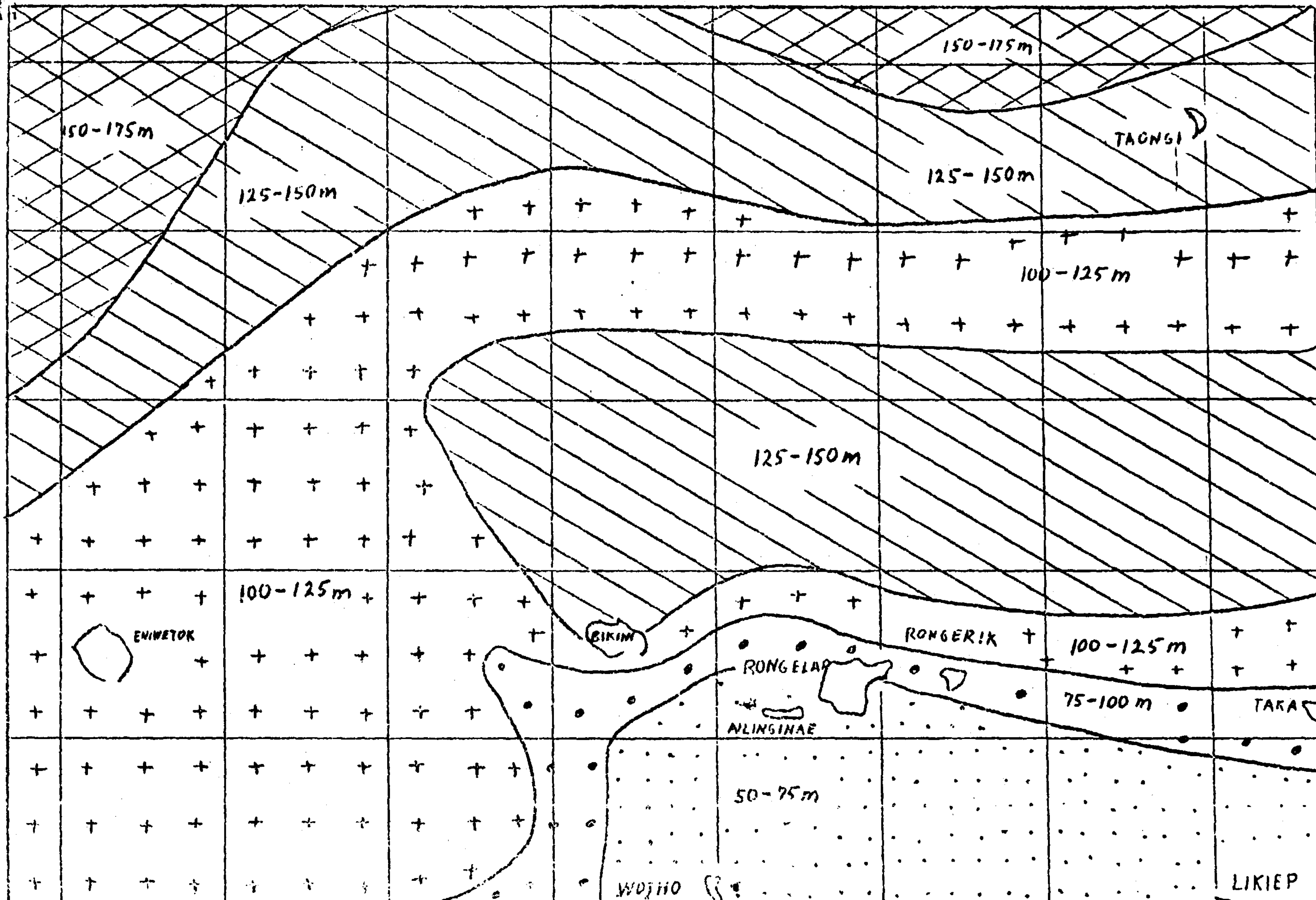

DEPTH OF MOST STABLE 25 METER LAYER

Fig. 12.

80D

[redacted]

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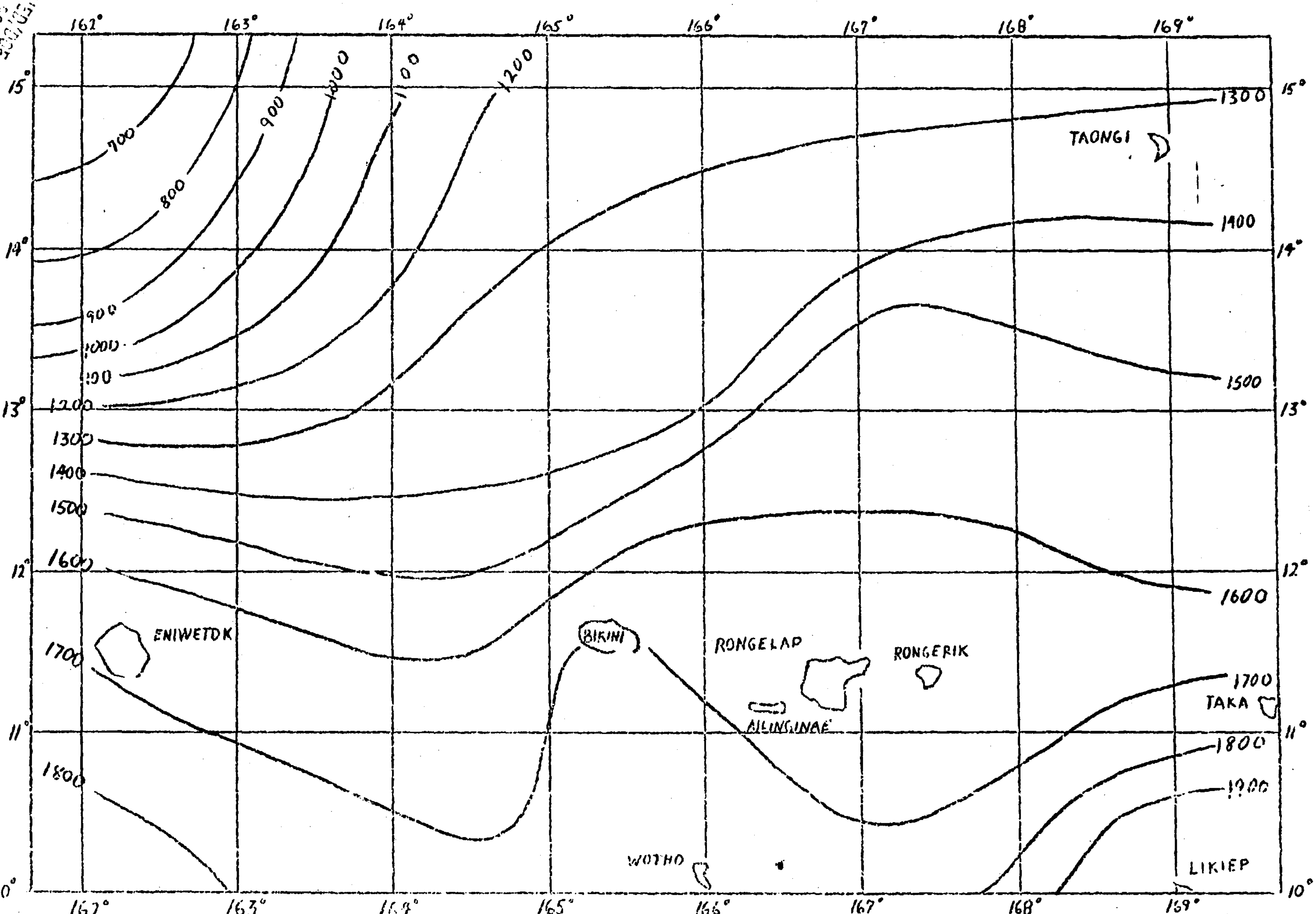

AVERAGE STABILITY 0 to 2?0 METER DEPTH

Fig. 13

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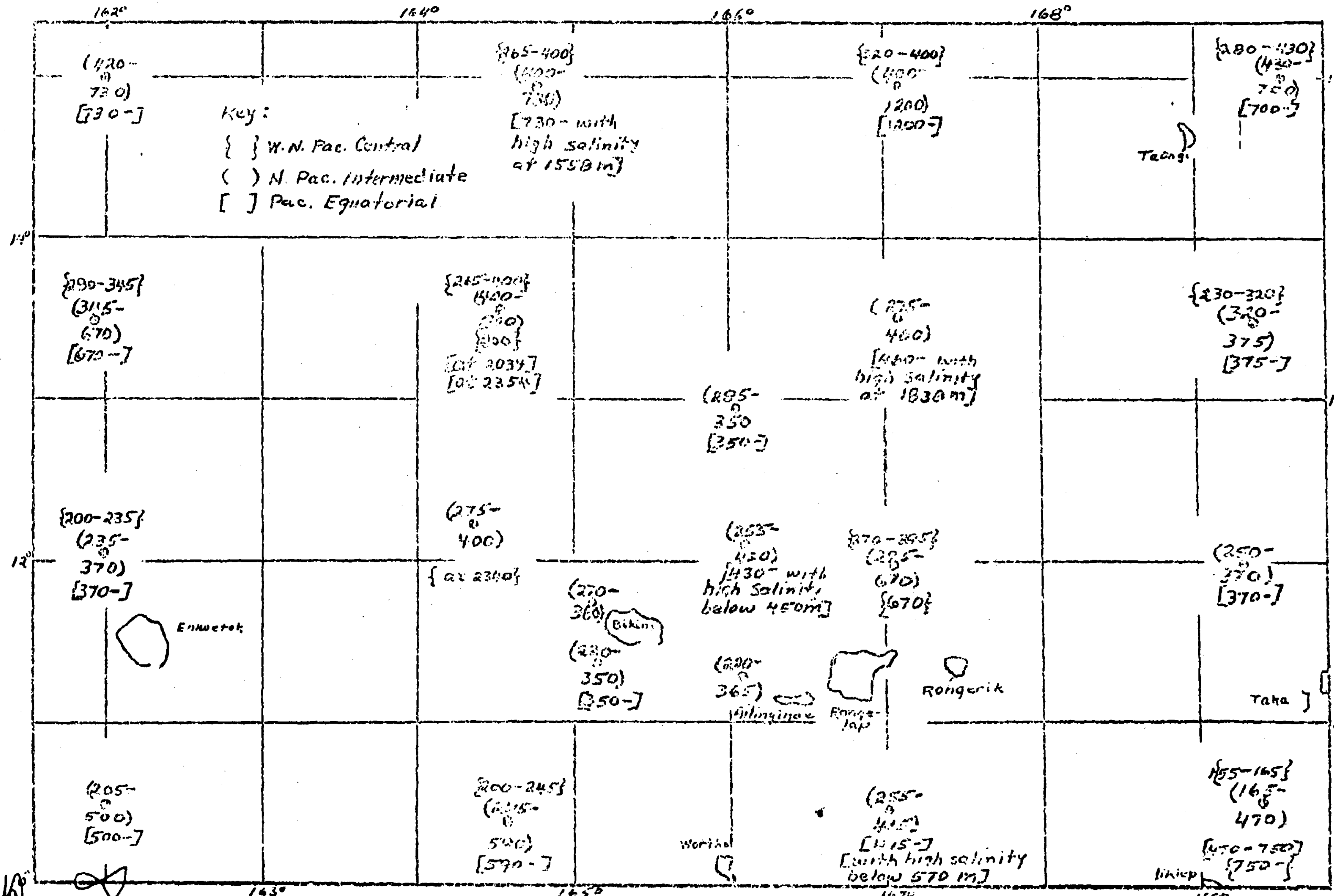

DEPTHS (IN METERS) OF VARIOUS WATER MASSES

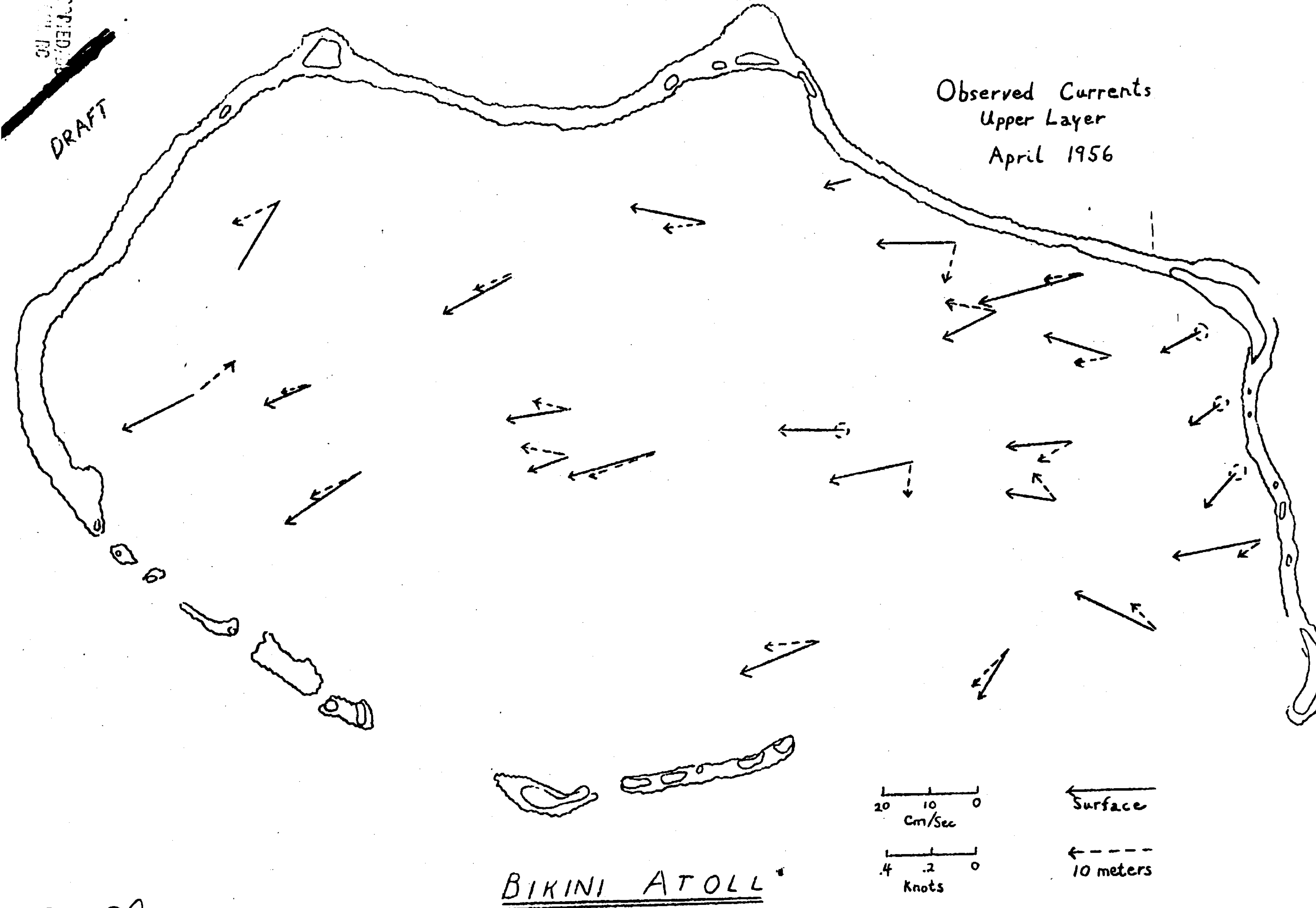
Observed Currents
Upper Layer
April 1956
20 10 0
Cm/Sec
.4 .2 0
Knots
Surface
10 meters
BIKINI ATOLL

Figure 15

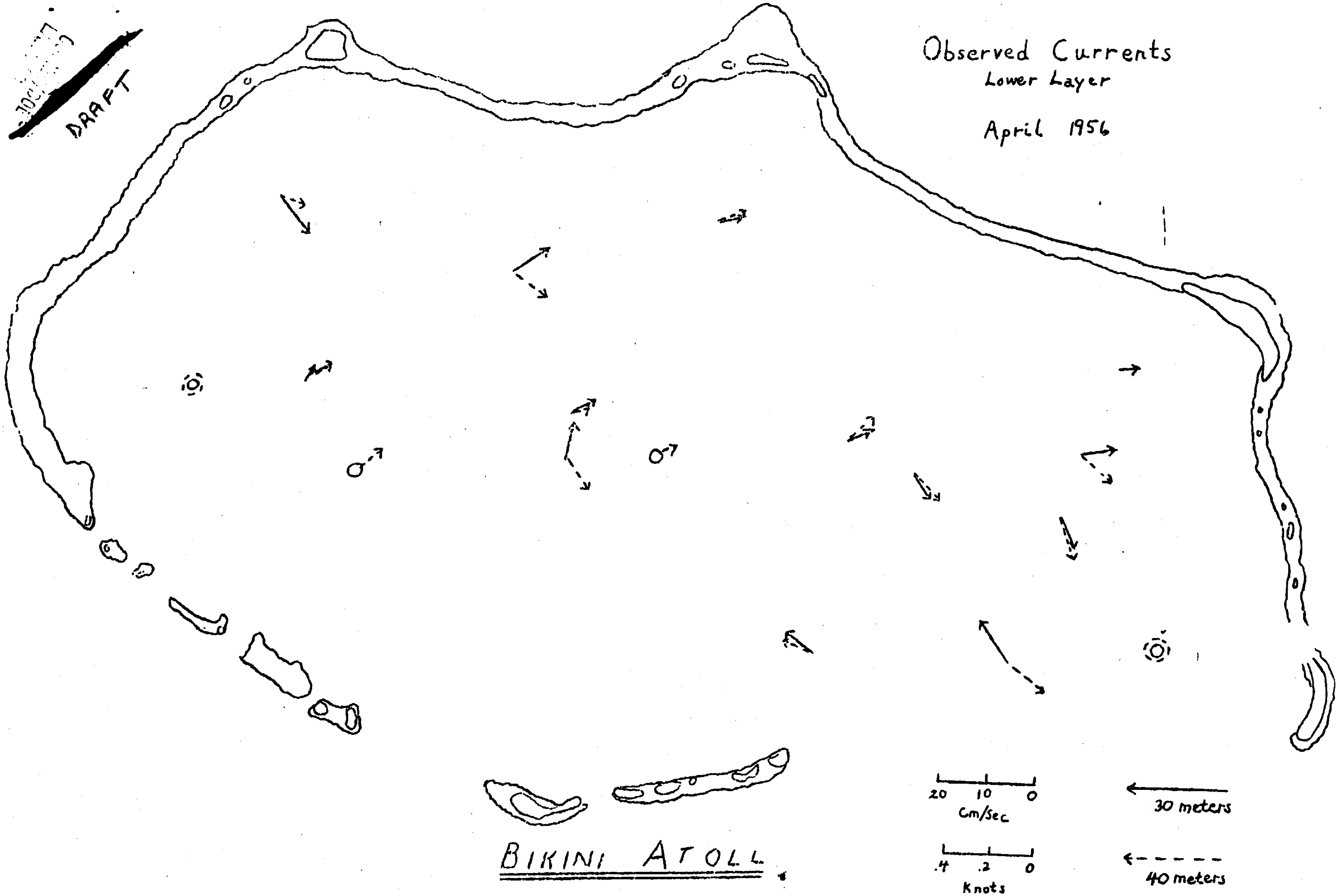
Observed Currents
Lower Layer
April 1956
20 10 0
Cm/sec
.4 .2 0
Knots
30 meters
40 meters
BIKINI ATOLL

Figure 16

C [redacted] DRAFT

Current Velocities
Five Hour Set of Observations Near Center of Lagoon

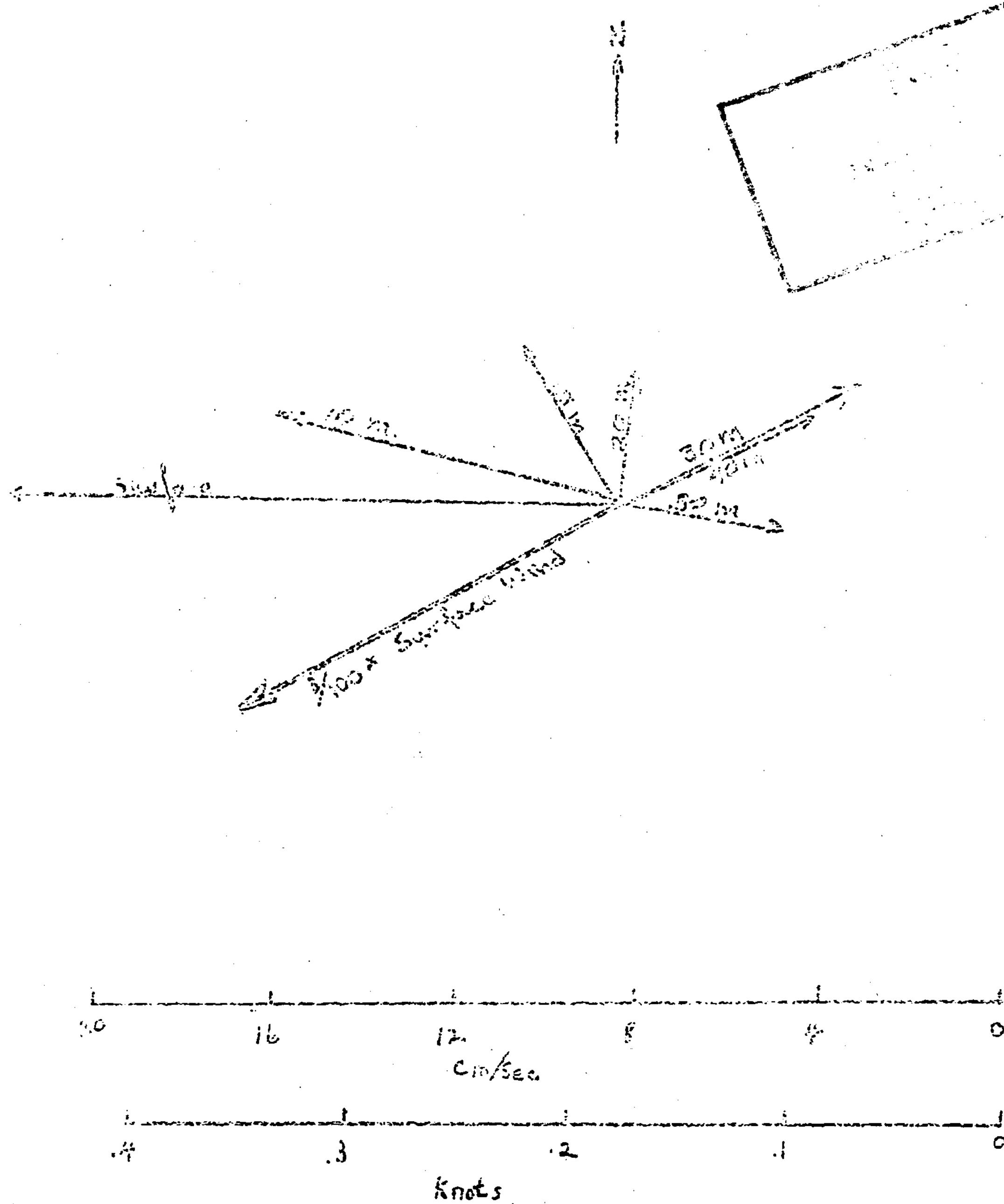

FIGURE 17

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Current Velocity

30 Meter Drift Drogues

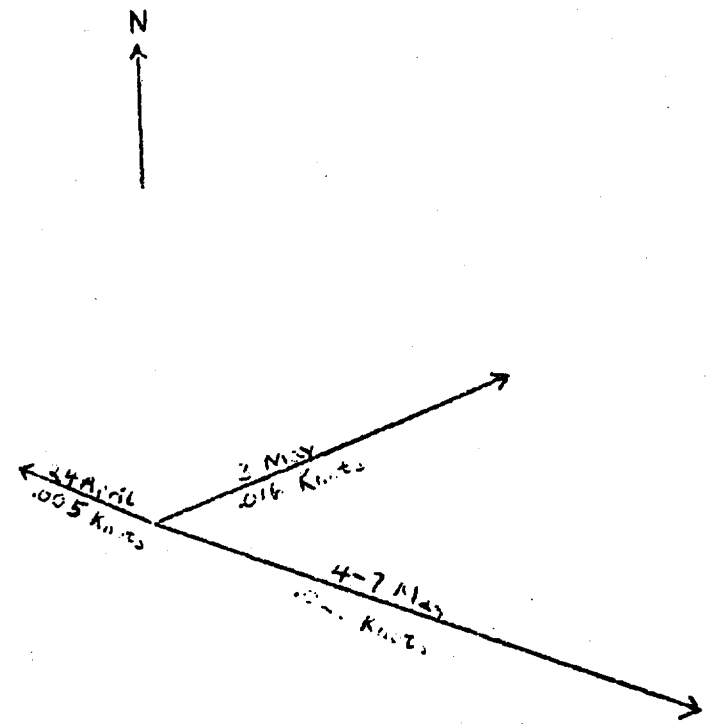

Figure 18

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