NOAA Technical Memorandum NMFS

NOVEMBER 1983

# SUMMARY OF ENVIRONMENTAL AND FISHING INFORMATION ON GUAM AND THE COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS: HISTORICAL BACKGROUND, DESCRIPTION OF THE ISLANDS, AND REVIEW OF THE CLIMATE, OCEANOGRAPHY, AND SUBMARINE TOPOGRAPHY.

L. G. Eldredge

NOAA-TM-NMFS-SWFC-40

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southwest Fisheries Center

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# PREFACE

This report was prepared under contract 81-ABA-1658 by Dr. L. G. Eldredge. The main objectives of the contract work were to review the published literature and prepare a digest of information on the history of Guam and the Commonwealth of the Northern Mariana Islands, on the geological formation and description of each island in the archipelago, and on the climatic, oceanographic, and submarine topographic features of the area. This document is one of two prepared to provide a comprehensive overview of the environmental and fishery information that has been published to date for the benefit of investigators currently involved in the field survey and resource assessment of the Mariana Archipelago. Because the report was prepared under contract, the statements, interpretation, and conclusions herein do not necessarily reflect the view of the National Marine Fisheries Service.

Richard N. Uchida
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# INTRODUCTION

The Resource Assessment Investigation of the Mariana Archipelago (RAIOMA) Program is a study by the Honolulu Laboratory which is conducted in close cooperation with the Governments of Guam and the Commonwealth of the Northern Mariana Islands and by the University of Guam Marine Laboratory. The investigation addresses the problems of determining the potential for development of crustacean, bottom fish, seamount groundfish, benthopelagic, and pelagic resources over the inner and outer shelves, shelf edges, reefs, and slope zones of these islands and adjacent seamounts.

In an attempt to provide a comprehensive overview of the environmental and fishery information that has been published to date, this review of the historical background and description of the islands, as well as information on climate, oceanography, and submarine topography, has been compiled to benefit RAIOMA investigators. Uchida (1983) has provided a review of the plankton communities and the fishery resources of the same geographic area.

This review includes environmental information from these islands, resulting from six first-hand observations and from letters, notes, and other unpublished information from many different visitors. Each island is discussed separately, beginning with Guam and moving northward. A bibliography of the northern islands (Eldredge 1983) has shown that little information is available and published in any language. It is anticipated that RAIOMA will provide data for furthering the scientific knowledge of these islands. The information presented on climate, oceanography, and bottom topography is drawn from a wide variety of literature. Some of this is rather old, but most of it dates back only to the mid-1940s. A little originated before World War II and is published in Japanese.

Because of the broad base included here, it is very likely that some information may have been overlooked. Anyone reading this and finding such omissions is urged to send a note to the author.

Many people should be acknowledged for their assistance with this project. Numerous individuals have read the manuscript and have made many valuable additions and comments. This report represents Technical Report 83 of the University of Guam Marine Laboratory.

## HISTORICAL BACKGROUND

The history of exploration in the Mariana Archipelago can be divided into four periods--early, Japanese, American, and recent.

In the earliest Spanish era, scientific collections were not the major effort of travel among the islands. Diego Luis de Sanvitores first arrived on Guam in 1665. He travelled north throughout the archipelago to Maug during 1668 and 1669 and discovered the remaining northern islands, claiming them for Spain. Anson visited Tinian in 1742 and described some of the island's features, including the wells and archaeological remains. La Perouse (1797) stopped briefly at Asuncion in 1786 and noted some plants. The first scientific expedition in the Marianas was led by Alessandro Malaspina in 1792. He visited only Guam, but reports by the naturalists and him were never fully completed. Beechey (1831), aboard H.M.S. Blossom, visited Asuncion in 1827 and further described the vegetation in a general manner.

Otto von Kotzebue, a Russian, and several naturalists visited Guam in November 1817 for six days. In March 1819 Louis de Freycinet stopped at Guam and remained there for several months. Zoologists Quoy and Gaimard and botanist Gaudichaud collected extensively. They also visited Rota and Tinian. Fedor von Lutke with ornithologist F. H. de Kittlitz landed at Guam briefly in March 1828 aboard the Astrolabe under the command of Dumont d'Urville.

It was not until the late 1880s that definitive efforts were made to collect scientific information about the northern islands. Don Eugenio Sanchez y Zayas sailed throughout the islands with the Governor of the Marianas in early 1866 aboard the Narvaez. He prepared a detailed study of the islands which appeared soon after (Sanchez y Zayas 1866). In the early 1870s Governor Don Luis de Ibanez y Garcia visited the islands and wrote a history and description of them (Ibanez y Garcia 1866). Alfred Marche travelled throughout the islands and collected information and specimens between April 1887 and March 1889. He visited most of the Mariana Islands as far north as Agrihan (Marche 1890, 1891). His collections resulted in additional publications on fish (Pellegrin 1898), birds and mammals (Oustalet 1895), and land snails (Quadras and von Moellendorff 1894). During May 1901, G. Fritz travelled to all the northern islands and described their general geology and flora. He planted coconuts, ironwood trees (Casuarina), and other plants on Guguan and Uracas. His report (Fritz 1902) served as the basis for several which followed. One of the most extensive works pertains to all the German islands of the Marianas (Prowazek 1913); however, much of the natural history is drawn from Fritz (1902). Prowazek described Rota, Tinian, and Saipan and provided an extensive list of the terrestrial flora.

Alexander Agassiz, aboard the Albatross, led the first American expedition to Guam in 1900. Numerous reports have resulted which include ones on fishes, birds, crustaceans, and sea cucumbers (Agassiz 1903). Alvin Seale from the B. P. Bishop Museum also visited Guam in 1900 and collected a number of birds and fishes (Seale 1901). One of the first general accounts of the Marianas was that of Costenoble (1905).

During the Japanese administration of the Marianas, a number of surveys and reports were published pertaining to botany and geology. Tayama (1936) dealt extensively with the geology and coral reefs of the islands, and Yoshii (1936) described the noncalcareous rocks of Pagan and other islands. Tanakadate (1940) visited Pagan and wrote a detailed description of the volcanos of that island. Botanical collections were made by R. Kanehira and R. Hosokawa at many of the islands (Kanehira 1934, Hosokawa 1934). Only one marine animal was reported upon during this time (Nishiyama 1942).

Following World War II, members of the Pacific Vegetation Project, including D. Anderson (in 1949) and F. R. Fosberg (in 1950), visited several islands. In 1949 Y. Kondo visited Pagan and Alamagan and collected land snails, including Partula gibba (Kondo 1970). Geological field work began in 1952 when J. T. Stark and J. I. Tracey, Jr. visited Pagan to investigate the sulfur content of the inner lake. During the summer of 1954 a team of field workers carried out the study which led to the publication of "Military Geology of Pagan" (Corwin et al. 1957). Although primarily a geological study, a number of natural history specimens were collected. These included plants, insects, land snails, and other organisms. The report is the most extensive one for any of the northern islands. Fosberg (1958) and Fosberg and Corwin (1958) reported on the plants. Reports on marine gastropods collected and deposited in the Smithsonian Institution appear in various issues of "Indo-Pacific Mollusca." Similar military geological studies were carried out at Guam (Tracey et al. 1959), Tinian (Doan et al. 1960), and Saipan (Cloud 1955).

The University of Guam Marine Laboratory was established in 1970 to carry out, in part, marine research in the archipelago, especially at Guam. To date the Laboratory has a list of 179 contributions and 81 technical reports.

More recently there have been several short trips to a number of islands. J. Villagomez of Saipan visited Pagan in July 1970 and collected algae and invertebrates. In February 1971, R. S. Jones, R. H. Randall, H. Kami, and R. Struck of the University of Guam and Guam's Divison of Aquatic and Wildlife Resources travelled to Maug, Agrihan, and Anatahan aboard the U.S.S. Grasp. They collected fishes and corals primarily, as well as some algae and invertebrates.

During 1971 the privately owned ketch Wanderer skippered by R. Hervin sailed to all the islands. In April 1971 the survey group visited only Pagan; in June 1971 and in July 1972 several other islands were surveyed. During all of these cruises algae, terrestrial plants, invertebrates (mainly opisthobranch mollusks), and fishes were collected.

The National Oceanic and Atmospheric Administration (NOAA) ship Townsend Cromwell cruised throughout the islands in April and October 1971 and took depth and temperature measurement which formed the basis for a report on the physical oceanography of the northern islands (deWitt 1972). DeWitt also listed 35 known Japanese and Russian hydrographic cruises which had taken place in these northern islands between 1936 and 1968.

In January 1975 the University of Guam Marine Laboratory conducted the first of two trips throughout the entire chain aboard the schooner New World. The major objective was a broad-based marine survey. This survey group included L. G. Eldredge and nine University students. During July of the same year, the New World again sailed to Uracas. This time L. G. Eldredge was joined by S. Amesbury of the University of Guam, E. A. Kay and C. Lamoureux of the University of Hawaii, and M. Falanruw of the Yap Institute of Natural Science, as well as five students. The second trip included some detailed terrestrial investigations. The algae have been reported by Tsuda and Tobias (1977a, 1977b) and the terrestrial plants by Fosberg et al. (1977). Popular accounts of these trips have appeared (Eldredge 1975, Ronck 1975).

A general account of all the Northern Marianas was published by Lehne and Gabler (1972). A report on the vascular flora (Fosberg et al. 1975) with additions, and one concerning the megapode (Falanruw 1975) have also been published.

In 1974 a team of geologists from the University of Arizona made short stops at Sarigan, Guguan, Pagan, and Asuncion but remained at Agrihan for about two-and-a-half weeks. In the summer of 1978 another group spent 3 weeks each at Sarigan (Meijer and Reagan 1982) and Alamagan. They also visited most of the other islands briefly during that summer. In 1979 they returned and spent some time at Guguan and Anatahan. Further investigations have been carried out at Guam.

In August 1976 the Lindblad Explorer with Sir Peter Scott and R. and V. Taylor aboard spent one day at Maug. In a report to the Resident Commissioner (Lindblad Explorer 1976), they sight-recorded 113 species of reef fish and recommended that the island be protected. A similar report followed their brief 1977 visit (Lindblad Explorer 1977).

Between 23 and 26 November 1977, five biologists from Guam, (R. T. Tsuda, L. G. Eldredge, P. Moore, M. Chernin, and S. Neudecker) visited Maug and conducted a natural history survey (Eldredge et al. 1977).

At the request of the Trust Territory of the Pacific Islands government, the Japan Marine Fishery Research Center conducted skipjack tuna pole-and-line fishery surveys (Japan Marine Fishery Research Center 1975, 1976, 1977) aboard the No. 20 Akitsu-Maru. Included in the survey

results are temperature profiles to depths of 250 m. Additionally, a bottom-handline fishing survey was conducted by the Micronesian Coordinated Development Co., Ltd. in 1976. The survey was carried out on the Daikatsu-Maru which visited Pagan, Agrihan, Asuncion, and Maug, as well as the southern islands (Micronesian Coordinated Development Co. 1976).

The U.S. Army Crops of Engineers sponsored a survey of the wetlands of Guam, Tinian, and Saipan in 1977 (Moore et al. 1977). In 1979 an ornithological survey was conducted at Guam, Tinian, Saipan, and Pagan (Tenorio and Associates 1979). Additional vascular plants were reported from Pagan (Fosberg et al. 1980).

During July 1978 the Commonwealth of the Northern Marianas sponsored a trip on the MV Olwol which included members from the Coastal Resources Management, Environmental Protection Agency, Historic Preservation Agency, and the U.S. Fish and Wildlife Service offices. They briefly visited all the islands.

In the summer of 1979, R. B. Clapp (U.S. Fish and Wildlife Service) visited six islands. He recorded several new bird distributional records, collected specimens for taxonomic investigations, and noted range extensions. Reptiles and mammals were also collected.

The RV Townsend Cromwell visited almost all the islands of the archipelago again during the summer of 1978. Under the auspices of the Pacific Tuna Development Foundation, the FV Typhoon carried out 8 months of exploratory fishing (May 1980-January 1981). Almost all the island areas, banks, and seamounts were sampled during that time. A wide variety of methods was used and a number of different fishes were collected (Hosmer and Kami 1981). The FV Typhoon also conducted fishery activity in early 1981 at Guam and around Tinian and Saipan.

In March 1981 eight University of Guam biologists visited Pagan under the auspices of the Commonwealth Office of Coastal Resources Management. The major objective of the project was a general natural history survey of the island to include marine studies, as well as wildlife, plant and lake investigations. Two months after the May 21 volcanic eruption, most of the same biologists returned to Pagan to survey the impact of the ash and scoria and lava flows. Eldredge (1982) briefly reported these findings.

The U.S. Fish and Wildlife Service and the Guam Aquatic and Wildlife Resources Division conducted a survey of the distribution and abundance of forest birds at Guam during June 1981. Between March and June 1982 a similar study in cooperation with the Commonwealth Division of Fish and Game, was conducted on Rota, Tinian, Aguijan, Naftan, and Saipan. Extensive plant collections were also made at that time.

In 1982 the National Marine Fisheries Service, Southwest Fisheries Center, Honolulu Laboratory initiated the Resource Assessment Investigation of the Mariana Archipelago (RAIOMA). Between April and August 1982; the RV Townsend Cromwell particiated in three extensive cruises (cruises 82-02, 82-03, 82-04) throughout the Archipelago. Bathymetric surveys

were conducted and chartlets of twelve banks and pinnacles have been produced (Polovina and Roush 1982). A similar survey is planned for late 1983 and early 1984.

During April 1983 five members of the University of Guam Marine Laboratory aboard the FV Pution Ta'se conducted an inshore environmental assessment, plankton survey, and preliminary precious coral dredging under the auspices of the Office of Sea Grant Programs around Pagan, Guguan, Anatahan, Saipan, and Aguijan and in July 1983 around Rota. Similar studies had been completed at Guam during the fall of 1982. In conjunction with these studies, a bibliography of the islands of the Active Arch (Esmeralda to Uracas) has been prepared (Eldredge 1983).

# THE ISLANDS

The islands of the Mariana Archipelago lie between lat. 13° and 20° N and are divided into two somewhat parallel arcs (Figure 1). The islands have also been referred to as the Ladrones Islands, Island de los Velas Latinos, Los Jardines, Los Prazeras, l'Archipel de St. Lazare, and les Iles Marianes (Bryan 1943). The outer or frontal arc is composed of the more southerly limestone islands of Guam, Rota, Aguijan, Tinian, Saipan, and Farallon de Medinilla. The inner or active arc extends north from Esmeralda Bank and Ruby Volcano to Farallon de Pajaros (Uracas). These are the only active volcanic islands in Micronesia and among them Agrihan is the highest. Most of these latter islands have been volcanically active during historic times.

The archipelago consists of two separate political entities. Guam, the largest and southernmost, is an unincorporated territory of the United States. The remaining islands comprise the Commonwealth of the Northern Mariana Islands.

Environmentally, a number of general publications refer to several islands of the entire archipelago. Earlier reports are those of Corte (1875) and Sanchez y Zayas (1866); Marche travelled widely and reported on several islands (Marche 1890, 1891). Following the Treaty of Versailles, the islands north of Guam became politically distinct from Guam. Fritz (1902) visited all the islands. His report was the basis for much of Prowazek's (1913) "Die deutschen Marianen." Lehne and Gabler (1972) summarized most of the more recent information, reporting on each island individually, providing brief notes on history, population, and physical features. Very few scientific investigations were carried out on Guam during the U.S. Naval administration other than the monumental botanical study by Safford (1905).

During the last 30 years, more biological information has been made available. Baker (1951) reported on all the birds of Micronesia, including those of the Marianas. Owen (1977) compiled a checklist of the birds by major island group--Marianas--rather than by specific island. Pratt et al. (1979) updated much information about native birds of the more southern islands.

Safford (1905) was among the first to detail the plants of Guam. The vegetation was described by Fosberg (1960) and Fosberg et al. (1975, 1977, 1980). Moore et al. (1977) mapped and inventoried wetlands on Guam, Tinian, and Saipan.

Land snails of the family Partulidae were described from Guam and Saipan by Crampton (1924) and further noted by Kondo (1970) including records from Aguijan and Pagan.

Few marine investigations have covered more than one island. Extensive (military) geological studies have been conducted at Guam, Tinian, Saipan, and Pagan, and these reports contain a wide variety of information some of which is also available in several different research publication series. Eldredge and Randall (1980) prepared an atlas of the

reefs and beaches of Rota, Tinian, and Saipan, as well as Aguijan and Farallon de Medinilla. They conducted a similar survey at Guam (Randall and Eldredge 1976).

The benthic algae is the only group which is widely known from throughout the northern islands (Tsuda and Tobias 1977a, 1977b). Corals, gastropods, crustaceans, and fishes from a wide variety of islands are presently being studied.

An integrated review of seven of the islands of the archipelago has been prepared in support of the National Park Service Natural Landmarks Program (Abbott et al. 1982). Potential National Natural Landmarks are evaluated, and Guguan, Alamagan, Pagan, Agrihan, Asuncion, and Uracas, as well as the northern tip of Saipan are proposed. On Guam four existing sites--Puntan dos Amantes, Facpi Point, Fouha Point, and Mount Lamlam--are reviewed and two--Cocos Lagoon and Pati Point--are proposed. A number of sites have also been proposed as Marine Sanctuaries under the 1972 Marine Protection Research and Sanctuaries Act administered by the National Oceanographic and Atmospheric Administration.

The islands north of Saipan have historically been referred to as the "Gani" (Le Gobien 1701). These islands were depopulated in 1695 to Saipan and later in 1698 to Guam and remained that way, apparently, until the late 1800s. Sanchez y Zayas (1866) remarked specifically that no inhabitants were seen at Agrihan. Corte (1875) does not refer to any. During his visit, Fritz (1902) reported on small populations.

Environmental information for these islands is very incomplete. First-hand observations from six visits, as well as from letters, notes, and so forth provided by other visitors form the basis for most of the information provided here for the "Gani."

Each island is discussed separately beginning at the south and moving toward the north.

GUAM

Guam is the largest island of the archipelago (Figure 2). It is located at lat. 13°28'N and long. 144°45'E. The highest elevation is 405 m (1328 ft), and the total area is 637 sq. km (246 sq. mi), 10% of which are reefs and lagoons. The island has been previously known as Guahan, Gujan, Guan, Gwan, San Juan, Guahan, Gujan, Guan, Gwan, San Juan, I. de St. Jean, Omia Jima (Bryan 1943).

A limestone plateau covers most of the northern half of the island. The southern half is composed of volcanic material and edged at most places with low, raised limestone. Fringing reefs surround most of the island. Barrier reefs are found at Cocos Lagoon and at Apra Harbor (Figure 3). Twelve small islets are found along the reefs. Cocos Island, at the southern end of Guam, is the largest.

Guam is the most well known island of the Marianas. Several studies have contributed to the knowledge of the coastal and reef areas. One of the first of these was a coastal survey conducted by Randall and Holloman (1974) who divided the island into 12 coastal sectors. They detailed the

coastal features of each, especially the geological units, soils, and hydrology. A selected bibliography and a review of the physical, chemical, and biological oceanographic literature for the waters surrounding Guam have been prepared (Eldredge and Kropp 1981 and MS[1]). Information about the island is summarized here.

Most of the beaches of Guam are composed of light-colored, calcareous sands, although a few in the south have dark-colored volcanic sand. Emery (1962) conducted an anlaysis of 58 beaches, and Randall and Eldredge (1976) mapped and noted the characteristics of the island's beaches. Shoreward of the beach, the narrow band of vegetation is called "the strand." Fosberg (1960) described strand vegetation, and Falanruw (1977) discussed the role of the strand in relation to the beach.

Much of Guam's coastline is outlined with rocky intertidal areas. Limestone and volcanic boulders are scattered on reef flats or are buttressed along raised headlands. Boulders are also predominant in areas of artificially filled shoreline. Nips are characteristic indentations found along rocky headlands. At sea-level wave-washed benches are located at several locations (Randall and Eldredge 1976).

Seagrass stands cover approximately 9% of the fringing and barrier reefs (Sealand 1978). Three species of seagrasses are known (Tsuda et al. 1977, Tsuda 1981). The distribution of these species has been mapped (Randall and Eldredge 1976).

Land birds have been described by Baker (1951), Pratt et al. (1979), and by ongoing studies at Guam's Division of Aquatic and Wildlife Resources. Fosberg (1960) described the vegetabtion, and Stone (1970) prepared a flora of the island. Wilder (1976) mapped the estuaries, Moore et al. (1977) described most of the wetlands along the shore and inland, and Best and Davidson (1981) inventoried the island's aquatic ecosystems.

ROTA

The southernmost island of the Commonwealth of the Northern Mariana Islands, Rota (Figure 4) is located at lat. 14°07'-14°12'N and long. 145°07'-145°18'E. The island has an elevation of 491 m (1612 ft) and an area of 85.2 sq. km (32.9 sq. mi). It has been previously known as Bota, Botah, Ile Sainte Anne, Isla de Rota, Luta I., Rota To, Santa Ana, Sapan, Sarpan, Sarpana, O'Rota, Sarpanta, Serpana, Zarpana, Zarpana, Zarpane (Bryan 1971).

The coastal area of Rota, which is composed entirely of raised limestone, has been completely mapped by Eldredge and Randall (1980). Steep cliffs and slopes edged by a sea-level bench are found along the southeastern shoreline (Figure 5), as well as around the southwestern peninsula. Several intermittent streams flow to the coast at the southernmost area, depositing some volcanic material which originated from the higher, interior lands.

A reef flat, as wide as 250 m, is the main feature of the northwestern shore. Most of this reef flat is narrower and raised slightly.

An irregular band of raised limestone is found along the outer margin of the reef flat. (This feature is found only at Rota.) Two somewhat parallel bands of this raised limestone are found toward the north. One is along the inner part of the platform and the other toward the outer part. In general the reef is relatively flat with occasional boulders and depressions containing sand and rubble (Eldredge and Randall 1980).

The shore is composed mainly of beachrock and intermittent raised limestone patches. Coral-algal-mollusk rubble and sand beaches are rare but may be found scattered among limestone patches.

The biota of Rota is not well known. An informal biological expedition was conducted by the Department of Biosciences, University of Guam in 1969 (Tsuda 1969a). More than 80 species of benthic algae have been reported (Tsuda 1969b). Seagrasses were reported by Eldredge and Randall (1980) for the first time. Nearly 150 species of fishes are known (Jones 1969). Numerous corals have been collected.

Land birds have been described by Baker (1951) and more recent records added by Pratt et al. (1979). Fosberg (1960) reported on the vegetation.

AGUIJAN

This small precipitous island is located at lat. 14°51'N and long. 145°34'E (Figure 1). The island has an elevation of 168 m (504 ft) and an area of 7.2 sq. km (2.7 sq. mi). It has been previously known as Agaigan To, Agiguan Insel, Agrigan, Aguigan, Aguiguan, Aguijan, Aguijon, Ile de Saint Angel, Santa Angel, and Santo Angel (Bryan 1971).

Aguijan is a nearly flat plateau composed entirely of limestone and surrounded by steep vertical cliffs with large limestone blocks at places, especially along the eastern shore. A narrow, sea-level bench is also found along the eastern side (Eldredge and Randall 1980). A reconnaissance geological survey was conducted by Burke et al. (1951) who described the limestone nature of the island.

No wide reef flats occur. Coral is diverse and actively growing in different areas. Tsuda (1971) noted that the only area which might be considered a coral reef occurred 1 km (0.6 mi) south of the northernmost tip of the island.

Naftan Rock (or Nafutan) is located off the southern end. This limestone pinnacle has an elevation of about 20 m (59 ft). Birds were noted and plants collected during the spring 1982 U.S. Fish and Wildlife survey.

TINIAN

This relatively flat island lies about 9.2 km (5 mi) southwest of Saipan (Figure 6). It is located at lat. 14°55'-15°06'N and long. 145°35'-145°41'E. The highest elevation is 178 m (584 ft), and the total area is 101.7 sq. km (39.3 sq. mi). The island has been previously known as Bona Vista, Buenavista, Ile de Bonavista, Tanian, Tenian To, Tinian

Insel, Tinianion, and Zinian (Bryan 1971).

Tinian's raised limestone is a result of complex block movement, sedimentation, and differential coral-reef growth (Doan et al. 1960). The entire shoreline has been described and mapped (Eldredge and Randall 1980). Most of the island is surrounded by low to high cliffs, many undercut at sea level. The southern and southeastern coasts are the highest and are nearly vertical. A sea-level bench is found nearly all around the island, although slumping has occurred in places. Large blocks and boulders buttress the cliffs. At a fault at Unai Chiget, the cliffs decrease in height and numerous blowholes and pools are found along the shore. Sea-level, wave-cut, notches or nips are found around the shore.

Beaches are not well developed except at Unai Dankulu (Figure 7) and at Tinian Harbor. Most are narrow with intermittent raised limestone. The calcareous sand is mixed with coral-algal-mollusk rubble.

The reef flats are generally narrow, varying in width from less than 15 m to 180 m (50 to 590 ft) at Tinian Harbor. Most have a shallow, irregular surface and a grooved margin. One patch reef is located along the southwest shore near the Tinian Harbor. It is oval in outline and has an irregular reef-rock surface with some patches of sand, gravel, and rubble. A barrier reef, now altered as a breakwater for the harbor, is attached to the shore by a fringing reef. The lagoon, originally about seven meters (23 ft) deep (Doan et al. 1960), has also been altered with the construction of shore-side and finger-pier docking facilities.

As part of an environmental impact survey, Jones et al. (1974) carried out extensive field studies at four sites at Tinian. They described the coastal and submarine physiography, conducted preliminary in-shore current studies, and recorded a total of 246 species of fishes, either observed or collected, 84 species of benthic algae, 129 species of corals, 36 species of gastropods, 21 species of echinoderms, as well as other marine invertebrates.

On land, the vegetation has been described by Fosberg (1960). Moore et al. (1977) mapped the wetlands at Hagoi on the northwestern plateau and Magpo on the south central area. They also inventoried the wetland vegetation. In addition to Baker (1951) and Owen (1977), information on bird populations is provided by Pratt et al. (1979) who reported that the Tinian monarch, Monarcha takatsukasea, thought to be decreasing in numbers, was very abundant.

SAIPAN

Saipan, the largest island in the Commonwealth of the Northern Mariana Islands, is located at lat. 15°05'-15°17'N and long. 145°41-145°50'E (Figure 8). Mt. Tagpochau, the highest elevation on Saipan, is 765 m (1554 ft). The island has an area of 120.6 sq. km (46.5 sq. mi) and has been previously known as Ile de Saint Joseph, Saepan, Saespara, Saipan Insel, Saipan To, San Jose, Saspan, Seipan, Sepan, Sespan, Swypan, Supan, Zeipan, and Zerpan (Bryan 1971).

Saipan is a complex island of dacitic and andesitic lava covered at most places by a variety of limestones and limestone-associated calcareous materials (Cloud et al. 1956). Volcanic material is exposed along the shore only on the east coast at Puntan Fanunchuluyan and Isleta Maigo Fahang (Bird Island) (Figure 9), near Puntan Hagman, and north of Puntan I Naftan. The remainder of the shore is limestone (Eldredge and Randall 1980).

Most of the coast is lined with low to steep headlands and cliffs. Much of it is buttressed with blocks and boulders. Raised limestone is landward of the reef flats at most places. Fine-sand beaches rim the barrier lagoon along the western shore. Most other beaches are composed of sand and gravel. All are composed of coral-algal-mollusk rubble. Mixed volcanic material is also present at the intermittent stream mouths along the east coast. The shore has been described and mapped by Eldredge and Randall (1980). Cloud (1955) analyzed the entire coast for military purposes and provided a map which related the degree of accessibility for each part of the shore.

The barrier reef with its associated lagoon is a major feature of Saipan. It extends along almost all the west coast and is wider and deeper in the northern half. Cloud (1959) carried out extensive field studies in the lagoon. He described habitats and established 16 different biotopes to identify these different habitats. Amesbury et al. (1979) used these same habitats for his survey of the fish resources of the lagoon. The lagoon has been mapped in detail through an analysis of aerial photographs, maps, and first-hand observations (Eldredge and Randall 1980).

In addition to Cloud's (1959) survey of the lagoon which included a tabular listing of nearly 700 species of organisms identified from each biotope, Goreau et al. (1972) examined 40 reef sites in relation to the probable effects caused by the crown-of-thorns starfish, Acanthaster planci. The survey by Goreau et al. included extensive observations on the cushion star, Culcita novaeguineae. Population, behavior, and selective feeding were noted as they related to the overall community structure. A definition of reef terms for Saipan was also provided. Along the shore Doty and Marsh (1977) conducted surveys between Unai Sadag Tase and the seaplane ramp at Puntan Flores. They were investigating the impact of the power barge "Impedence." These were the first quantitative measurements made in the area. Sediments, currents, and physical and chemical characteristics are reported. Biological investigations included algae, seagrasses, invertebrates, fish, and plankton. Amesbury and Doty (1977) noted the differences between the plankton from the inner and outer parts of the harbor and suggested that there might be only a little mixing between the two areas.

A small islet, Managaha, is a major feature just outside the westernmost part of the barrier reef. This low islet is heavily vegetated and now a cultural preserve under the Mariana Islands Constitution.

Fringing reefs vary in width to nearly 200 m at Bird Island. Most are relatively flat with exposed blocks and boulders at places. Corals are widely scattered and common on deeper reef flats. Their relative

abundance is shown for all areas (Eldredge and Randall 1980).

Seagrasses are a predominant feature of the barrier lagoon. A mixture of three species carpets the entire bottom in places, especially in the southern half (Tsuda et al. 1977). The relative abundance and distribution of seagrasses are also shown by Eldredge and Randall (1980).

On land, the vegetation has been described by Fosberg (1960). Moore et al. (1977) mapped and inventoried seven wetland sites, of which the largest was Susupe Marsh. They noted the very restricted mangrove areas near the commercial facilities in the barrier lagoon. The birds were described by Baker (1951). Recently Pratt and Bruner (1978) rediscovered the megapode from areas at the northern end and along the eastern side. Pratt et al. (1979) described the present status of many of the endemic species.

FARALLON DE MEDINILLA

Located approximately 83 km (45 mi) northeast of Saipan, this precipitously raised limestone island lies generally in a northeast-southwest direction (Figure 10). It is located at lat. 16°01'N and long. 146°05'E, its highest elevation is about 81 m (266 ft); Fritz (1902) reported the highest elevation as 30 m (98 ft) high. The area of the island is about 0.9 sq. km (0.35 sq. mi). It has been previously known as Bado Shima, Bird I., Farallon Paxaros, Island Pexaros, Madinilla, Medeinizya, Medinija To, Medinilla I., Medinizea, Medinizya To, Paxaros, Rocher, Rocker, Urasas, and Urakas (Bryan 1971).

This island is the least known of the southern limestone islands. Although the actual discovery date of the island is unknown, the French explorer Freycinet noted the island in 1819. Corte (1875) referred to it as a bare table land. Fritz (1902) landed on the island, climbed to the top and reported on the low brush and vegetation.

In their atlas, Eldredge and Randall (1980) represented the island as having nearly vertical cliffs with some slumping along the northeastern shore. They provided three photographs and an outline map. At various areas of the island large blocks and boulders have eroded and formed small islets.

The island has been a bombardment range for the U.S. Navy and Air Force since 1971. The U.S. Navy (1974) prepared a Draft Environmental Impact Statement and a Navy team made a very brief visit to the island via helicopter. Their report does not mention specific organisms.

In general, Farallon de Medinilla is the only island in the archipelago from which no, or very few, biological specimens have been collected.

A 20-fathom shoal area is present about 1.8 km (1 mi) north of the island. The banks surrounding the island have recently been charted (Polovina and Roush 1982).

ESMERALDA BANK and RUBY VOLCANO

Two active volcanoes are located at the southern end of the active or inner arc. Esmeralda, the more southern, rises to within 30 m (98 ft) of the surface. The diameter at the base of this 1,300-m (4,264 ft) high volcano is 9 km (14.5 mi). It has a central caldera which is 300 m (984 ft) deep and 2 km (3.2 mi) across (Stern and Bibee 1980). The most recently reported eruption of Esmeralda was in April 1982.[2] Surface water bubbling and steam vapor were observed. During an April 1975 eruption, the discolored boiling spots were observed in a north-south pattern (Figure 11). Gavrilenko et al. (1980) and Gavrilenko (1981) reported on a January 1978 eruption. The topography of the Bank has been mapped by Polovina and Roush (1982).

The other, Ruby Volcano, was first named following an April-May 1966 eruption (Johnson 1973). Sofar hydrophones located at Enewetak Atoll and Wake Island recorded background noise which showed an origin at lat. 15°10'N and long. 145°54'E. This volcano has a depth of about 210 m (689 ft).

ANATAHAN

Anatahan, the southernmost of the northern islands, is located at lat. 16°22'N and long. 145°40'E (Figure 12) and has an elevation of 788 m (2,585 ft) and an area of 32.3 sq. km (12.5 sq. mi). It has been previously known as Amalgam, Anatacan, Anatahan Insel, Anatahan To, Anatahan, Anatans, Anataxam, Anataxan, Anatayan, Anathahun, Anatjan, Anatiajan, Ile de San Joachim, Inatajan, Matan, Natan, San Joaquin, and San Joaquine (Bryan 1971).

Anatahan is unusual in that its shape is basically rectangular; its longer axis is oriented east-west. High, irregularly sculptured land slopes toward the water from the craters of two extinct volcanoes (Figure 13). No volcanic activity has been reported during historic times. Recently dated rocks from the northern coast show them to be the oldest reported from the northern islands.

Steep cliffs and headlands outline most of the shore. Large rounded blocks and boulders buttress cliffs in areas somewhat protected. At the "Obs. Spot" on the navigational chart, (DMA Chart No. 81086) the shore is composed of rounded, irregularly placed boulders as large as 0.5 m (1.6 ft), which form one or two high berms depending on surf conditions. Immediately to the north low headlands gradually become volcanic buttresses with shallow tide pools landward. Very few, widely scattered areas have small grain-sized sand beaches. Truncated basaltic platforms occur along the southwestern shoreline.

Along the high intertidal zone the gastropods Littorina pintado and Nerita plicata were relatively common. On the upper surfaces at the water level, the snail Purpura persica was also relatively abundant. This snail was found commonly throughout the northern islands, although it rarely occurs at Saipan and Guam.

In deeper water large rounded blocks and boulders and isolated sand

patches can be seen. Isolated corals are found widely scattered on the upper surfaces of these blocks and boulders. Coral growth is not luxuriant.

More than 120 species of terrestrial plants have been reported (Fosberg et al. 1975). Specimens were also collected in July 1981. Birds are not abundant. As many as 20 to 30 fruit bats could be counted at a time. Goats are very common.

Curiously, Anatahan was the site of an interesting drama from 1944 to 1951. Several Japanese nationals were stranded on the island because of World War II. Their plight was described by Maruyama (1954) and later made into a movie.

SARIGAN

Sarigan, an extinct volcano, is located at lat. 16°42'N and long. 145°47'E (Figure 14). The elevation is 549 m (1,801 ft), and the area is 5 sq. km (1.9 sq. mi). The island has been previously known as Chereguam, Cherega, Cheregua, Cheroga, Cheruguan, Ile de Saint Charles, San Carlos, Sarigan Insel, Sarignan, Sarigoan, Sariguan, Seriguwan, and Sarigwan To (Bryan 1971).

Of all the northern islands, Sarigan is one which has no historically recorded volcanic activity.

The shoreline is made up primarily of high cliffs and steep slopes. Low, irregular lava is located along the southwest coast. Much of the uplands appear to be in various stages of erosion (Figure 15).

Almost nothing is known about the marine biota; nothing has been published. On land, 128 species of vascular plants have been reported (Fosberg et al. 1975). Baker (1951) listed the birds known to occur. During a visit in the summer of 1978, Ludwig[3] reported that megapodes were relatively abundant, based on the 10 to 15 adults he saw during a single hike. He also commented on seeing some behavioral interaction and limited flying by some individuals. Fritz (1902) noted seeing large "countless" numbers of seabirds; however, similar observations were not made by Ludwig.[3]

Numerous goats were seen in January 1975[4] and again in July 1978 by Ludwig[3] who counted as many as 50 at a time grazing on the slopes.

Both Fritz (1902) and Ludwig[3] noted extensive archaeological material, including latte stones and pottery.

Along with Maug, this island is protected as an uninhabited island to be "used only for the preservation of birds, fish, wildlife and plant species" by the Constitution of the Commonwealth of the Northern Mariana Islands (Article XIV, Natural Resources), marine resources (Section 1) and uninhabited islands (Section 2).

GUGUAN

Guguan is a complex island with a barren active volcano and an old vegetation-covered cone. The island is located at lat. 17°19'N and long. 145°51'E (Figure 16). Its highest elevation at the southern half is 301 m (988 ft), and its total area is 4.2 sq. km (1.6 sq. mi). It has been previously known as Gaugan, Giges, Gregan, Greguan, Grijes, Guagan, Guegon, Gugan, Gugua, Guguam, Guguan Insel, Guguwan, Guan To, Ile de Sainte Philippe, Saint Philips, San Falipe, San Felipe, and San Filipe (Bryan 1971).

Reported dates of volcanic activity vary. Tanakadate (1940)[5] reported eruptions in 1819 and 1901, and Corwin[5] reported minor activity in the 1860s and explosive activity in the 1880s. The volcano is still active because in 1975 steam was intermittently being emitted from the northern cone which is surrounded by a crust of yellowish sulfur-like material; however Ludwig[3] did not observe any steam being emitted during his summer 1978 visit. Along the west coast warm sand was felt at shallow depths.

The shoreline is very irregular; most of it is steep cliffs. At areas along the southwest shore, low truncated basaltic platforms are found. Between two 15-m (49.2 ft) headlands along the west coast is a narrow, round boulder and cobble shore which is quite well protected and would generally afford the best landing site, depending on sea-state conditions. A small embayment surrounded by vertical cliffs, presumably the remnants of a volcanic cone, is located along the east coast. Ludwig's[3] observations were made along the east coast; the other ones have been made along the west coast. To the north and northwest the shore is composed of vertical cliffs buttressed with eroded blocks which have sharp, uneroded sides. A lava flow enters the water along the northwest shore (Figure 17). The southern end of the island shows extensive slumping and erosion.

Offshore the bottom is composed mainly of large, rounded, eroded boulders covered with a low algal turf. Farther offshore in deeper water the bottom becomes pavement like. At individual and isolated areas patches of sand and gravel are found.

Other descriptions of the island are also contradictory. Corte (1875) stated that it has an elevation of about 610 m (2,000 ft). Fritz (1902) indicated that the height of the southern half was 50-60 m (164-197 ft) and that the northern half was lower. Corte (1875) also indicated that there was a brackish water lagoon large enough for boats to enter along the western shore. Fritz (1902) described a crater at the west which had "fallen in." Additionally, there is confusion concerning Ibanez y Garcia's (1886) and Corte's (1875) description of an island later named Farallon de Torres, which was about 30 km (16 mi) south of Guguan. Fritz (1902) considered that Ibanez's description of the two islands to be an error.

Intertidal and shallow-water animals were collected during January and July 1975 and July 1981.[4] A wide variety of echinoderms were observed. Numerous coral and associated crustaceans and gastropods were

also observed. A number of herbivorous fishes were present.

Baker (1951) reported the known birds. Eldredge (1975) estimated that there were more than 50,000 sooty terns along the slopes of the northern volcano. This island has the greatest number of seabirds observed throughout the archipelago. Boobies, tropic birds, frigate birds, and noddy terns were abundant.

Coconut crabs and other land crabs were abundant. Ronck (1975) reported on the "zoo-sized assortment of birds." Bats were relatively common and could be seen most times during the day. Small rats were common in the interior of the southern part. A total of 57 species of vascular plants have been reported (Fosberg et al. 1975, 1977).

ALAMAGAN

This steep-sloped island is located at lat. 17°35'N and long. 145° 51'E (Figure 18). Its elevation is 744 m (2,441 ft) and area is 11.2 sq. km (4.7 sq. mi). The island has been previously known as Alamagan Insel, Alamguan, Almagan, Alemagen, Alimagan, Aramagon To, Artemagan, Artomagan, Ile de la Conception, La Conception, Ora-Magan, and Uramagan (Bryan 1971).

The only recorded volcanic activity for Alamagan is a minor event in the 1860s and a lava and ash eruption in 1885, although fumes are intermittently observed.[5] Fritz (1902) reported "warm springs of fresh water" in the northern part of the island.

The coastal area is very irregular and consists mainly of low headlands and steep cliffs. There are no small-grain sand beaches. A large boulder and cobble shore, located near the village along the southwest coast, is the only place to land at the south. Features of the remaining shores are unknown. The southern end of the island is marked by very large erosion scars, exposing light-colored basalt material (Figure 19).

Offshore at the anchorage the substrate looks like a fringing reef limestone platform which is covered with a low growth of algae. Large Acanthaster planci were observed, as well as several sea cucumbers.

A total of 178 species of vascular plants are known (Fosberg et al., 1975), and birds are recorded (Baker 1951). Fritz (1902), Yawata (1940), and Ludwig[3] mentioned several archaeological sites.

PAGAN

Pagan is the largest and the most complex island among the northern group. It is located at lat. 18°03'-18°10'N and long. 145°43'-145°49'E (Figure 20). The maximum elevation is 569.9 m (1,870 ft) at the southern end of the island and the area totals 47.7 sq. km (18.5 sq. mi). The island has been previously known as Agan, Ile de Saint Ignace, Pagan Insel, Pagan To, Pagaon, Pagara, Pagon, Papan, Paygan, Pegan, Pegon, Pragan, Praien, Prajan, Pemplie de Volcans, Remplie de Volcaus, San Ignace, and Saint Ignace (Bryan 1971).

The island has an extensive history of vulcanism. Explosive eruption took place between 1820 to 1830 and during the last half of the 19th century. Marche (1890) reported a violent eruption occuring around 1870. Since 1900, eruptions have been reported in 1909, 1917, 1923, and 1925 (Tanakadate 1940). Ash was ejected during the last two; lava flowed to the west from Mt. Pagan in 1925. The island's geophysical history is described in detail in Corwin et al. (1957).

On May 15, 1981, Mt. Pagan erupted violently, depositing more than 90 million cubic meters (118 million cubic yd) of ash and other volcanic material by May 28. Lava, originating at three newly formed vents, flowed to the north, south (Figure 21), and west to depths of 3 to 30 meters (9.8 to 98.4 ft). Ash and scoria settled as deep as 200 cm (78.7 in) in some areas toward the northwest (Banks 1981). A team of U.S. Geological Survey scientists visited Pagan immediately following the eruption and collected samples which are presently being examined.[6] [The impact of the eruptions will be discussed later.]

Pagan's 43.4 km (27 mi) coastline is diverse. Most of it is composed of near-vertical headlands and steep slopes. Truncated volcanic platforms are found along the west coast. Beaches, varying in length from 50 m to 1000 m (164 to 3,280 ft), are scattered among low headlands. Most beaches are composed of cobble-sized material. Beaches composed of fine-sized material are found only along the west and southwest shore of the northern half of the island. All the southern beaches consist of large, coarse material.

Raised reef limestone and limestone conglomerate shores are found in restricted areas at the north (Talagi), along the east (from Regusa to Apansantate and at Inai Dikiki), and at the west (Liyan). They are uplifted as much as 1 m (3.3 ft) and the surface is pitted. Surge channels are elevated and blow holes are common. These are the only raised limestone shores in the northern islands. Most of these shores have a mixed limestone-volcanic sand beach landward. Cobble beaches with mixed limestone are found scattered around the island (Corwin et al. 1957).

More recently, 19 beaches on Pagan were investigated (Doan and Siegrist 1979) for their suitability as a source of fine aggregate. The composition, texture, and size variation of the beach material and the dimensions of the beach are presented along with expected inshore surf conditions.

In general terms Corwin et al. (1957) described the offshore environmental condition as:

Class I. At more recent lava flows the coastal shelves are very narrow and have rough, rocky bottoms. In some areas there is no shelf, in others it may extend seaward as much as 450 m (1,476 ft). Most of the bottom is composed of lava, lava blocks, and cobbles. Sand patches are widely scattered.

Class II. These moderately wide shelves with corals and algal growth are found around much of the northern half of th island.

Class III. Along the isthmus, at the southern end, and at the

northeastern side of the island these wide to very wide shelves gently slope seaward. The bottom is rough rock and coral and algae are found.

Class IV. This very wide shelf area is found only along the western shore from Bandera to Puntan Laguna. It is characterized by having a moderate slope and a smooth volcanic bottom. The outer edge is about 1400 m (0.7 mi) offshore at a depth of 183 m (100 fathoms). More superficially, much of the accessible shore is composed of large boulders, low headlands, or sandy beaches. The dock site at Bandera is an example of a boulder zone both intertidally and subtidally. Cobble-sized volcanic boulders are eroded and wave washed. To the north at Katchu, low headlands with nearly vertical walls rise off the bottom from about 2 m (6.5 ft). Further offshore elevated and isolated boulders are the bases for coral colonies. Toward the southern end much of the shoreline is high, steep cliffs and, in places, low, narrow shore is composed mainly of rounded volcanic boulders. Large ones are found at the water's edge, and a mixture of sizes, subtidally.

Two lakes are found at Pagan. They are thought to be quite young geologically, having been formed about 200 years ago.[6] Before the recent volcanic eruption the inner lake (Lagunan Sanhalom) had a length (NNE-SSW) of 560 m (1,840 ft), a width (E-W) of 525 m (1,720 ft), average depth of 15 m (50 ft), and an area of 0.174 sq. km (43 acres). The outer lake (Lagunan Sanhiyong) (Figure 21) had a length (N-S) of 759 m (2,640 ft), width (E-W) of 310 m (1,020 ft), an average depth of 12 m (40 ft), and an area of 0.160 sq. km (39.5 acres) (Corwin et al. 1957). Following the volcanic eruption the shoreline of the inner lake was reduced by about 2 m on all sides. Between 12 and 40 cm of ash and scoria were measured near the inner lake.[6] The hot springs along the southeast shore were filled with volcanic material, but the water along that shore has remained very warm.

Corals are abundant in the shallow-water areas. True coral reef development is limited--reefs may be found at Salafai along the southwest shore and at Apansantate along the southwestern shore. Extensive coral communities occur around most of the island wherever there is stable substrate. During a trip in March 1981, Randall[7] collected representatives of 111 species belonging to 37 genera.

During survey trips in 1975 and March and July 1981, several hundred gastropod and crustacean specimens were collected and are currently being examined. The marine algae are known from previous records (Tsuda and Tobias 1977a, 1977b), and additional material is also being investigated. Approximately 200 species of fishes were collected or observed in the field during a March 1981 visit.

On land more than 200 species of vascular plants have been reported (Fosberg et al. 1975, 1977, 1980). Additional species were recorded during the March and July 1981 survey. Baker (1951) reported on the birds. Monitor lizards are common, and bats occur throughout the island.

A note should be added about the effects of the May 1981 eruption on the island. Five biologists from the University of Guam visited Pagan in July 1981. The lava flows obliterated all vegetation in their paths. Leaves of trees were shed or damaged by the ash and scoria fall. After the eruption every species of plant seen previously were found somewhere on the island. Toward the southern end, the vegetation appeared unaffected. The lakes appeared quite similar, chemically, to that found before. Shoreline, intertidal, and shallow-water habitats were severely disturbed (Eldredge 1982). Where surf has altered the scoria, original physical conditions are returning. At the north end at Talagi more than 200 cm (78.7 in) of scoria covered the shoreline and low headlands, as well as filled a large blowhole. The intertidal gastropods found previously along the shore were totally absent or very much reduced in numbers. The white-sand beach at Regusa is covered with black volcanic material. The elevated spurs and grooves are filled with scoria and have been cut off from water circulation by a low volcanic berm. Gastropod and algal zonation observed in March was seriously altered by floating scoria and pumice. Subtidally, low encrusting corals were smothered, and upright branching forms were heavily damaged. At Kachu 94 colonies were counted. Of these 38 (40%) were alive, 41 (44%) were dead, and 15 (16%) were heavily damaged. At the bay south of Bandera, of 59 coral (Pocillopora elegans) colonies, 27 (46%) were alive, 8 (13%) were dead, and 24 (41%) were heavily damaged.

AGRIHAN

With the highest elevation in the Marianas, Agrihan is located at lat. 18°46'N and long. 145°40'E (Figure 22) and has an elevation of 965 m (3,166 ft). The land area is 44 sq. km (18.3 sq. mi). The island has been previously known as A-Grega, Agrega, Agrigan, Agrigarn, Agriguan, Agrijan, Agrijon, Aguijan, Ajujan, Agurigan To, Agurijan, Ergua, Gilen, Greca, Gregua, Greguna, Greje, Griga, Grigan, Guanan, Guerga, Ile de Sainte Francois Xavier, San Francisco Javier, and Volcan de Griga (Bryan 1971).

Although relatively inactive, Agrihan's volcano erupted ash in 1917 (Hasegawa 1917; Tanakadate 1940). More recently Stern (1978) provided an in-depth review of the geology of Agrihan. He noted three geomorphological provinces--shoreline, slopes, and central caldera--and detailed the stratigraphy and petrography.

Elevated cliffs and steep slopes characterize the coastline. Pebble-sized black sand beaches are found only along the southwestern shore (Figure 23). These are as wide as 30 m (98.4 ft) and may have a high seaward berm during seasons of heavy surf. A berm was present during the summer of 1978,[3] as well as during a January 1975 visit.[4]

Very little is known about the biota. A single dive was conducted north of a low headland along the west coast. The shore was rough, irregular lava broken into blocks which gently sloped to deeper water where the bottom was a smooth, eroded, polygon-like pavement. Few animals, other than limpets, were observed in the intertidal zone. Occasional heads of Pocillopora were present on slightly elevated blocks and boulders. A low encrusting form of fire coral (Millepora) was

predominant, and the sea urchin Diadema setosum was common. The asteroid Linckia multifora was found in great numbers and were unusual because of their large size and because many were found in various stages of regeneration.

On land, nearly 150 vascular plant species have been recorded (Fosberg et al. 1975). The birds are listed by Baker (1951), although Borror (1947) specifically discussed those of Agrihan. Jouanin (1959) added the record of a nesting colony of black-footed albatross reported at Agrihan in 1888.

ASUNCION

The nearly perfect cone of Asuncion is located at lat. 19°40'N and long. 145°24'E (Figure 24). The island has been previously known as Asomson, Asoncon, Asoncun, Asongsong, Asonson, Assomption, Assongsong, Insel, Assongsong Is., Assongsong, Assonguson To, Assumption, Asumcion, Asumpcion, Asuncion, Chemecho, Chemecoa, Cherpshn, Cheroshuns, Ile de l'Assomption, Insel de l'Assomption, Isle de Volcan, Las Mojas, Semoguan, Sonsong, Volcan Grande, Volcano Grande, and Volcgrande (Bryan 1971).

The island, which has an elevation of 891 m (2,923 ft) and an area of 7.3 sq. km (2.8 sq. mi), has had a somewhat quiet geological history during historic times. During an explosive eruption in 1906, lava flowed,[5] forming the distinctive inverted chevron halfway down the west slope (Figure 25). Minor eruptive activity occurred during the early 1920s but none is known since, although the volcano is still active as evidenced by intertidal hot springs.[4]

The shoreline is composed mainly of low to high steep cliffs and isolated truncated basaltic platforms and associated pools. These pools end along the southeastern shore. Much of the shore along the east and northeast coast shows extensive erosion. A shore of large, oval cobble-sized boulders is found along the west coast. No sand-grain-sized beaches were observed.

A small hot spring was found along the west coast near a wide basaltic platform. Along a landward-seaward line the following temperature and salinity measurements were recorded seaward from the spring during a low tide (July 8, 1975):[4]

| Temperature (°C) | Salinity (°/°°) |
|---|---|
| 39 + | 8.884 |
| 39 + | 7.774 |
| 31.8 | 31.085 |

The ambient seawater temperature was 20.8°C and salinity was 34.42°/₀₀ At high tide when the pools were filled, the salinity was the same as ambient (34.44°/₀₀), and the temperature ranged from a high of 32°C to ambient.

Little is known of the marine biota. In the deeper water the coral community is relatively rich. Several gastropods have been collected. In the intertidal zone the major animals are abalone (Haliotis sp.), as abundant as 4 per sq. m, and sea urchins (Colobocentrotus mertensi).

Fritz (1902) visited the island and noted that the plants of earlier settlers had "gone wild" and were widely spread. A total of 70 plant species are now known from Asuncion (Fosberg et al. 1975, 1977). There appears to be a relatively distinct vertical distribution of vegetation forms. Coconuts, pandanus, and hibiscus form a zone from above the strand or wave-washed areas to about 100 m (328 ft). Above this, a zone of swordgrass continues upward, becoming sparse, until volcanic material is the major cover. Swordgrass is the major vegetational form throughout the east side of the island.

Fritz (1902) related an interesting story about the possibility of English treasure being buried at Asuncion. He briefly told of a Spanish governor's unsuccessful search for the treasure and the realization that the treasure might be at Pagan.

MAUG

Three islets comprise the island of Maug which is located at lat. 20°01'N and long. 145° 13'E (Figure 26). The island has been previously known as Bato, Buvi, Eunas I., Las Monjas, Les Isles Uracas, Madug, Mahao, Manao, Mang, Mangs, Mao, Mauga, Maui, Mauo, Mayug, Mogu To, Monjas, Moug, Mougu To, Ota, Ota-Mao, Sainte Laurent, San Lorenzo, Tina, Tuna, Tunas I., Urac, Uraccas, Urakas Is., Urracas, and Urracus (Bryan 1971).

The three islets are North Island (=Kita Shima) with an elevation of 227 m (746 ft); East Island (=Higashi shima) with an elevation of 215 m (709 ft); and West Island (=Nishi shima) with an elevation of 178 m (591 ft (Figure 27)

Notes on the island's geology were first made by Fritz (1902) who described the geology and vegetation in very general terms. He remarked on the basaltic dikes. Under the League of Nation's mandate, a number of Japanese scientists visited the islands beginning in 1922. Tayama (1936) considered all three islets as being originally part of a single volcano called Maug Volcano. Following a brief visit, Tanakadate (1940) discussed the form of the volcano and the composition of the material. It is conjectured that the present form of Maug resulted from a massive and explosive eruption.

A weather station was established at the summit of East Island in 1939, and a small fish processing plant was once located at the west shore at East Island (Eldredge et al. 1977). Remnants of the concrete work at both places presently remain.

The shoreline is irregular. On the ocean side of the island most of the shore is either consolidated headland or composed of small eroded materials. At the water level the coastline is either vertical or undercut. The islands form steep slopes between 45° and 60°. Rough

water generally makes access to the ocean side hazardous. On the lagoon side the islets are almost vertical in slope, although narrow areas allow access to the heights. The remnants of a masonary trail can be seen along the north end of East Island. Vertical basalt dikes with intermittent stratified unconsolidated material are major visual features of North and West Islands. East Island is the highest; West Island has a very irregular outline.

Most of the shoreline is composed of large rounded boulders or low, consolidated headlands. A few scattered "beaches" are at the bases of East Island. A man-made bulkhead is located near the north end and a low, truncated offshore basaltic mound is situated off the north end of East Island. At the north tip of this island the shore is composed of unconsolidated cobble-sized boulders is located at the west end of North Island.

Toward the center of the lagoon, most of the substrate is consolidated basaltic boulders veneered with scattered broken boulders, presumably resulting from terrestrial erosion. A narrow, smooth limestone terrace is found along the east side of West Island. This extends from shore 5 to 10 m (16.4 to 32.8 ft), gradually slopes to a depth of 25 m (82 ft) and then drops out of sight. The shallow terrace along the north end of East Island is covered with a mixed basaltic-and-bioclastic sand. Throughout the lagoon the terrace is narrow and becomes very deep close to shore. Along the south shore of North Island depths of 64 to 90 m (35 to 49 fathoms) are found.

The entire lagoon has been swept to a depth of 15 m (49 ft). The northwest entry channels has been swept to depths of 4.6 m (15 ft). During the November 1977 natural history survey, a Japanese trolling boat passed through this channel and exited through the south passage.

The biota of Maug is among the better known of the northern islands. A natural history survey was carried out during November 1977 (Eldredge et al. 1977).

Seventy-four species of scleractinian and four of nonscleractinian corals have been reported. This probably represents only a portion of the total number of coral species. The most diverse area was midway along the eastern shore of West Island where the terrace is as wide as 50 m (164.0 ft). Here large ramose-columnar colonies of *Acropora irregularis* dominated the inshore area. Further offshore *Millepora platyphylla*, *Porites lutea*, and *Goniastrea* sp. were predominant. A narrow, well developed fringing reef was observed at the seaward side along the southern end of West Island where coral coverage was high and species composition diverse. Within the lagoon no reefs are being actively formed. In general, the coral development should be considered that of a coral community.

Characteristically, the algal communities are predominantly low-lying, turflike forms which are fed upon by a great number of herbivorous fishes. A total of 60 species of benthic algae are currently known from Maug (Tsuda and Tobias 1977a, 1977b, Eldredge et al. 1977). The collection of *Laurencia succisa* represents a new record for

Micronesia, and Homeostrichus flabellatus, known previously in Micronesia from dredged specimens from Guam, was abundant along the lagoon side of East Island.

A wide variety of marine invertebrates is known from Maug. Two species of abalone commonly occur. The sea urchin (Colobocentrotus mertensi) is the most abundant intertidal invertebrate and may have an abundance as great as 26 individuals per quarter meter square. Eight-six species of gastropds have been recorded.[11] Twenty-one echinoderm species, 4 soft coral species, and a black coral (Cirripathes sp.) are also known.

The greatest fish abundance and diversity were found along the reef communities at the north end of East Island and the central part of West Island. The most abundant fishes were kyphosids and acanthurids within all the habitats examined. Two species of pomacentrids found on the seaward side of West Island were not found within any of the lagoon observations. Sharks were relatively abundant during the November 1977 survey, as well as during the Commonwealth 1978 survey. A total of 232 species of fishes have been reported as a result of five different and separate examinations.

Some terrestrial observations have been made at Maug (Eldredge et al. 1977). The plants have been listed (Fosberg et al. 1975, 1977) and further vegetation patterns have been noted (Eldredge et al. 1977). In general, low growing grasses, sedges, and vines (Ipomoea, Wollastonia, Cyperus, Capparis) cover the slopes. Larger trees (Terminalia, Pisonia, Hibiscus) form distinctive groves. Pandanus tectorius is present, and large stands of Crinum are present on East and North Islands. The ironwood (Casuarina) and coconut (Cocos nucifera) are found only at the top and on the outer slopes of East Island. A total of 59 terrestrial vascular plants are known.

A few specimens of a widespread terrestrial snail (Succinea sp.) were collected at an elevation of 60 m (197 ft) on East Island. Juvenile earthworms (Dichogaster sp.) were collected from among leaf litter.

Sixteen species of birds are reported from Maug. Yamashina (1940) made the first bird sightings. The major report is that of Baker (1951) who studied all the bird fauna. Falanruw (1975) reported the megapods, and Owen (1977) prepared a checklist of the birds.

Fruit bats (Pteropus mariannus) were observed in November 1977, as were several species of skinks. Small rats were seen in an abandoned cistern and around the weather station ruins.[4]

The island has been considered as a site for an oil-transshipment facility. Maug is now protected as an island to be "maintained as uninhabited place[s] and used only for the preservation of bird, fish, wildlife, and plant species" by the Constitution of the Commonwealth of the Northern Mariana Islands (Article XIV, Natural Resources), marine resources (Section 1) and uninhabited islands (Section 2).

URACAS or FARALLON DE PAJAROS

This round island is covered with recent lava except for two promon-

tories along the southern shore. One promontory has an elevation of about 60 m (197 ft) (Figure 28). The island is located at lat. 20°32'N and long. 144°54'E. Its elevation is 334 m (1,047 ft), and its area is 2.04 sq. km (0.79 sq. mi). The island has been previously known as Ana, Desieria, Farallon and Poraro, Farallon de Pajajos, Farallon de Pajaros, Guaban, Guy Rock, La Ingelesa, Pajaros, Poraro, Rocher de Guy, Urac, Uracas Insel, Urakas, Urakasu To, Uricas, Urracas y Farallon de Pajaros, and Vogelinsel (Bryan 1971).

Little vegetation is present on the volcano slopes except on these raised promontories which remain from pre-1900 eruptions (Figure 29). Records of eruptions are not well documented. The first reported minor eruption was in the mid-1860s; the first with lava flows in the late 1870s. Steaming and minor eruptions have been noted almost continuously since the 1900s.[5] On DMA Chart No. 81086 a note reads, "Profile of island reported changed by violent volcanic eruption (1943)." Between 1975 and 1978 an eruption formed a major hydrothermal vent along the northeastern shore which is emitting a colored-water plume rich in iron and manganese.[12] This same plume was observed in mid-July 1981.[6] Also an ash eruption apparently occurred during 1977-78, since fresh ash showed little evidence of rain erosion and was present along the shore headlands, having been unaffected by seasonal rain or high surf. A different colored plume was observed in July 1975 along the west shore.

The shoreline consists primarily of eroded lava blocks and low cliffs. Small, narrow "beaches" occur in isolated areas and probably disappear with volcanic activity. Only a few intertidal organisms are present--littorines (L. pintado), limpets (Cellana sp.), grapsid crabs (Grapsus tenuicrustatus), and sea urchins (Colobocentrotus mertensi)--along with some filamentous algae. These probably represent the first stage of recolonization of the newly deposited shoreline. In deeper water bare boulders and isolated sand patches form the substrate for scattered coral growth. Several species of fish, including many moray eels, were observed. On the more elevated boulders coral growth was richer, and a few gastropods were collected.

On land about 11 species of plants have been reported (Fosberg et al. 1975). Seven species of seabirds were observed in July 1975,[4] and the megapod has recently been reported (Falanruw 1975).

BANKS

Zealandia Bank, located at lat. 16°53'N and long. 145°51'E, is a low exposed bank of different reported heights. Fritz (1902) indicated that the Bank was about 2 m (6.6 ft) high; Lehne and Gabler (1972) reported 0.6 m (2 ft). The "Sailing Directions for Pacific Islands" volume I (1964) provided information that the bank "consists of two rocks, that dry about 0.6 m (2 ft) and lie about 0.8 km (0.5 mile) apart, northeast and southwest" (p. 389). During April 1983 Zealandia Bank was visited by University of Guam researchers. Two exposures were noted. A short dive at the more northern one showed that it was straight sided and rose from a flat-topped platform about 30 m (100 ft) in depth. [Lehne and Gabler (1972) also referred to this area as Papaungan.]

Supply Reef, located at approximately lat. 20°10'N and long. 145°04' E, is circular in outline. The "Sailing Directions for Pacific Islands" (1964) reported the reef as "having a least depth of 4-1/2 fathoms on its south. It is marked by discolored water and by breaking seas" (p. 392). Corwin[5] provided a sketch of Supply Reef adapted from that of Tayama (1936). Coarse ash covers the north half of the entire cone.

Galvez Bank and Santa Rosa Reef, banks west of Rota and Saipan and north of Farallon de Medinilla, "Bank A," and Arakane Reef have recently been mapped and figured (Polovina and Roush 1982).

# CLIMATE

The climate of the Mariana Archipelago is uniformly warm and humid throughout the year and can be considered tropical toward the south and somewhat subtropical toward the north. The annual variation of mean monthly temperatures range from 2°C (3°F) at Guam to 3°C (5°F) at Pagan (Corwin et al. 1957). There are two well defined seasons--a dry season extends from January through May, and a wet season from July through November. [Corwin et al. (1957) stated that the dry season at Pagan was from November to June and the wet season from July to October.] The remaining months are considered transitional and may be either wet or dry depending upon the overall periodic cycle.

The most extensive climatic review for Guam is that of Blumenstock (1959) and for Pagan, that of Corwin et al. (1957). A short updated review for Guam is that of Eldredge and Kropp.[1] An overall description of western Pacific weather was prepared by the U.S. Weather Bureau (1943). "Local Climatological Data" is compiled continuously at Guam by the National Climatic Center of the Environmental Data and Information Service. Additional information is available from the National Oceanography Command Detachment (formerly Fleet Weather Central/Joint Typhoon Warning Center) at Guam and from the Naval Environmental Prediction Research Facility at Monterey, California. Predicted astronomical data for 1983 has been prepared by the Naval Oceanography Command Detachment (1982).

## Air Temperature

The temperature at sea averages 27° to 29°C (80° to 84°F) with a monthly variation of 1°C (2°F) (U.S. Weather Bureau 1943). Between lat. 10° and 20°N this variation may increase 2°C (4°F). More specifically, the air temperature at lat. 10°-15°N and long. 140°-145°E is 27°C (80°F) and at lat. 15°-20°N and long. 140°-145°E, 28°C (81°F), as calculated from the U.S. Weather Bureau (1943), averaged for the years between 1881 and 1933. North of lat. 25°N, a wide range of temperatures prevail.

Temperature on land also varies little. At Guam the coolest months are January, February, and March and the warmest are May and June. The range between the coolest and warmest months is slightly less than 2°C (3°F). The differences between the monthly minimum and maximum temperature recorded between 1941 and 1980 was 35°C (95°F) in September 1957, although Blumenstock (1959) reported an earlier temperature of 38°C (100°F). The lowest temperature was 12°C (54°F), recorded in March 1965 at the Weather Bureau Building at an elevation of 120 m (361 ft). Temperature data for Guam are presented in Table 1.

At Pagan, Corwin et al. (1957) noted that the observed maximum temperatures were more variable than the minimum temperatures. During July, August, and September the observed temperatures ranged between 26.6°C (79.8°F) and 36.4°C (97.6°F), the mean being 31.8°C (89.2°F).

Humidity

The relative humidity is high throughout the year. At Guam the relative humidity averages 77 percent at 1600, 90 percent at 2200, and 92 percent at 0400 (Table 2). Extremes do occur but rarely does the humidity drop to less than 60 percent. Humidity lower than 40 percent has never been observed (Blumenstock 1959).

At Saipan 6-year measurements showed a relative humidity of 88 percent at 0600 and 74 percent at 1400 (Meteorological Office 1975). The mean relative humidity at Pagan was 83 percent, resulting from 67 observations made during the summer of 1954 (Corwin et al. 1957). At 1400 the average minimum humidity was 74 percent, and the average maximum was 87 percent in the early morning between midnight and 0600.

The decrease in relative humidity between Guam and Pagan should be noted as indicative of a less tropical climate toward the north.

Wind

The entire western Pacific area is dominated by the east and northeast tradewinds. In the western part, west of long. 140°E, monsoonal winds develop. Here at sea there is a shift from northerly winds during the winter to southerly winds during the summer (U.S. Weather Bureau 1943). The annual mean surface wind velocity is shown in Figure 30. The average surface wind drift direction, constancy, and force is shown in Figure 31.

In the ocean area around the Mariana Archipelago, the northeast tradewinds predominate during most of the year except during the summer months. These winds are present in about 35 percent of the observations annually near the equator (U.S. Weather Bureau 1943). During the winter occasional north, northwest, and west winds may be observed, and during the summer southeast tradewinds may occur. Further north between lat. 20° and 25°N, northeast and east winds occur about 47 percent of the time.

Specifically for the area between long. 140° and 145°E (U.S. Weather Bureau 1943) the average sea wind velocities near the equator are light and show little seasonal differences. Between lat. 5° and 10°N the annual mean velocity south of the archipelago is about 9 knots with distinct seasonal differences. During the winter the mean velocity is as high as 14.5 knots in February, and during the summer as low as 4.9 knots in August. For lat. 10° to 15°N, the mean velocity is 9.4 knots. The high mean is 13 knots for January, and the low is 8.4 knots for July and August, showing less extremes than to the south. For lat. 15° to 20°N the mean velocity is 10.1 knots. Speeds of more than 10 knots are found during eight months. The lowest speed of 7.6 knots was recorded during June. North of lat. 20°N the mean velocity decreased to 9.6 knots.

West of the Marianas the speeds range from 10 to 15 knots monthly from October to March and 8 to 11 knots from April to September (U.S. Weather Bureau 1943). The summer monsoon affects a wide seaward area, and the winds are lighter eastward through the Marianas.

On the islands during the dry season a more northerly element occurs and the winds blow as much as 90 percent of the time. Characteristics of winds at Guam are shown in Table 3. Highest winds occur in late morning and afternoon, and lightest winds, at night (Eldredge and Kropp ). Other seasonal differences also occur. The tradewinds weaken during the wet season and may be interrupted by tropical cyclonic disturbances (Figure 32).

The percentage frequency of wind direction by speed and hour for Guam, Saipan, and Pagan is shown in Tables 4, 5, and 6, respectively.

## Rainfall

Rainfall varies markedly geographically and seasonally. Rainfall increases at Guam between July and November during the wet season when more than 60 percent of the annual rain fall. Rain falls on about 75 percent of the days. The average monthly rainfall is about 357 mm (14 in) during August, September, and October; however, more than 569 mm (26 in) were recorded in October 1979. Tropical cyclones occur during the wet season. During the dry season--January through May--as much as 20 percent of the annual rain may fall. Generally less than 54 mm (5 in) has been recorded for each month. Even though tropical cyclones are rare during the dry season, Typhoon Pamela passed directly over Guam in May 1976 and dropped 686 mm (27 in) of rain, the highest 24-hour rainfall on record. The average annual rainfall is 2286 mm (90.6 in) (EDIS 1981); however, generally the rainfall is somewhat greater in the mountainous southern half with 2794 mm (110 in). Normal monthly rainfall averages, maximum and minimum monthly rainfall, and mean number of days of rainfall are presented in Table 7.

A 19-year average rainfall at Saipan was 2080 mm (82.2 in) (Meteorological Office 1975). At Pagan Corwin et al. (1957) stated that the rainfall was probably 1776-2030 mm (70-80 in) because of the differences in relation to the convergence zone. The decrease in rainfall is another indication of the less tropical climate toward the north.

## Storms

Small-scale storms, mainly squalls and thunderstorms, may periodically dominate isolated areas. At sea thunderstorms occur more often at night than during the day (U.S. Weather Bureau 1943). Island land masses create conditions for thunderstorms. At Guam frequency increases during the wet season with an average of six in July and seven in August. Thunderstorms are rare during the dry season, none having been reported during February or March (EDIS 1981). For Saipan 17 to 18 thunderstorms have been reported annually (U.S. Weather Bureau 1943). Figure 33 shows the mean annual number of thunderstorm days for the archipelago.

Squalls and gales occur more commonly during the wet season where sudden gusts of winds can cause sudden rainfall. Often several such squalls can be seen along the horizon. During the dry season the tradewinds may bring about sudden winds with gusts to 22 knots. Less than 5 percent squall frequencies are found from lat. 15° to 30°N. South of

lat. 15°N (0°-15°N) these frequencies may be more than 6 percent (U.S. Weather Bureau 1943).

Gale winds vary and may be associated with cyclones or cyclone generation. They have been reported to occur 1 to 6 percent of the observations at long. 140° to 145°E between March and September and in November (U.S. Weather Bureau 1943). Two- and 100-year return periods of expected extreme wind gusts at Guam (Station 35) are shown in Figure 34.

Tropical Cyclones

Cyclones are counterclockwise wind circulation patterns formed in a central calm core or "eye." The relatively narrow, 74-93 km (46-58 mi) in diameter, band of winds and trailing spiral rains cause considerable damage when they reach land.

Cyclone patterns are differentiated by speeds in an internationally agreed upon scheme:

| | |
|---|---|
| Tropical depression | Maximum sustained winds not greater than 33 knots; |
| Tropical storm | Maximum sustained winds between 34 and 63 knots; |
| Typhoon | Maximum sustained winds greater than 64 knots; |
| "Supertyphoon" | Sustained center winds of 130 knots (gusts to 160 knots). |

Because of their high frequency in the western Pacific, (Figure 35) tropical cyclones have been examined in detail. Climatological statistics--frequency, intensity, movement, and environmental conditions--were analyzed by Gray (1970). In particular, the effect of cyclones at Guam has been studied by Holliday (1975) and Brown and Brand (1975). Gray (1970), using data collected from 1900 to 1969 with most emphasis on those collected between 1946 and 1969, detailed the origin, tracks, and positions of cyclonic disturbances, as well as trade-wind cloud associations. These disturbances originated over a wide area of the western Pacific. The initial locations of tropical disturbances which later became typhoons or tropical storms are shown in Figure 36. The locations where these disturbances reached typhoon intensity are shown in Figure 37. Figure 38 details the initial detection locations for June of cyclonic disturbances which later reached typhoon or tropical storms or depressions. The heavy solid line separates pure tropical cyclones (A) from subtropical cyclones (B). About 80-85 percent of all tropical cyclones are A type, the remaining 15-20 percent are B types and develop generally at latitudes north of 15° and 18°N. Subtropical (B) cyclones are formed within the tradewind area only during summer and early autumn and are not associated with the equatorial trough. Tropical (A) cyclones are formed within a deep tropospheric easterly current where vertical and horizontal wind shears show peculiar characteristics (Gray 1970).

The mean annual number of typhoons located in the western Pacific is

shown in Figure 39. Guam and the Marianas lie southeast of the main area of activity (Holliday 1975).

Typhoons are considered to affect Guam when they pass within 333 km (207 mi) of the island. Nearly 70 percent of those reported between 1948 and 1975 approached Guam from the southeast (Figure 40) (Holliday 1975). The majority of these passed south of a point 111 km (69 mi) north of the island. Some (16-22 percent) did not approach from a uniform direction but looped or stalled (Figures 41 and 42). The forward speed of the majority of storms ranged between 7 and 16 knots, averaging 11.5 knots. Storms approach more slowly between April and August than between November and March. Typhoon Hester (December 1952) passed Guam at a speed of 22 knots.

Winds vary during the passage of typhoons. Maximum sustained wind speeds in relation to longitude are shown in Figure 43 and in relation to month are shown in Figure 44 from data for the years 1953 to 1968.

During Typhoon Pamela (May 1976) winds gusted to 145 knots and were in excess of 100 knots for six hours (Joint Typhoon Warning Center 1977). A speed of 125 knots was reported for Typhoon Karen (November 1962) before the Weather Service anemometers failed. The strongest wind on record was recorded at Miyako Jima (Ryukyu Islands) at 166 knots during Typhoon Cora (September 1966) (Holliday 1975).

Rainfall is exceedingly variable and depends on the storm's winds, speed of forward motion, and rain gauge location. The greatest 24-hour rainfall recorded was that of 686 mm (27 in) during the passage of Typhoon Pamela. Earlier records are Tropical Storm Alice (October 1953) with 465 mm (18.3 in), Typhoon Amy (May 1971) with 252 mm (9.92 in). Usually about 102 mm (4 in) of rain is common during the passage of a typhoon.

Between 1948 and 1975, more than 70 cyclones were tracked within 333 km (207 mi) of Guam. Only 26 (35 percent) were of typhoon strength at their closest (Holliday 1975). The greatest number occur during the wet season, October and November having the highest number. Tropical storms have been reported during every month (Figure 45). The yearly frequency has been irregular since 1954 (Figure 46). Typhoon Pamela occurred in 1976 and Tropical Storm Tip in 1979. An analysis of cyclones near Guam indicates that there is a probability of one significant typhoon occurring every seven years. November has the greatest frequency of storms (Holliday 1975). A high number of cyclones has been tracked for that month (Figure 47).

For Guam Brown and Brand (1975) evaluated Apra Harbor as a typhoon "haven" and discussed its facilities, wind and wave action, storm surge, and topographical effects before and after cyclonic activity. Because of the lack of wind-breaking topography and because of the harbor's westward opening, Apra Harbor was not recommended as a typhoon haven. Their data were based on 107 tropical cyclones passing near Guam between 1947 and 1973.

Unfortunately, no analyses of storm conditions have been conducted

for any of the other islands in the Marianas. The "Annual Tropical Cyclone Report" (formerly Annual Typhoon Report) is compiled by the National Oceanography Command Center (Fleet Weather Central/Joint Typhoon Warning Center) at Guam. Each details the cyclones of the year for a wide area of the western Pacific from their origin to their dissipation, and a best track of each is also given. During the past several years Typhoon Dinah (November 1980) passed over Saipan; Typhoon Carmen (August 1980) passed near Guguan; Typhoon Faye (September 1978) circled around Pagan and Agrihan and moved toward the northwest; Tropical Storm Ivy (October 1977) circled around Alamagan and became a typhoon toward the northwest; Tropical Storm Carla (May 1974) passed over Saipan, and 95 percent of the crops were damaged, Pagan and Agrihan reported 45 percent damage; Typhoon Ida (September 1972) passed over Pagan; Typhoon Olga (October 1972) passed near Asuncion; and Typhoon Faye (October 1971) passed north of Saipan. Seidel (1903) noted that a typhoon passed over Maug and Uracas on 30 August 1858. Lehne and Gabler (1972) noted typhoons at Rota in 1911 and at Pagan and Agrihan in September 1907. Holliday (1975) detailed the typhoons occurring between 1671 and 1975 with special emphasis on those occurring since 1946.

# CHEMICAL OCEANOGRAPHY

## Salinity

Mean annual surface salinities are shown in Figure 48 (Robinson 1976). More specifically, the quarterly mean salinity at 10 m is shown in Figures 49-52. A low-salinity region is noticeable at approximately the Equator and 10°N between two areas of higher salinity. Generally, the Mariana Archipelago lies within this area of low salinity. Barkley (1968) showed an increase in salinity toward the north especially during the second quarter. This low salinity may have originated in the eastern Pacific and moved westward, and it may have been joined with other low-salinity water entering through the Mollucca Passage (Cannon 1966).

In the northern part of the Mariana Archipelago, deWitt (1972) showed that the surface salinity ranged from 34.39°/₀₀ to 34.94°/₀₀ during April and May 1971 (spring Townsend Cromwell cruise), whereas the salinity ranged between 34.36°/₀₀ and 34.79°/₀₀ during November 1981 (fall Townsend Cromwell cruise) (Figures 53 and 54). Salinity increased toward the north during the spring (deWitt 1972) as Barkley (1968) had earlier suggested.

DeWitt (1972) discussed vertical salinity structure in detail. In deeper waters, low salinity water (North Pacific Intermediate Water) was present along a layer at the 135 cl/t surface. The depth decreased from greater than 550 m (1,804 ft) at lat. 21°N to approximately 40 m (1,312 ft) at lat. 15°N in the spring, and from approximately 650 m (2,132 ft) at lat. 23°N to less than 555 m (1,820 ft) at lat. 17°N in the fall (Figures 55 and 56). High salinity water (tropical water) was present approximately along the 370 cl/t surface. During the spring the 370 cl/t surface sloped from less than 100 m (328 ft) at lat. 21°N downward to greater than 175 m (574 ft) at lat. 15°N, and during the fall this surface sloped from slightly more than 100 m (328 ft) at lat. 23°N to approximately 175 m (574 ft) at lat. 17°N (Figures 55 and 56).

At Guam, the observed salinity and density profiles are typical (Figure 57). At Cabras Island a salinity of 34.30°/₀₀ was reported from the surface and 35.13°/₀₀ at 150 m (492 ft) (Lassuy 1979). The minimum mean salinity occurred at 496 m (1,625 ft). At Tanguisson Point during a nine-month sampling period in 1969, surface salinities ranged from 33.83 to 34.63°/₀₀ with a mean of 34.28°/₀₀ (Jones et al. 1976). A T-S diagram has been prepared for the waters off Cabras Island (Figure 58). Since all values are positive, the water in the area is in "stable equilibrium" (Lassuy 1979).

At Pagan, surface salinity was reported at 33.80°/₀₀ and at a depth of 100 m the average salinity was 34.99°/₀₀ (Corwin et al. 1957).

The mean surface water density at Guam was $25.7\sigma_{15}$ at a mean temperature of 28.5°C for a period between 1949 and 1969. The maximum density was $28.1\sigma_{15}$ at 32°C and the minimum, $19.9\sigma_{15}$ at 24°C (U.S. Dept. Commerce 1970).

## Oxygen

In a research cruise track approximately 10° west of the Marianas, Masuzawa (1967) reported a layer of oxygen with a concentration of less than 1.5 ml/l below the thermocline which extended from the coast of Japan southward to lat. 3°N. A depth change occurred near lat. 15°N (Figure 59).

At Guam, mean dissolved oxygen and total carbon dioxide measurements from the surface at Cabras Island to 905 m (2,970 ft) are given in Figure 60. In the mixed layer above the thermocline, $O_2$ concentration is high and $CO_2$ relatively low. Below the thermocline, $O_2$ production decreases rapidly reaching a minimum at about 400-500 m (1,310-1,640 ft). The maximum $CO_2$ concentration is reached at about 500-1,000 m (1,640-3,280 ft) (Lassuy 1979).

## Nutrients

The most detailed and recent information concerning the vertical distribution of nutrients in the Marianas is that of Lassuy (1979) for Cabras Island, Guam. Nitrate-nitrogen ($NO_3$-N), nitrite-nitrogen ($NO_2$-N), and reactive phosphorus (orthophosphate, $PO_4$-P) were measured during an annual cycle (February 1978-February 1979) from the surface to a depth of 883 m (2,900 ft). Nitrite-nitrogen was negligible or undetectable at all depths. Nitrate-nitrogen and orthophosphate were always present in measurable amounts and increased with depth (Figure 61).

## pH and Alkalinity

Mean values for pH and alkalinity from the surface to 918 m (3,010 ft) off Cabras Island are shown in Figure 62. The pH minimum closely coincides with the $\Sigma CO_2$ maximum between 800 and 900 m (2,625 and 2,953 ft) (Lassuy 1979).

## SEA-SURFACE TEMPERATURE

Sea-surface temperatures vary only slightly throughout the year, ranging between 27.2°C and 29.4°C (80.9°F and 84.9°F) (Emery 1962). Figures 63-74 show the 15-year monthly mean sea-surface temperature for the western Pacific. In an area bounded by long. 140°-145°E and by lat. 10°-15°N, the maximum temperature observed was slightly more than 34°C and the minimum slightly less than 25°C (Figure 75). Maximum, mean, and minimum monthly sea-surface charts are provided by LaViolette (1970). Temperatures are generally lowest in February and March and highest in August and September.

In the Marianas, deWitt (1972) reported surface temperatures ranging from 27.4 to 29.7°C in April-May and 28.6 to 29.7°C in November (Figures 76 and 77). During April-May surface temperatures increased toward the south.

At Guam, a 10-year period (1963-1972) of surface temperatures taken at Tanguisson Point by the Guam Divison of Aquatic and Wildlife Resources represents a nearshore seasonal temperature regime (Figure 78). The mean temperature during the period was 27.6°C (82°F), the lowest 25.6°C (78°F), and the highest 29.4°C (84.1°F). The range of annual means for the 10 years was 27.4°C to 27.9°C (81.3°F to 82.2°F) (Jones et al. 1976).

Reef-flat temperatures (29.3°C or 84.7°F) tend to be about 2°C (3.6°F) higher than nearshore surface water. On rare occasions reef-flat temperatures may be as high as 33.9°C (93°F), occurring during extended low tides (Jones et al. 1976).

At Pagan a mean shallow-water temperature of 27.40°C was reported for a 268-day sample in 1977 (Wyrtki[13]).

### Thermocline

As the temperature decreases with depth three distinct temperature regions can be noted--a well-mixed surface layer, a thermocline area of rapid decrease of temperature, and a deep cold layer. These layers in the vicinity of Cabras Island are shown in Figure 79. The mixed surface layer generally extends to depths of 90-125 m (300-400 ft) where the temperature rapidly begins to decrease. Additionally, summaries of the National Oceanographic Data Center (NODC) expendable bathythermograph (XBT) data for the Marianas show minimum, maximum, and average temperatures from the surface to 760 m.

More specifically, at Guam the mean monthly temperatures from the surface to 915 m (3,000 ft) are shown in Figure 80. For waters in the northern areas of the Marianas, deWitt (1972) detailed temperatures from lat. 15° to 21°N along long. 142°E to depths of 1,000 m (Figures 81 and 82).

During fishery surveys in 1975, 1976, and 1977 the Japan Marine Fishery Resource Research Center (1975, 1976, 1977) carried out temperature profile studies along the Marianas. The results of each of

three years is shown in Figure 83).

For a survey of depths to the tops of the thermocline for each month, Robinson (1976) mapped the western Pacific on a very broad basis (Figures 84 to 95).

# CURRENTS

## Surface Currents

The major sea-surface current influencing the Mariana Archipelago is the North Equatorial Current which flows westward through the islands. At Guam the current speeds range from 0.6 knots in December and January to 0.2 knots in August. Circulation patterns are shown in Figures 96 and 97. The current moves somewhat to the north along the northern end of the archipelago. The Subtropical Countercurrent is also associated with the northern part of the archipelago. The Kuroshio moves northward toward Japan along the Asian coast.

For the western Pacific the mean direction and force of 1°-quadrangle surface currents, as well as a current rose showing frequency of direction and average drifts within the directions for each 5° quadrangle, are shown for each month (Figures 98-109).

More specifically for the Marianas, deWitt (1972) discussed the current regimes in relation to 0-, 200-, and 500-decibar surfaces for two seasons--spring (April-May, 1971) (Figures 110-112) and fall (November, 1971) (Figures 113-115). During the spring the surface currents were markedly different from the 200- and 500-decibar surfaces. The surface shows a narrow eastward flow, whereas the deep waters flowed westward. A surface eddy (lat. 17°30'N, long. 145°30'E) is not present in deeper water; however, all depths indicate an anticyclonic eddy (lat. 19°N, long. 143°E) and a westward movement (lat. 17-18'N, long. 148°30'E) (deWitt 1972).

The westward flow had a speed as great as 30 cm/sec at the surface at lat. 21° and 23°N, and a similar southeasterly speed at lat. 17°-18°N, long. 142-143°E.

## Subtropical Countercurrent

Yoshida and Kidokoro (1967) investigated the eastward surface current movement between lat. 20° and 25°N which was tentatively described as the Subtropical Countercurrent. Additional information indicated an eastward flow and confirmation of this was based on monthly bathythermograph and reversing thermometer data (Robinson 1969).

The Subtropical Countercurrent can be traced from long. 122°E to at least long. 160°E and is usually considered to lie between lat. 20° and 25°N. The current varies with season and location. It has an eastward velocity of 0.2 to 1.3 knots with an average speed of 0.5 knots, a width of 170 km (100 mi), and a depth of 300 m (Uda and Hasunuma 1969). The general location of the Subtropical Countercurrent is shown in Figure 116. Yoshida and Kidokoro (1967) described the strongest flow between January and May, but Robinson (1969) suggested that there was an eastward flow during other months also.

The most detailed survey of this current was that of deWitt (1972). During two cruises (spring and fall), he reported a narrow, 100-km (60-

mi) wide eastward surface flow. Eddies were found during both seasons. The eastward flow was greater during the spring; little evidence was reported for an eastward flow during the fall.

## Nearshore Currents

Numerous nearshore current surveys have been conducted in many geographically separated locations at Guam, as well as at Tinian (Jones et al. 1974) and at Saipan (Doty and Marsh 1977). Guam information has been summarized by Eldredge and Kropp.[1] Huddell et al. (1974) conducted surveys during February, March, August, and September 1971 along the leeward (west) coast of Guam.

## BOTTOM TOPOGRAPHY

The islands of the Mariana Archipelago comprise the Mariana Ridge (Figure 117); Guam, Rota, Tinian, Saipan, and Farallon de Medinilla on the frontal arc, the remaining islands on the somewhat parallel active arc, the active arc. The bottom topography of the archipelago reflects these geologic features (Figure 118). Profiles taken during 1969 show the relative bathmetry of the areas as B-C-D on Figures 119 and 120. The southern islands lie on a common contour of 1000 fathoms (Figure 121). More specifically, the depths off Guam increase more rapidly toward the west (Figure 122). The deep-sea sediments around Guam show areas of reef debris, volcanic mud, and Globigerina ooze (Figure 123).

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7. Randall, R. H. (Marine Laboratory, University of Guam). Personal communications.

8. Myers, R. F. (Marine Laboratory, University of Guam). Personal communications.

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12. Meijer, A. (Department of Geology, University of Arizona). Personal communication.

13. Wyrtki, K. (Hawaii Institute of Geophysics, University of Hawaii). Data on temperature and sea level at Pagan, 1977-1978.

Table 1. Temperatures (°F), normal and extremes for Guam; highest and lowest records for 24 years (EDIS 1981).

| Month | Normal Daily max. | Normal Daily min. | Monthly | Extremes Record highest | Extremes Year | Extremes Record lowest | Extremes Year |
|---|---|---|---|---|---|---|---|
| Jan. | 83.2 | 71.5 | 77.3 | 87 | 1978 | 56 | 1978 |
| Feb. | 83.3 | 71.3 | 77.3 | 88 | 1960 | 59 | 1959 |
| Mar. | 84.5 | 71.0 | 77.7 | 89 | 1965 | 54 | 1965 |
| Apr. | 85.6 | 72.5 | 79.0 | 90 | 1960 | 59 | 1965 |
| May | 86.4 | 73.1 | 79.4 | 91 | 1970 | 62 | 1960 |
| Jun. | 86.7 | 72.9 | 79.8 | 91 | 1975 | 63 | 1972 |
| Jul. | 86.2 | 72.6 | 9.4 | 93 | 1966 | 66 | 1959 |
| Aug. | 86.1 | 72.2 | 79.1 | 91 | 1968 | 67 | 1974 |
| Sep. | 85.8 | 72.4 | 79.1 | 95 | 1957 | 61 | 1958 |
| Oct. | 85.6 | 72.3 | 78.9 | 91 | 1957 | 65 | 1976 |
| Nov. | 85.4 | 73.2 | 79.2 | 89 | 1980 | 62 | 1957 |
| Dec. | 84.1 | 72.9 | 78.5 | 89 | 1866 | 61 | 1980 |
| Year | 85.1 | 72.3 | 78.7 | 95 | 1957 Sep. | 54 | 1965 Mar. |

Table 2. Relative humidity (percent) for Guam. The 0400 records are for period 1970-1972; 0100, for 13 years; 1600 for 13 years; 2200 for 12 years (EDIS 1981).

| | Relative humidity (percent) | | | |
|---|---|---|---|---|
| Month | Hour 0400 | Hour 1000 | Hour 1600 | Hour 2200 |
| Jan. | 88 | 77 | 76 | 86 |
| Feb. | 88 | 76 | 74 | 86 |
| Mar. | 88 | 75 | 74 | 86 |
| Apr. | 90 | 74 | 73 | 87 |
| May | 92 | 73 | 73 | 89 |
| Jun. | 92 | 76 | 75 | 90 |
| Jul. | 94 | 79 | 78 | 93 |
| Aug. | 96 | 81 | 80 | 94 |
| Sep. | 96 | 81 | 81 | 94 |
| Oct. | 95 | 80 | 80 | 93 |
| Nov. | 91 | 80 | 81 | 91 |
| Dec. | 88 | 78 | 78 | 88 |
| Year | 92 | 78 | 77 | 90 |

Table 3. Wind characteristics for Guam. Given are mean speed records for six years, prevailing direction for seven, and fastest speed and direction for 22 years (EDIS 1981).

| Month | Mean speed m.p.h. | Prevailing Direction | Fastest Speed m.p.h. | Direction | Year |
|---|---|---|---|---|---|
| Jan. | 8.2 | E | 37 | NE | 1979 |
| Feb. | 10.2 | NE | 36 | NE | 1962 |
| Mar. | 9.0 | E | 32 | NE | 1977 |
| Apr. | 8.9 | E | 64 | SW | 1963 |
| May | 8.3 | E | 76 | NE | 1976 |
| Jun. | 6.4 | E | 32 | E | 1976 |
| Jul. | 5.1 | E | 34 | E | 1963 |
| Aug. | 4.8 | E | 43 | SE | 1979 |
| Sep. | 4.7 | E | 35 | E | 1976 |
| Oct. | 6.2 | E | 44 | W | 1968 |
| Nov. | 7.8 | E | 80 | NE | 1962 |
| Dec. | 9.1 | E | 35 | SW | 1963 |
| Year | 7.4 | E | 80 | NE | 1962 Nov. |

Table 4. Percentage frequency of wind direction by speed and by hour for Guam. (U.S. Naval Weather Service Command 1971b).

| | Wind Speed (knots) | | | | | | | | | Hour (GMT) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WND DIR | 0-3 | 4-10 | 11-21 | 22-33 | 34-47 | 48+ | TOTAL OBS | PCT FREQ | MEAN SPD | 00 | 03 | 06 | 09 | 12 | 15 | 18 | 21 |
| N | 0.3 | 1.2 | 0.8 | 0.2 | * | .0 | 297 | 2.5 | 11.3 | 3.1 | 2.0 | 2.6 | 1.7 | 3.1 | 2.2 | 2.8 | 2.6 |
| NE | 0.9 | 8.7 | 14.3 | 2.6 | .1 | .0 | 2959 | 26.5 | 12.3 | 26.1 | 27.1 | 26.9 | 27.6 | 26.7 | 25.5 | 26.9 | 25.6 |
| E | 1.5 | 17.5 | 22.9 | 2.3 | .1 | .0 | 5013 | 44.3 | 11.8 | 42.9 | 44.6 | 44.2 | 45.8 | 44.2 | 44.1 | 42.7 | 44.8 |
| SE | 0.9 | 5.9 | 3.8 | 0.4 | * | .0 | 1301 | 11.0 | 10.6 | 11.8 | 12.2 | 9.3 | 10.5 | 9.1 | 12.2 | 10.8 | 13.1 |
| S | 0.7 | 2.7 | 1.7 | 0.4 | * | * | 681 | 5.6 | 10.2 | 5.9 | 6.0 | 5.5 | 6.3 | 5.9 | 5.1 | 4.6 | 5.1 |
| SW | 0.5 | 1.9 | 1.6 | 0.5 | .1 | * | 564 | 4.6 | 11.3 | 4.7 | 4.6 | 4.8 | 4.2 | 4.3 | 4.4 | 5.0 | 4.4 |
| W | 0.4 | 1.4 | 0.7 | .1 | * | .0 | 322 | 2.6 | 9.7 | 2.9 | 1.8 | 3.5 | 2.0 | 3.2 | 3.1 | 2.9 | 1.9 |
| NW | 0.2 | 1.0 | 0.4 | 0.1 | * | * | 204 | 1.7 | 9.0 | 1.1 | 1.1 | 2.7 | 1.7 | 1.5 | 2.1 | 2.2 | 1.5 |
| VAR | 0.0 | 0.0 | 0.0 | 0.0 | .0 | .0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| CALM | 1.1 | | | | | | 136 | 1.1 | 0.0 | 1.3 | 0.5 | 0.4 | 0.3 | 2.1 | 1.4 | 2.0 | 1.0 |
| TOT OBS | 806 | 4717 | 5166 | 753 | 37 | 2 | 11481 | | 11.9 | 1455 | 1411 | 1618 | 1409 | 1694 | 834 | 1552 | 1508 |
| TOT PCT | 6.5 | 40.3 | 46.2 | 6.7 | .3 | * | | 100.0 | | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

Table 5. Percentage frequency of wind direction by speed and by hours for Saipan. (U.S. Naval Weather Service Command 1971b).

| | Wind Speed (knots) | | | | | | | | | Hour (GMT) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WND DIR | 0-3 | 4-10 | 11-21 | 22-33 | 34-47 | 48+ | TOTAL OBS | PCT FREQ | MEAN SPD | 00 | 03 | 06 | 09 | 12 | 15 | 18 | 21 |
| N | 0.3 | 1.5 | 0.8 | 0.1 | * | .0 | 408 | 2.9 | 9.9 | 2.5 | 3.0 | 3.7 | 3.4 | 3.0 | 1.9 | 2.7 | 2.3 |
| NE | 0.8 | 8.0 | 13.5 | 2.6 | * | .0 | 3480 | 24.9 | 12.5 | 22.2 | 24.0 | 26.6 | 26.3 | 25.7 | 28.6 | 24.8 | 23.6 |
| E | 1.5 | 19.0 | 24.9 | 2.2 | * | .0 | 6765 | 47.7 | 12.0 | 49.3 | 48.2 | 45.2 | 45.7 | 48.6 | 45.8 | 46.2 | 50.0 |
| SE | 0.7 | 6.2 | 4.5 | 0.3 | * | .0 | 1723 | 11.9 | 10.6 | 12.8 | 12.4 | 10.5 | 11.2 | 11.5 | 12.6 | 12.3 | 12.1 |
| S | 0.6 | 2.4 | 1.5 | 0.4 | * | .0 | 724 | 4.8 | 9.6 | 5.2 | 4.4 | 5.4 | 4.9 | 4.0 | 4.7 | 5.4 | 4.9 |
| SW | 0.4 | 1.5 | 1.0 | 0.3 | * | .0 | 485 | 3.2 | 9.6 | 3.3 | 3.6 | 3.9 | 3.6 | 2.4 | 2.8 | 2.8 | 3.1 |
| W | 0.4 | 1.1 | 0.5 | 0.1 | * | .0 | 310 | 2.0 | 8.9 | 2.2 | 2.1 | 2.2 | 2.5 | 1.8 | 1.6 | 2.0 | 1.8 |
| NW | 0.3 | 0.8 | 0.3 | * | .0 | .0 | 203 | 1.4 | 8.8 | 1.3 | 1.6 | 1.5 | 1.6 | 1.1 | 1.0 | 1.7 | 1.0 |
| VAR | 0.0 | 0.0 | 0.0 | 0.0 | .0 | .0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| CALM | 1.2 | | | | | | 174 | 1.2 | 0.0 | 1.2 | 0.7 | 0.9 | 0.8 | 2.0 | 1.1 | 2.1 | 1.1 |
| TOT OBS | 923 | 5845 | -6633 | 849 | 26 | 0 | 14276 | | 11.9 | 1694 | 2369 | 1784 | 2084 | 1800 | 887 | 1544 | 2114 |
| TOT PCT | 6.2 | 40.4 | 47.1 | 6.1 | .2 | .0 | | 100.0 | | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

Table 6. Percentage frequency of wind direction by speed and by hour for Pagan. (U.S. Naval Weather Service Command 1971a).

| | Wind Speed (knots) | | | | | | | | | Hour (GMT) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WND DIR | 0-3 | 4-10 | 11-21 | 22-33 | 34-47 | 48+ | TOTAL OBS | PCT FREQ | MEAN SPD | 00 | 03 | 06 | 09 | 12 | 15 | 18 | 21 |
| N | 0.4 | 1.9 | 1.3 | .2 | .0 | .0 | 420 | 3.8 | 9.5 | 3.0 | 3.6 | 4.1 | 5.0 | 4.0 | 3.1 | 4.3 | 3.3 |
| NE | 0.9 | 8.8 | 12.7 | 2.7 | .1 | .0 | 2756 | 25.1 | 12.3 | 24.6 | 25.7 | 23.9 | 27.5 | 23.3 | 26.6 | 23.7 | 26.4 |
| E | 1.2 | 17.9 | 22.3 | 2.8 | .1 | .0 | 4736 | 44.3 | 12.3 | 45.5 | 42.5 | 44.9 | 43.2 | 43.3 | 45.9 | 42.5 | 45.9 |
| SE | 0.9 | 6.8 | 4.7 | 0.5 | * | .0 | 1365 | 12.8 | 10.7 | 14.0 | 13.5 | 12.4 | 11.5 | 13.1 | 12.3 | 14.2 | 11.9 |
| S | 0.6 | 2.6 | 1.9 | 0.4 | .1 | .0 | 607 | 5.7 | 10.3 | 6.4 | 6.5 | 7.1 | 5.8 | 5.3 | 4.3 | 4.9 | 5.2 |
| SW | 0.4 | 1.3 | 0.9 | 0.3 | .1 | .0 | 334 | 3.1 | 10.0 | 2.7 | 3.1 | 3.3 | 2.7 | 4.4 | 2.2 | 3.3 | 3.1 |
| W | 0.2 | 1.1 | 0.6 | 0.2 | * | .0 | 224 | 2.1 | 8.9 | 1.6 | 1.9 | 1.8 | 2.0 | 2.2 | 2.5 | 2.5 | 2.1 |
| NW | 0.2 | 1.0 | 0.3 | 0.1 | .0 | .0 | 175 | 1.6 | 8.2 | 1.5 | 1.9 | 1.4 | 1.8 | 1.8 | 1.3 | 1.3 | 1.8 |
| VAR | 0.0 | 0.0 | 0.0 | 0.0 | .0 | .0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| CALM | 1.4 | | | | | | 155 | 1.4 | 0.0 | 0.8 | 1.1 | 1.1 | .5 | 2.6 | 1.8 | 3.2 | 0.4 |
| TOT OBS | 670 | 4454 | 4840 | 780 | 32 | 0 | 10776 | | 11.9 | 1441 | 1134 | 1469 | 1355 | 1331 | 1224 | 1430 | 1392 |
| TOT PCT | 6.2 | 41.5 | 44.8 | 7.2 | .3 | .0 | | 100.0 | | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

Table 7. Rainfall characteristics (in inches) for Guam; records are for a 24-year period (EDIS 1981).

| Month | Normal | Monthly max. | Rainfall (in inches) Year | Monthly min. | Year | 24-hour max. | Year |
|---|---|---|---|---|---|---|---|
| Jan. | 5.16 | 20.39 | 1976 | 1.99 | 1964 | 6.26 | 1976 |
| Feb. | 4.26 | 14.79 | 1980 | 0.67 | 1960 | 9.24 | 1980 |
| Mar. | 2.94 | 16.94 | 1971 | 0.59 | 1965 | 3.55 | 1972 |
| Apr. | 4.03 | 19.55 | 1963 | 0.50 | 1965 | 6.37 | 1974 |
| May | 4.49 | 40.13 | 1976 | 0.90 | 1959 | 27.00 | 1976 |
| Jun. | 5.19 | 11.53 | 1958 | 1.52 | 1969 | 4.55 | 1958 |
| Jul. | 9.59 | 20.00 | 1972 | 4.74 | 1957 | 5.17 | 1969 |
| Aug. | 12.16 | 25.66 | 1974 | 3.87 | 1965 | 7.81 | 1971 |
| Sep. | 14.08 | 24.34 | 1980 | 6.79 | 1969 | 7.48 | 1965 |
| Oct. | 14.40 | 26.05 | 1979 | 6.63 | 1976 | 10.14 | 1979 |
| Nov. | 8.51 | 18.14 | 1957 | 2.08 | 1973 | 7.26 | 1957 |
| Dec. | 5.85 | 16.19 | 1963 | 2.22 | 1977 | 6.09 | 1963 |
| Year | 90.66 | 40.13 | 1976 | 0.50 | 1965 | 27.00 | 1976 |
| | | | May | | Apr. | | May |

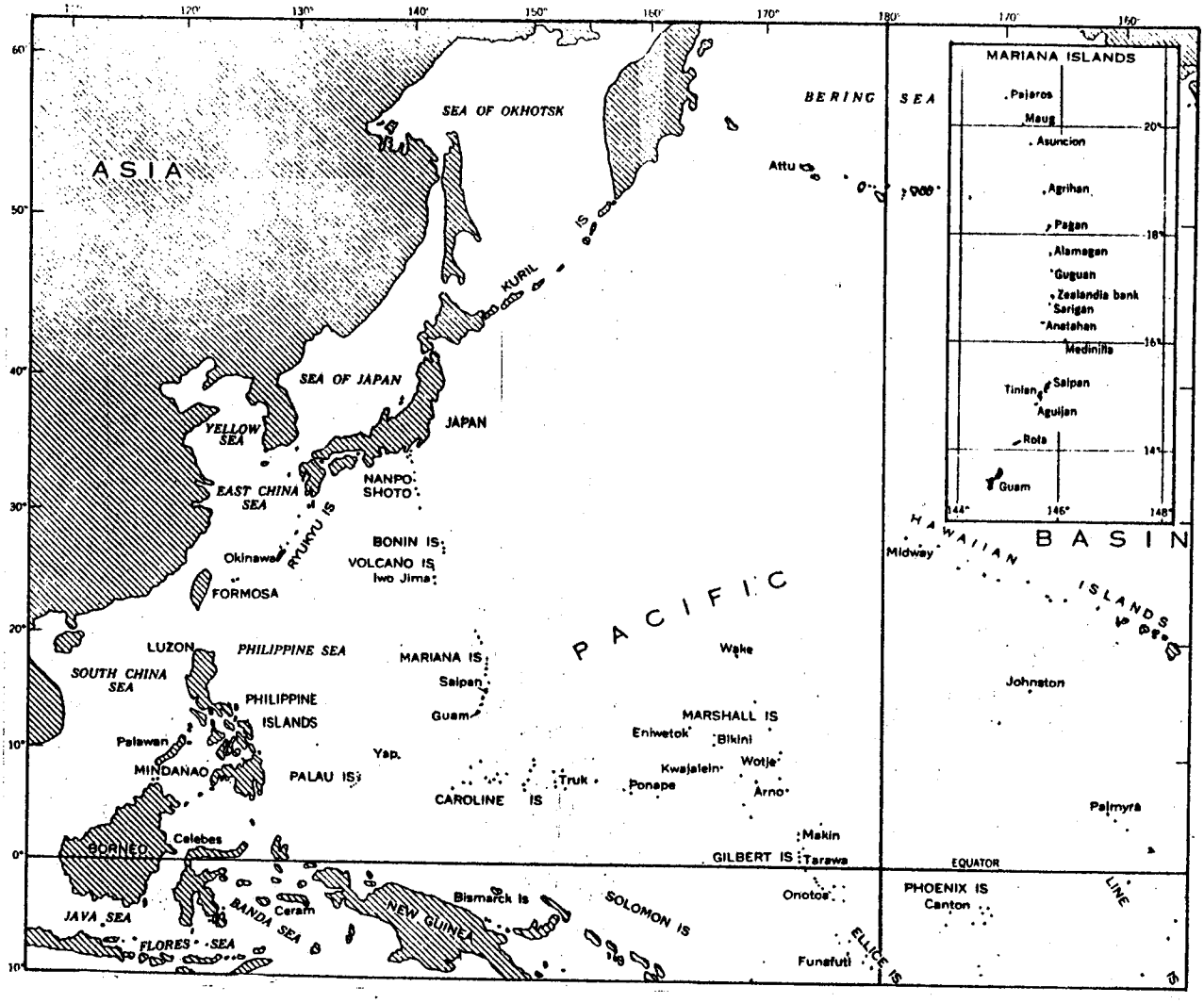



Figure 1.--Index map of the western Pacific Ocean showing the location of Guam and the Mariana Islands (Tracey et al. 1964).

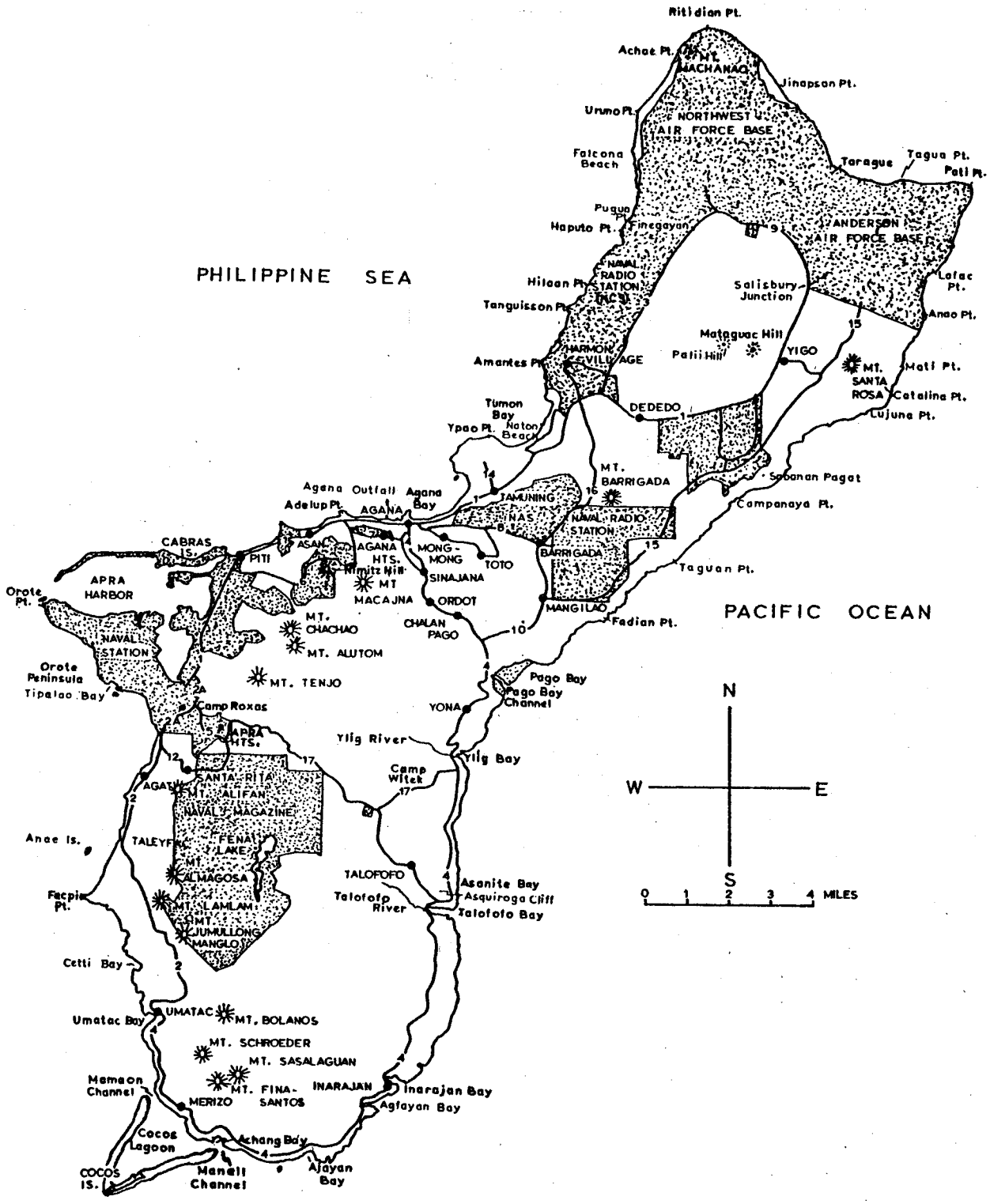



Figure 2.--General location map of Guam, showing military reservation boundaries, major highways, villages, mountains, and other place names (Randall and Holloman 1974).

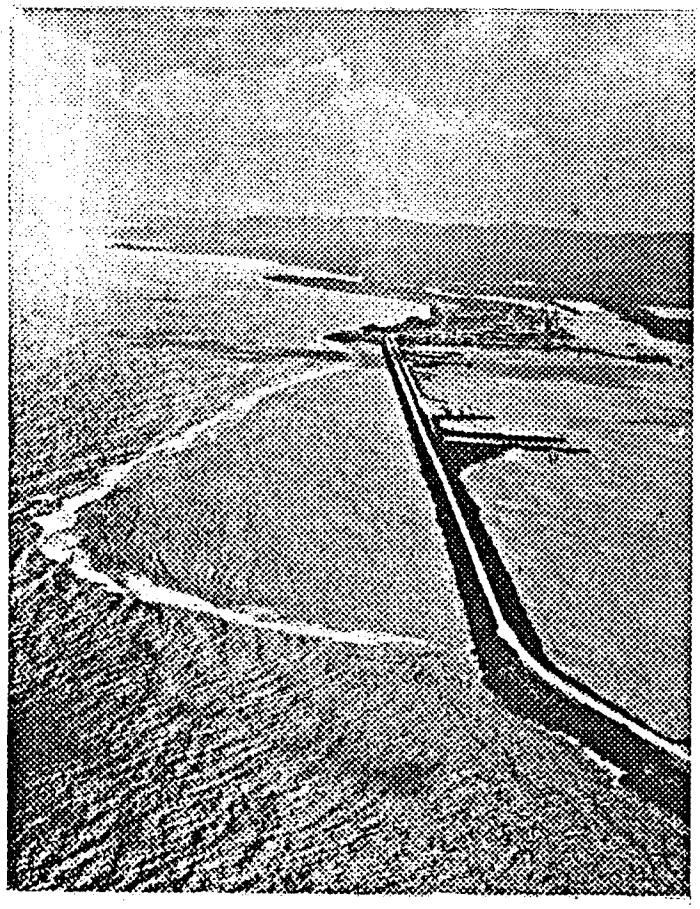


Figure 3.--Luminao Barrier Reef and Glass Breakwater at Apra Harbor, Guam.

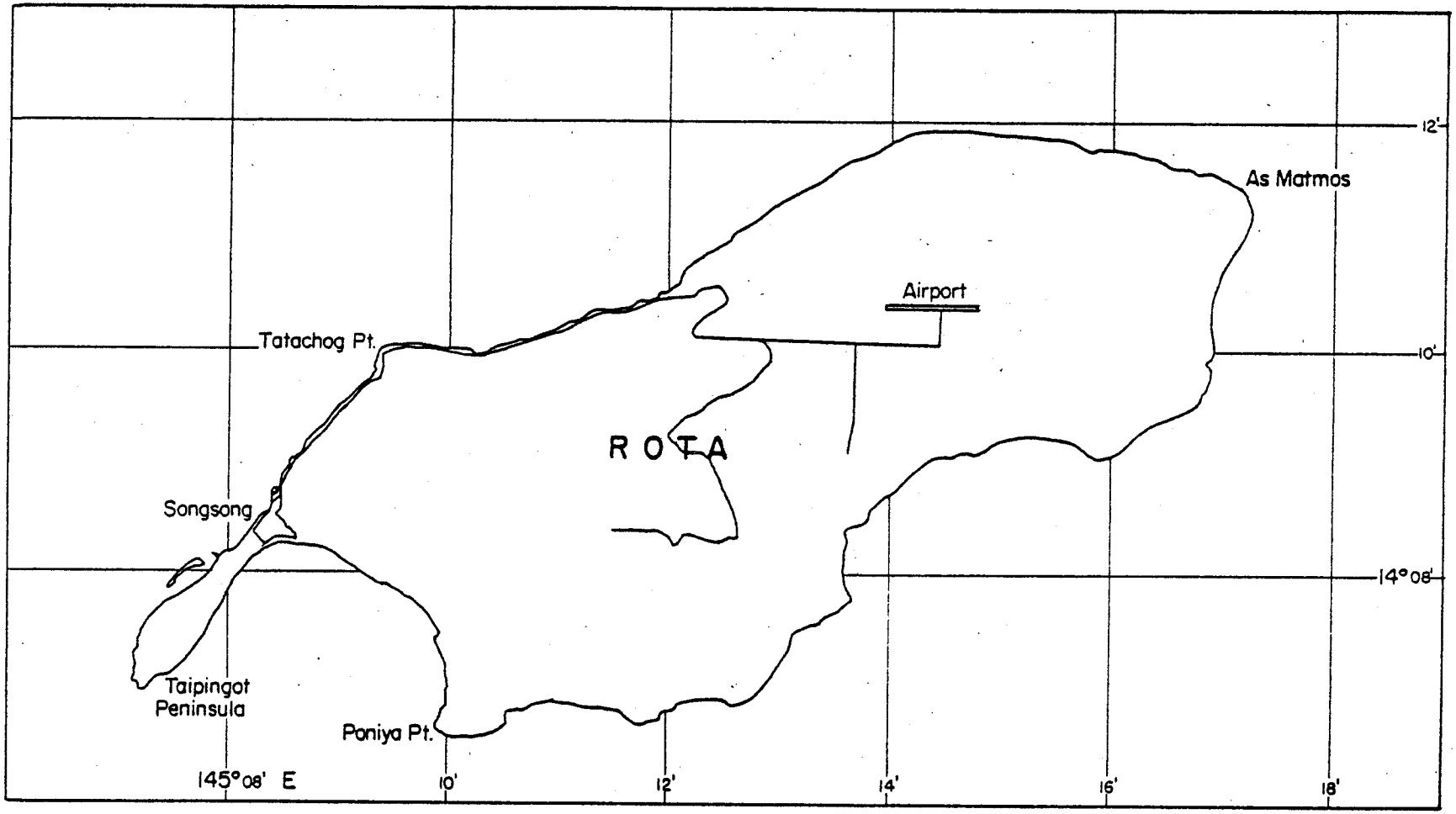



Figure 4.--Index map of Rota.

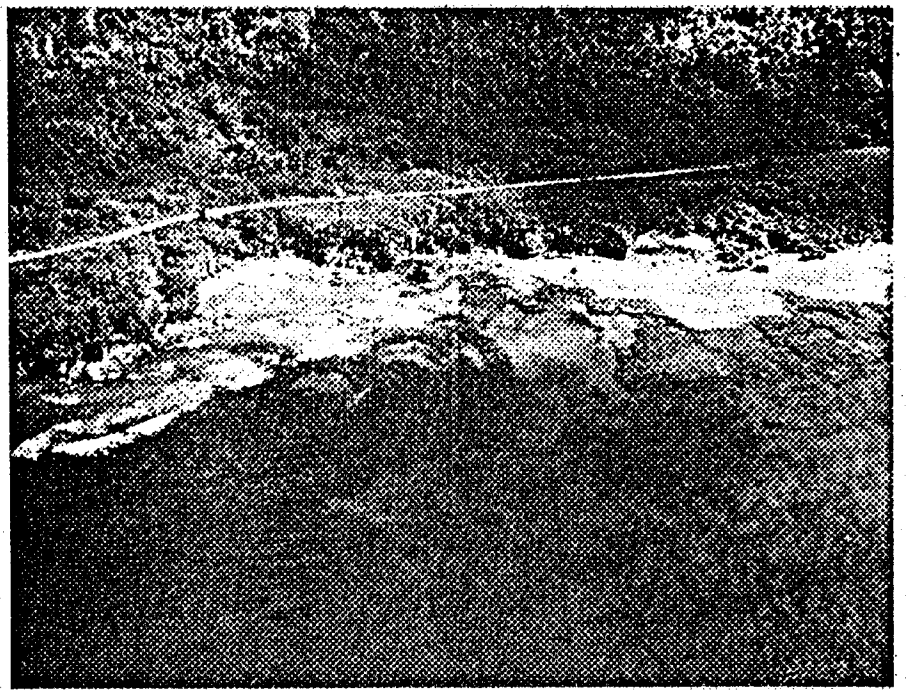


Figure 5.--Eastern side of Sasanhaya, Rota.

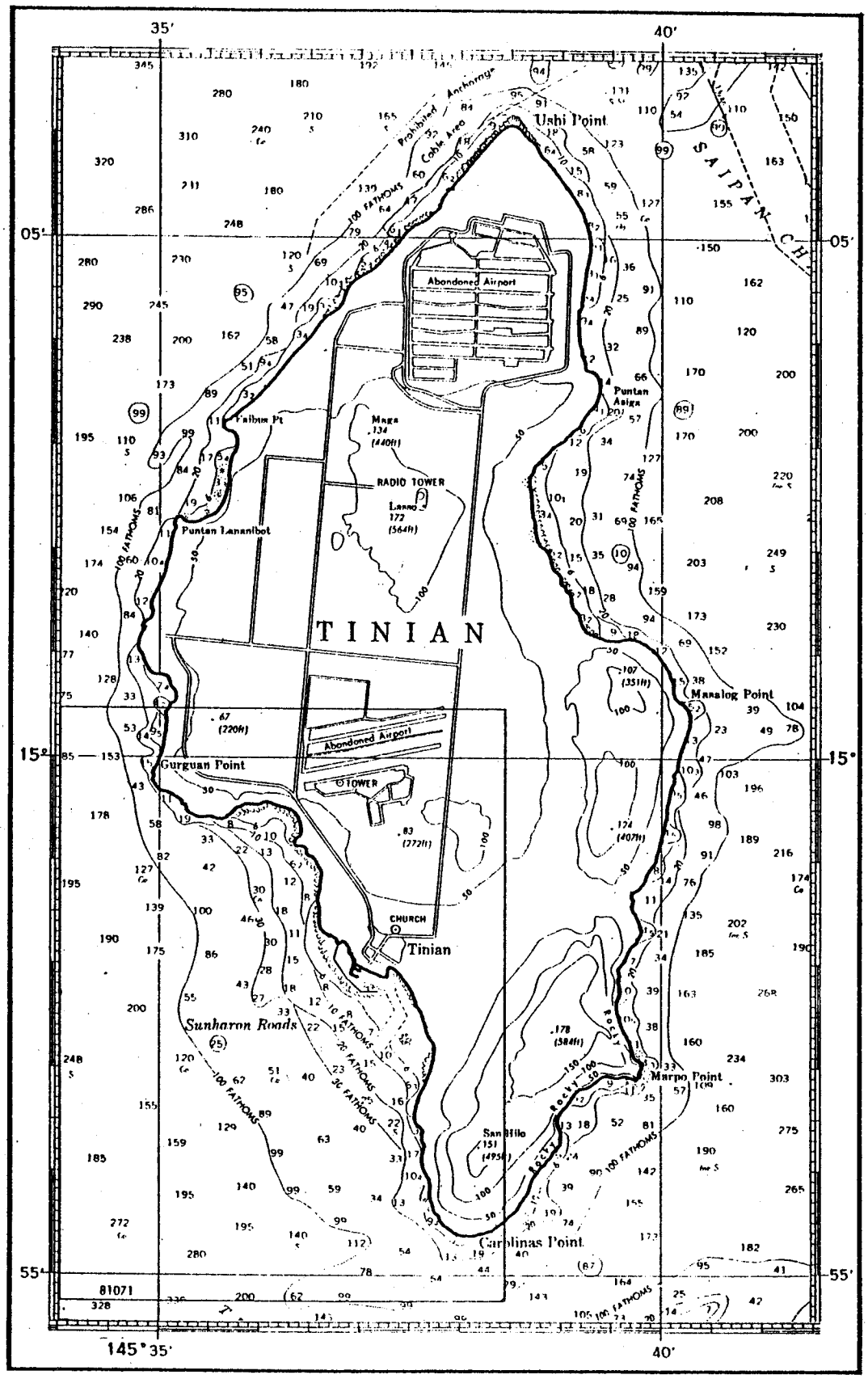



Figure 6.--Index map of Tinian.

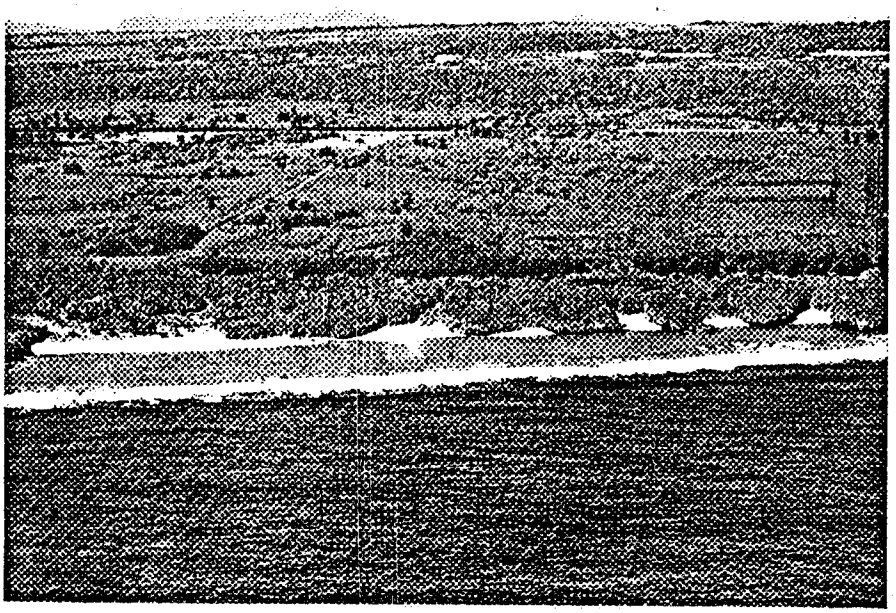


Figure 7.--Unai Dankulü, Tinian.

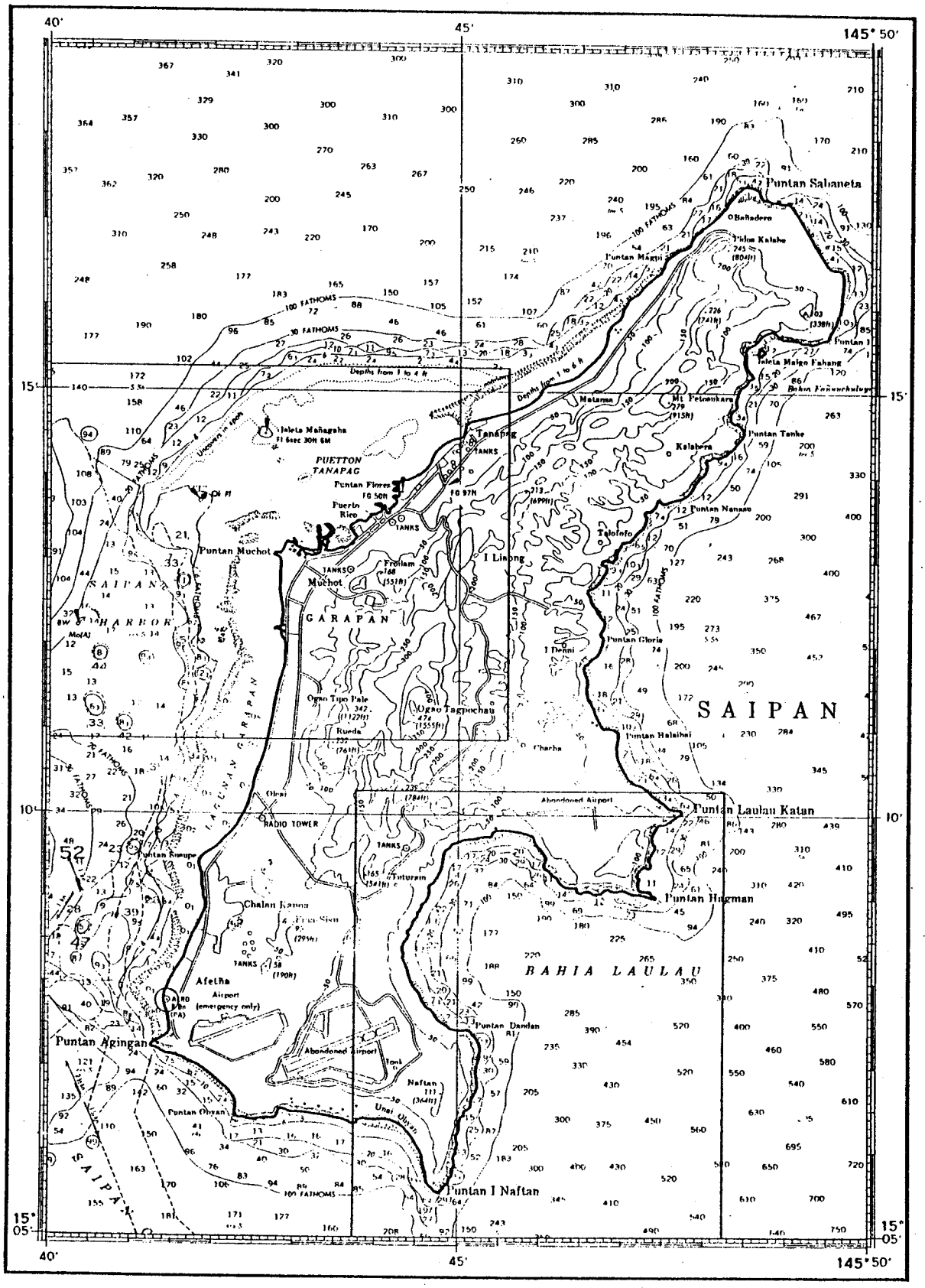



Figure 8.--Index map of Saipan.

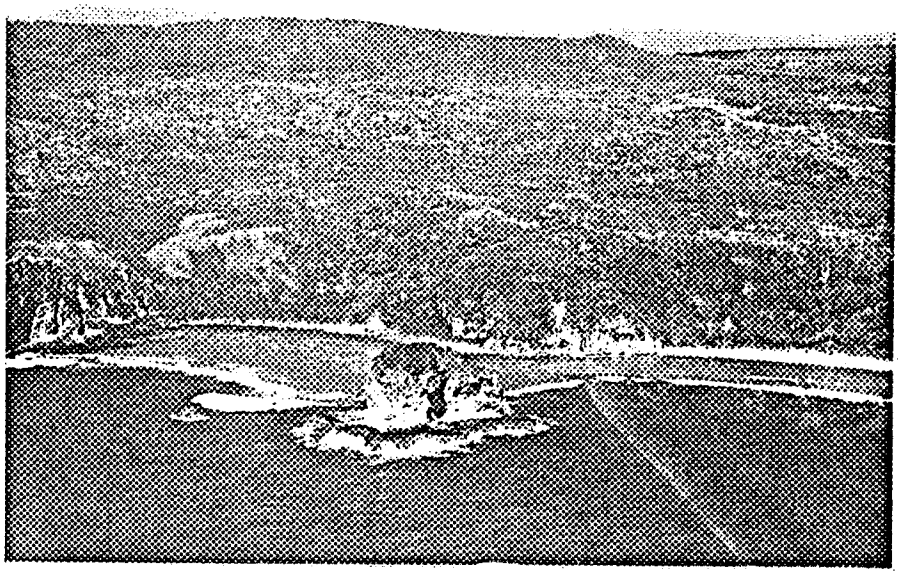


Figure 9.--Isleta Maigo Fahang (Bird Island), Saipan.

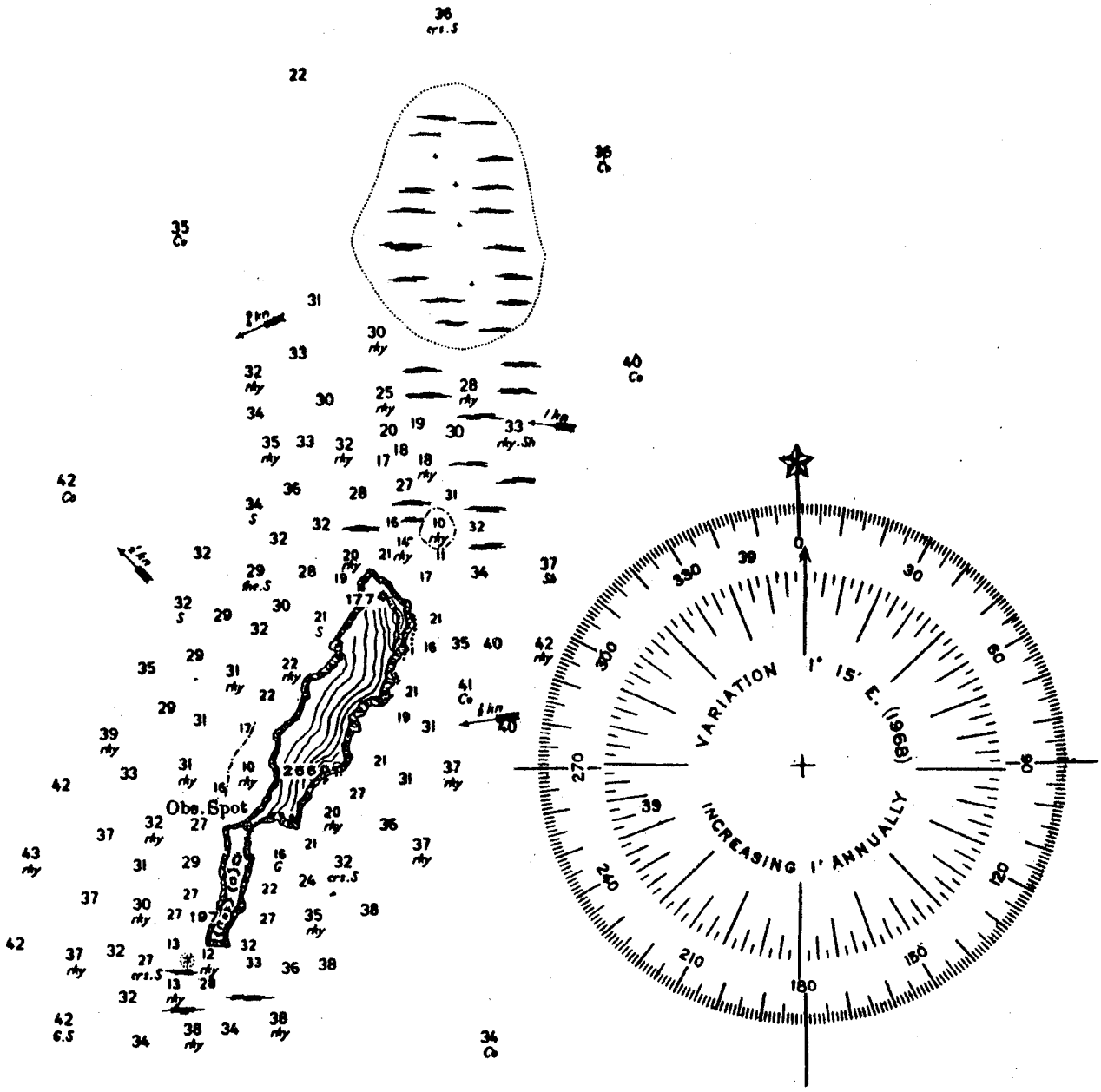



Figure 10.--Index map of Parallon de Medinilla.

Figure 11.--Surface discoloration at Esmeralda, April 1975 (photo by R. Ronck).

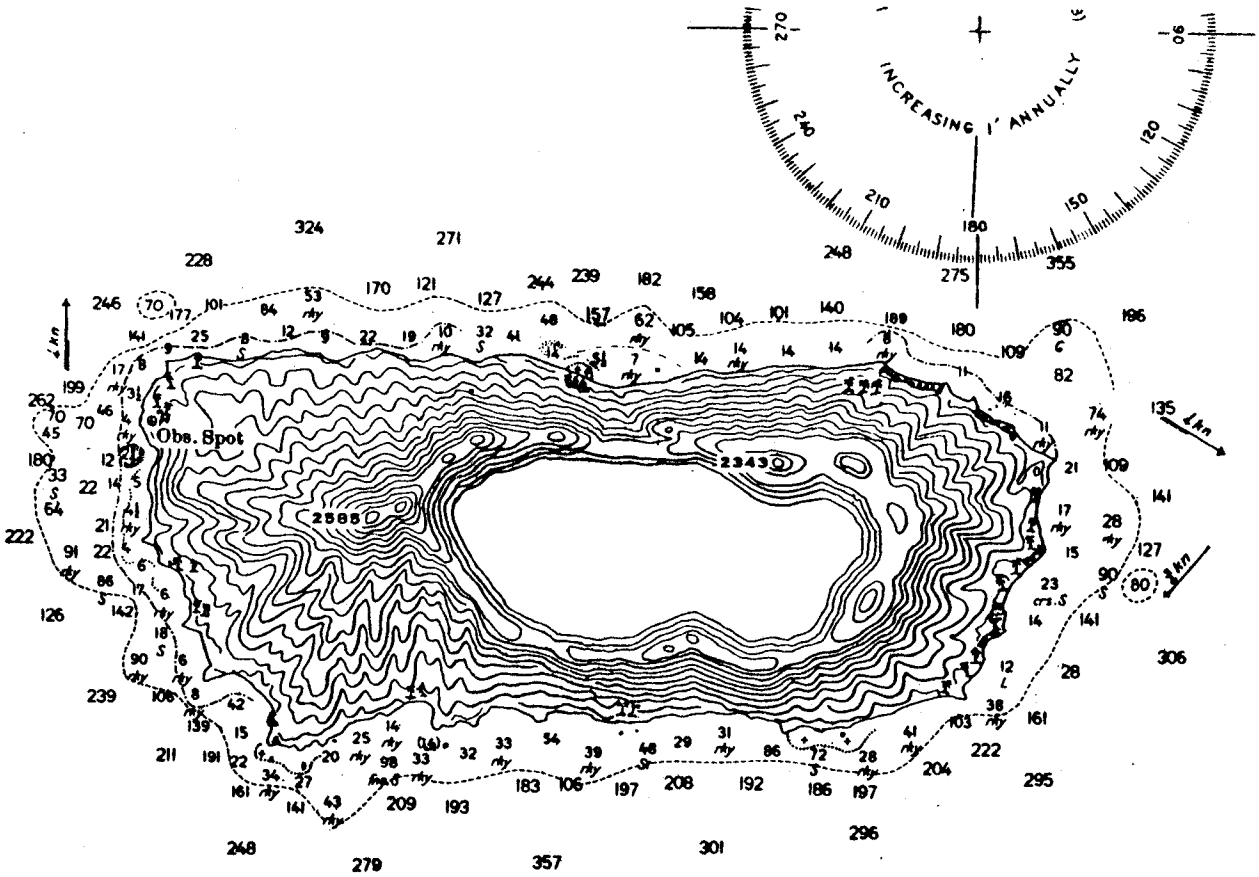



Figure 12.--Index map of Anatahan.

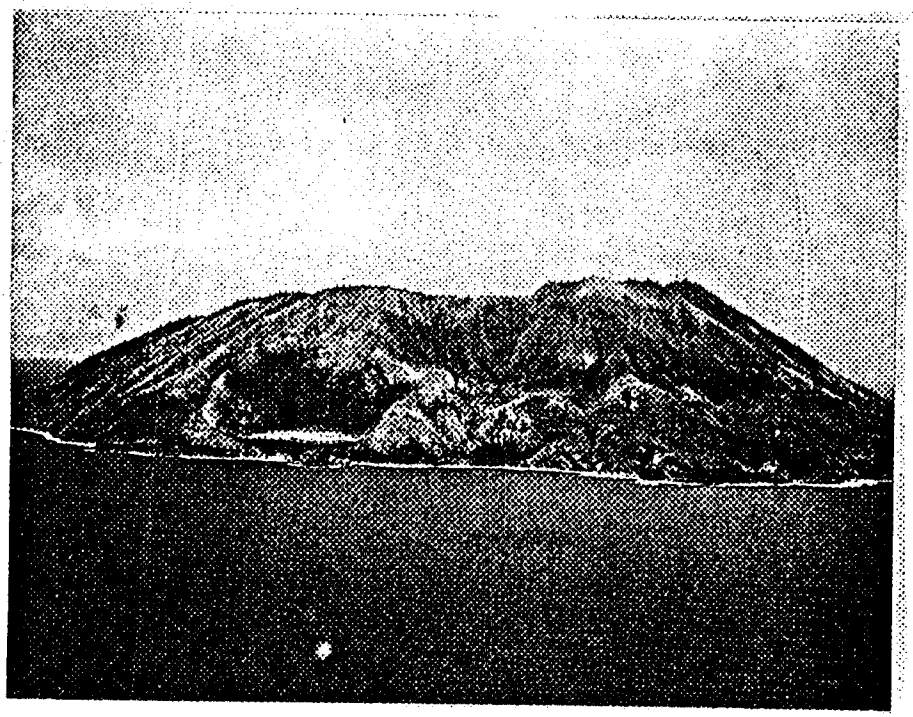


Figure 13.--Aerial photograph of Anatahan.

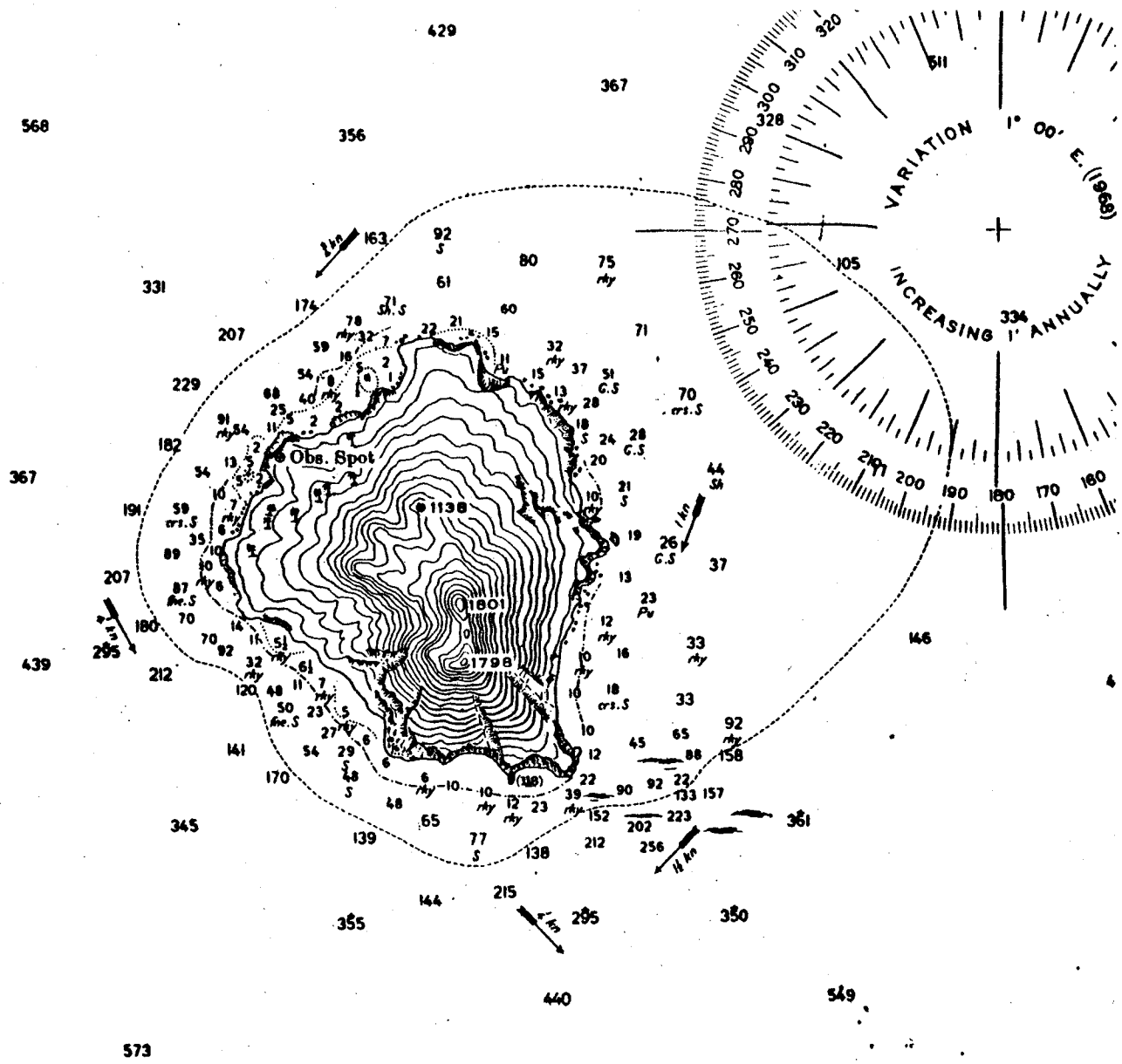



Figure 14.--Index map of Sarigan.

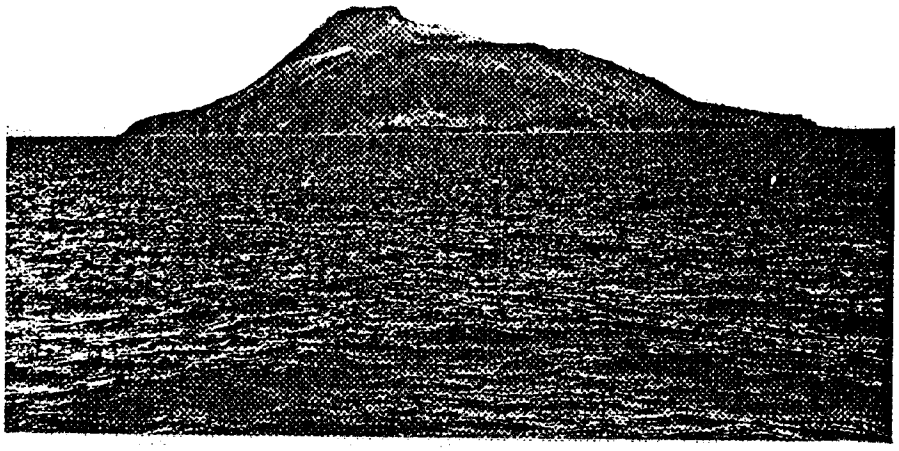


Figure 15.--Sarigan.

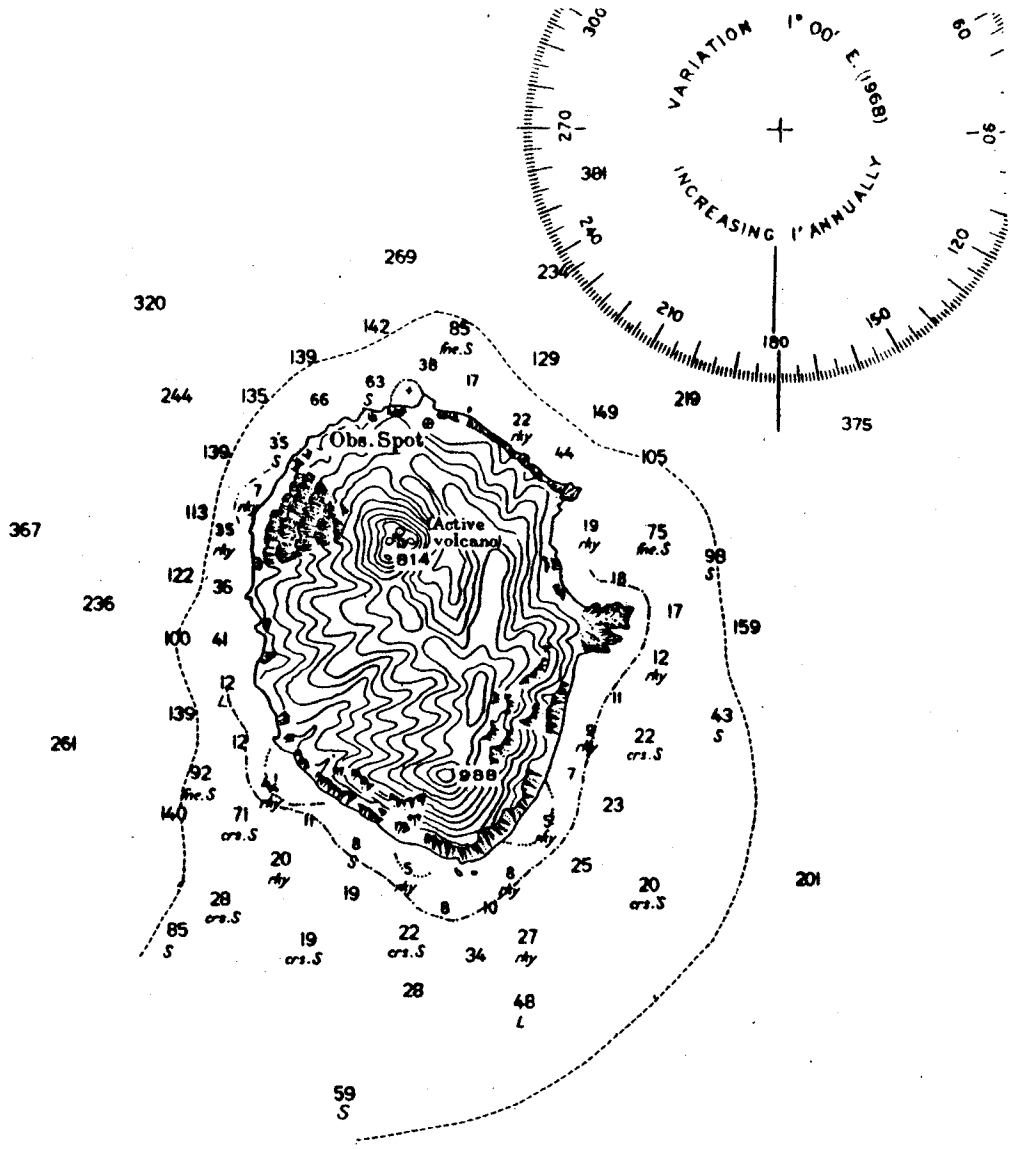



Figure 16.--Index map of Guguan.

Figure 17.--Aerial photograph of northern end of Guguan.

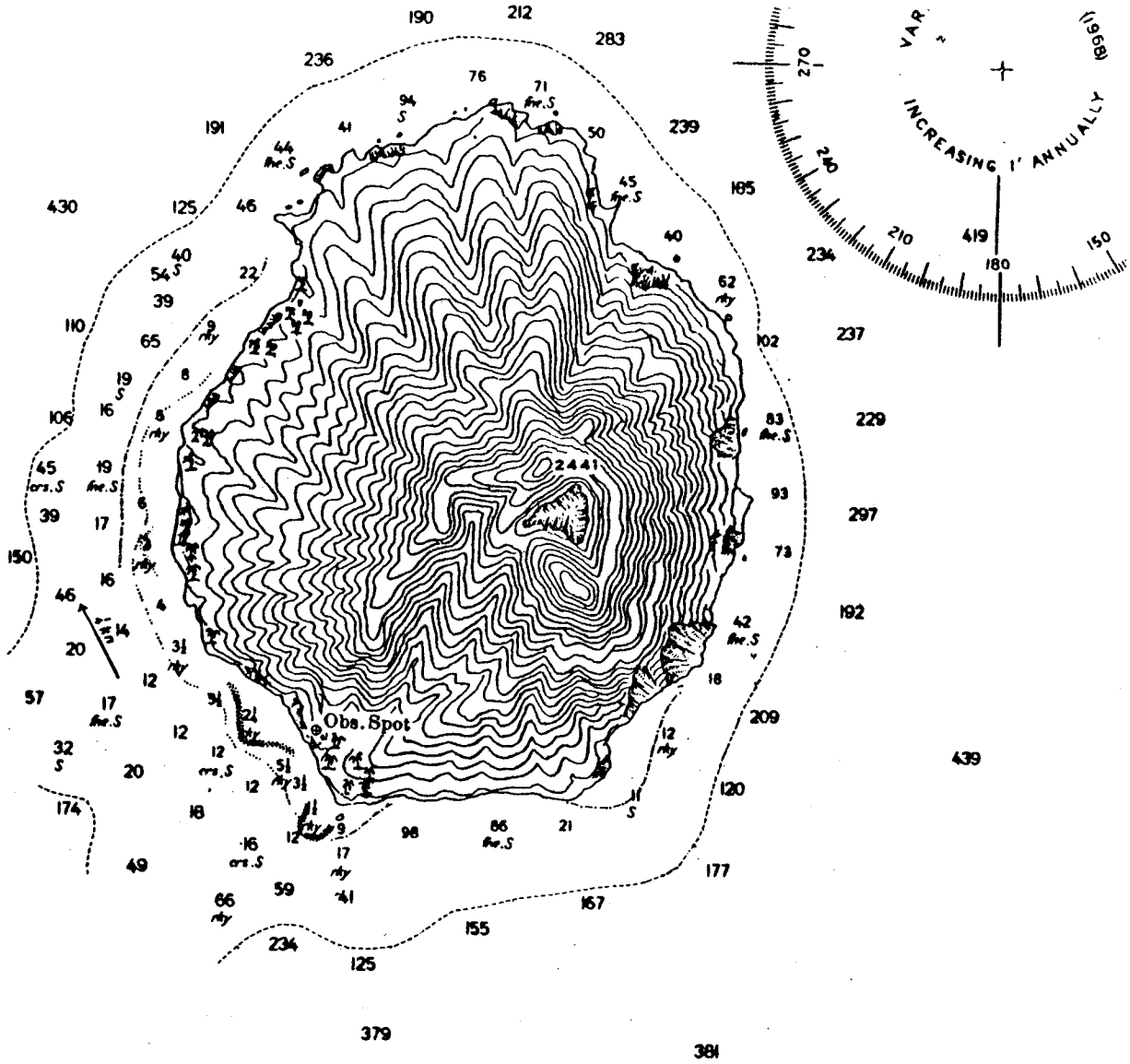



Figure 18.--Index map of Alamagan.

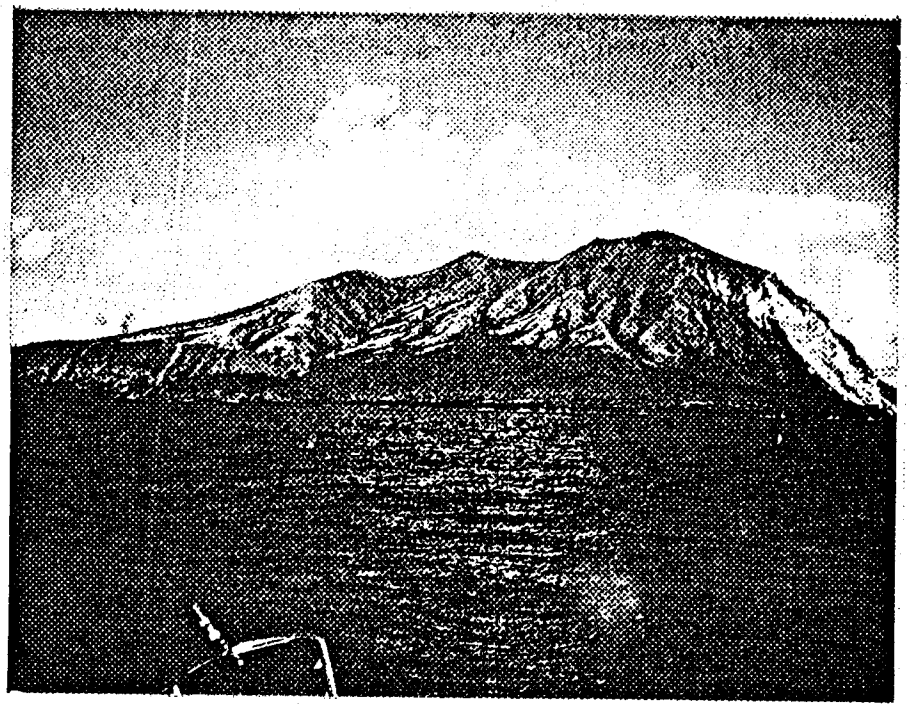
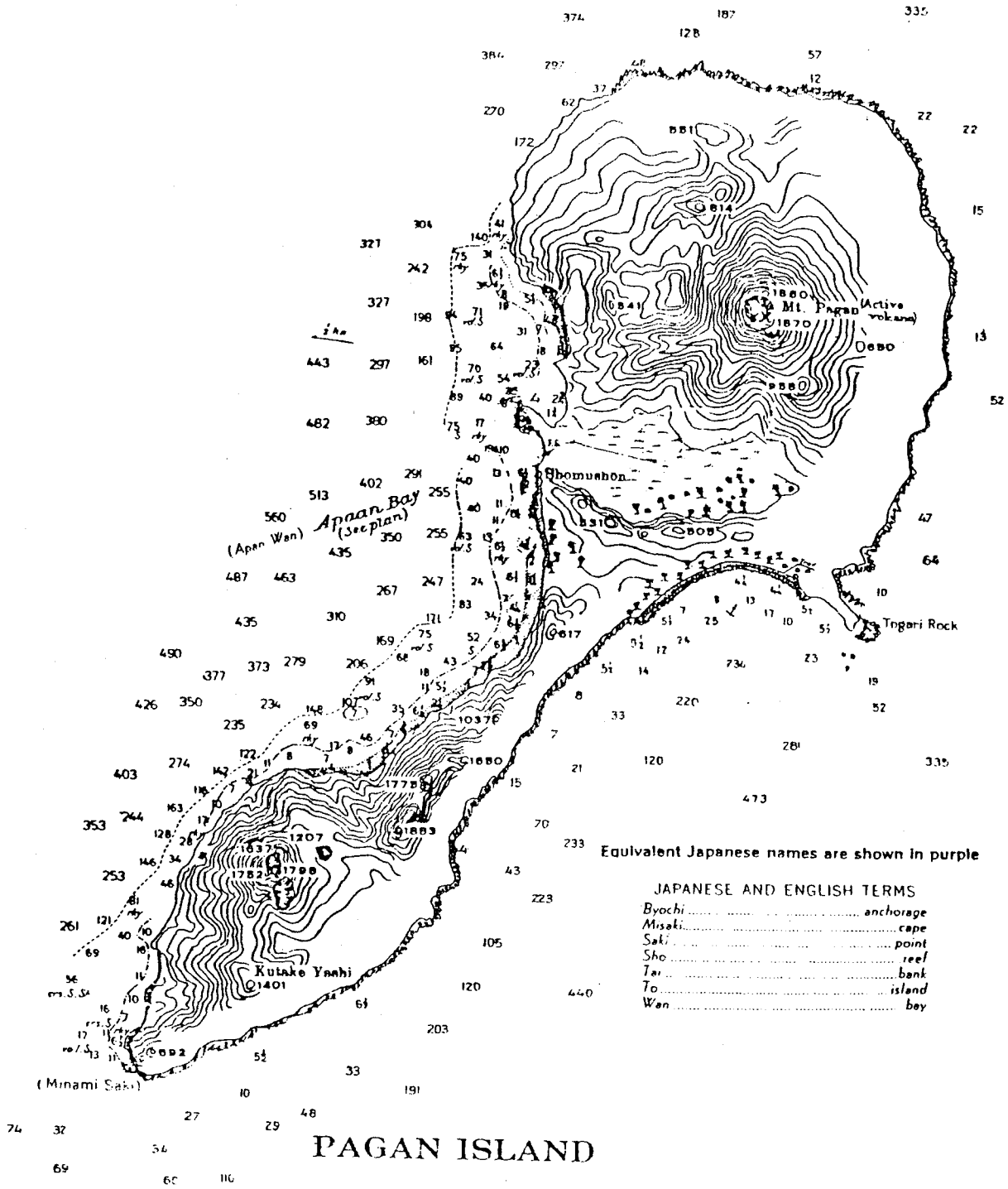


Figure 19.--West coast of Alamagan.




PAGAN ISLAND

Figure 20.--Index map of Pagan.

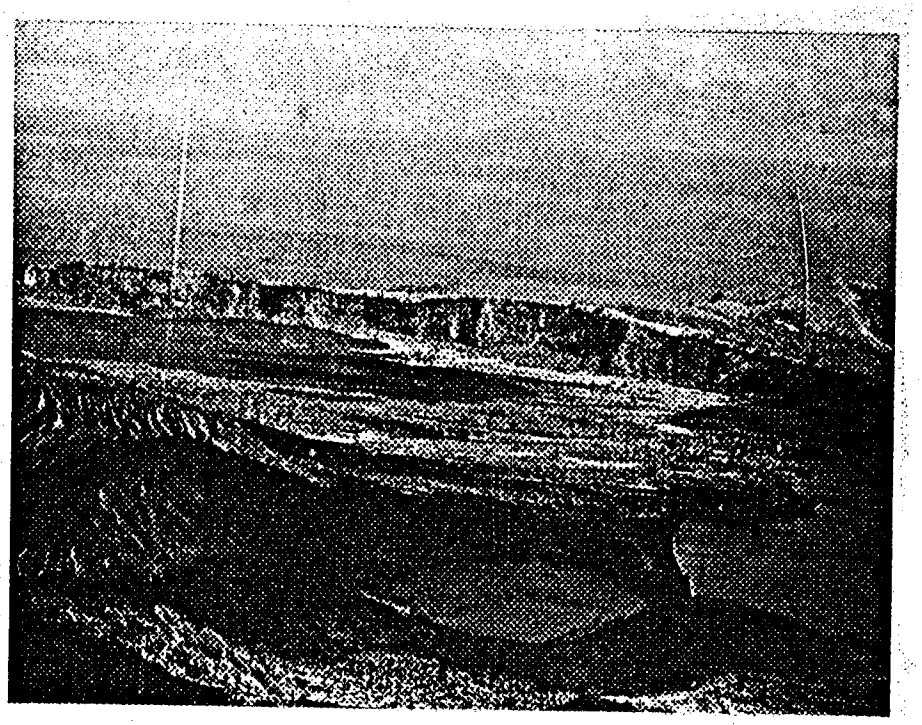


Figure 21.--Aerial photograph of northern Pagan showing the outer lake and the caldera rim; dark area in center is lava flow from May-1981 eruption (U.S. Navy photo).

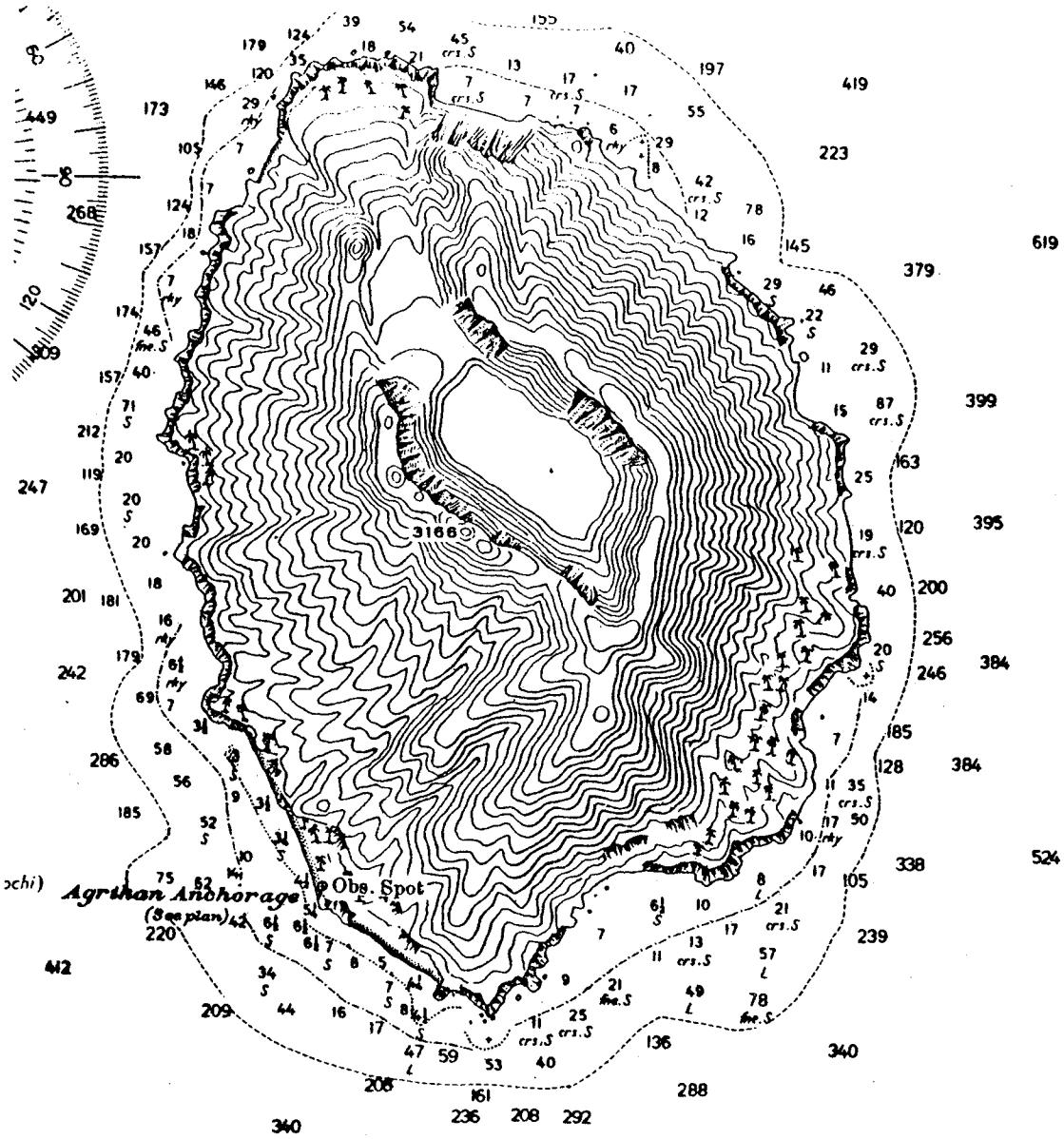



Figure 22.--Index map of Agrihan.

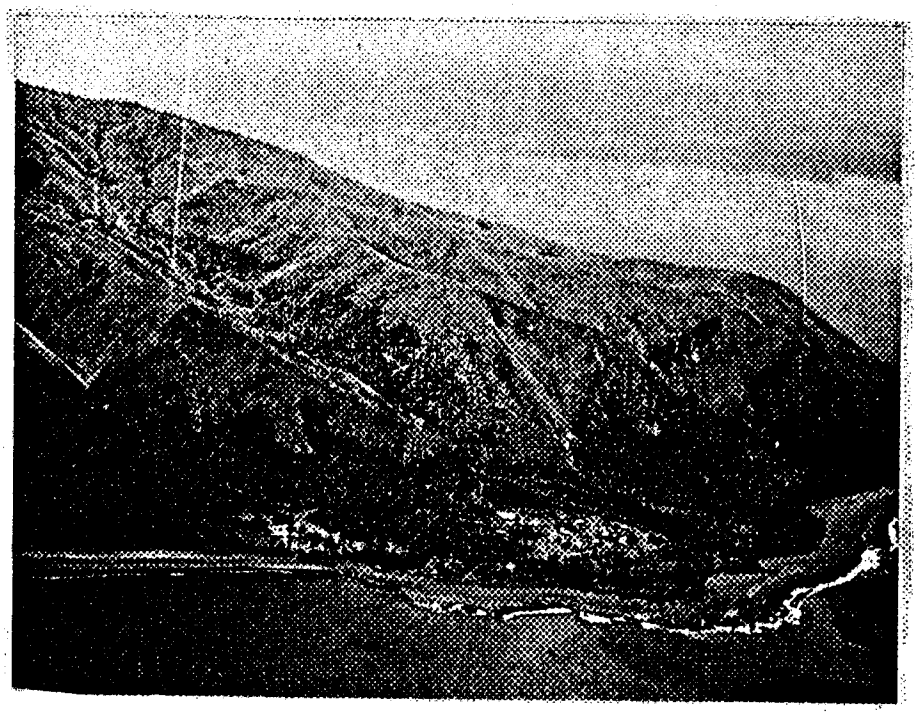


Figure 23.--Village area at southwest corner of Agrihan.

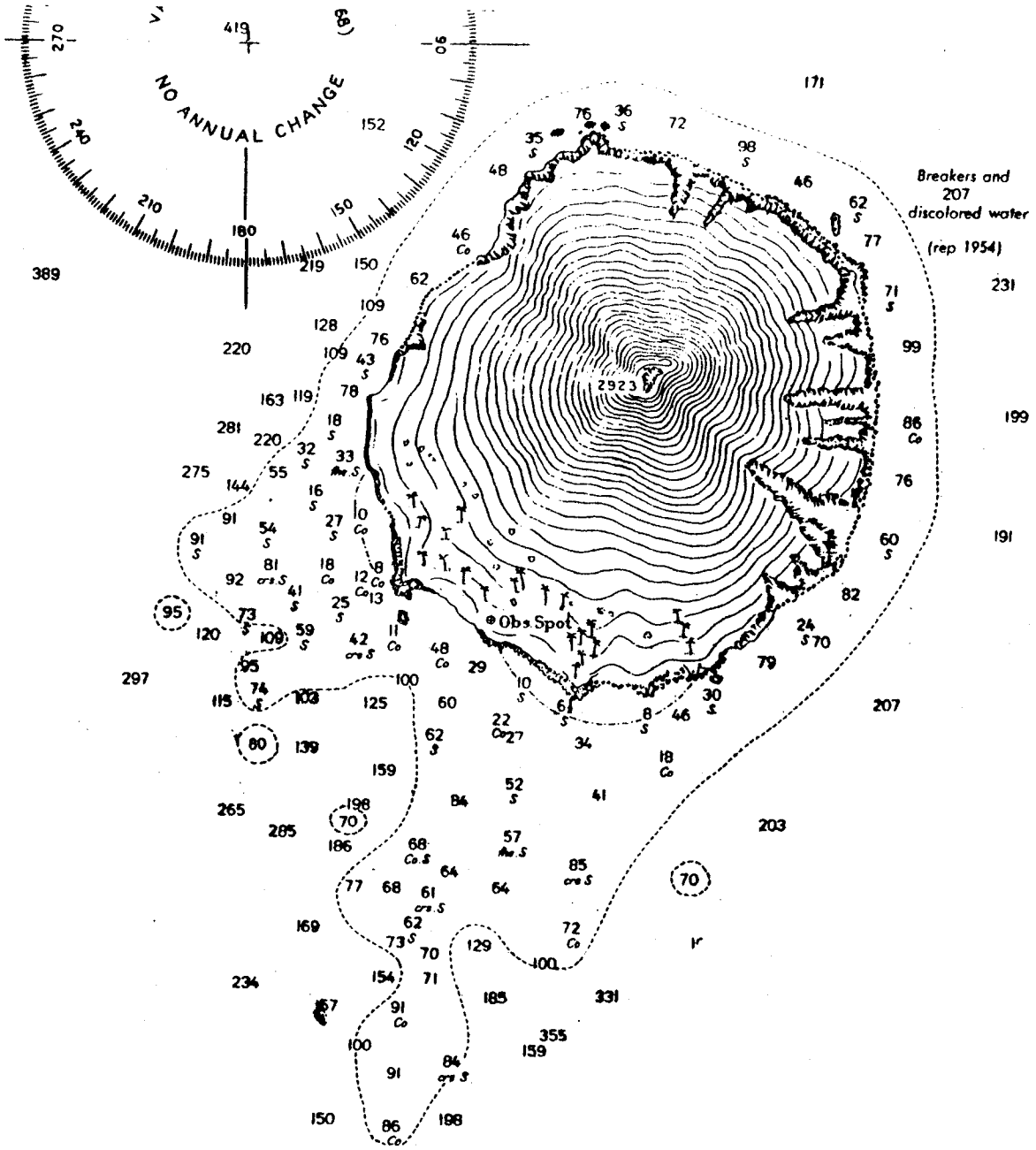



Figure 24.--Index map of Asuncion.

Figure 25.--West slope of Asuncion with inverted chevron of lava from 1906 flow.

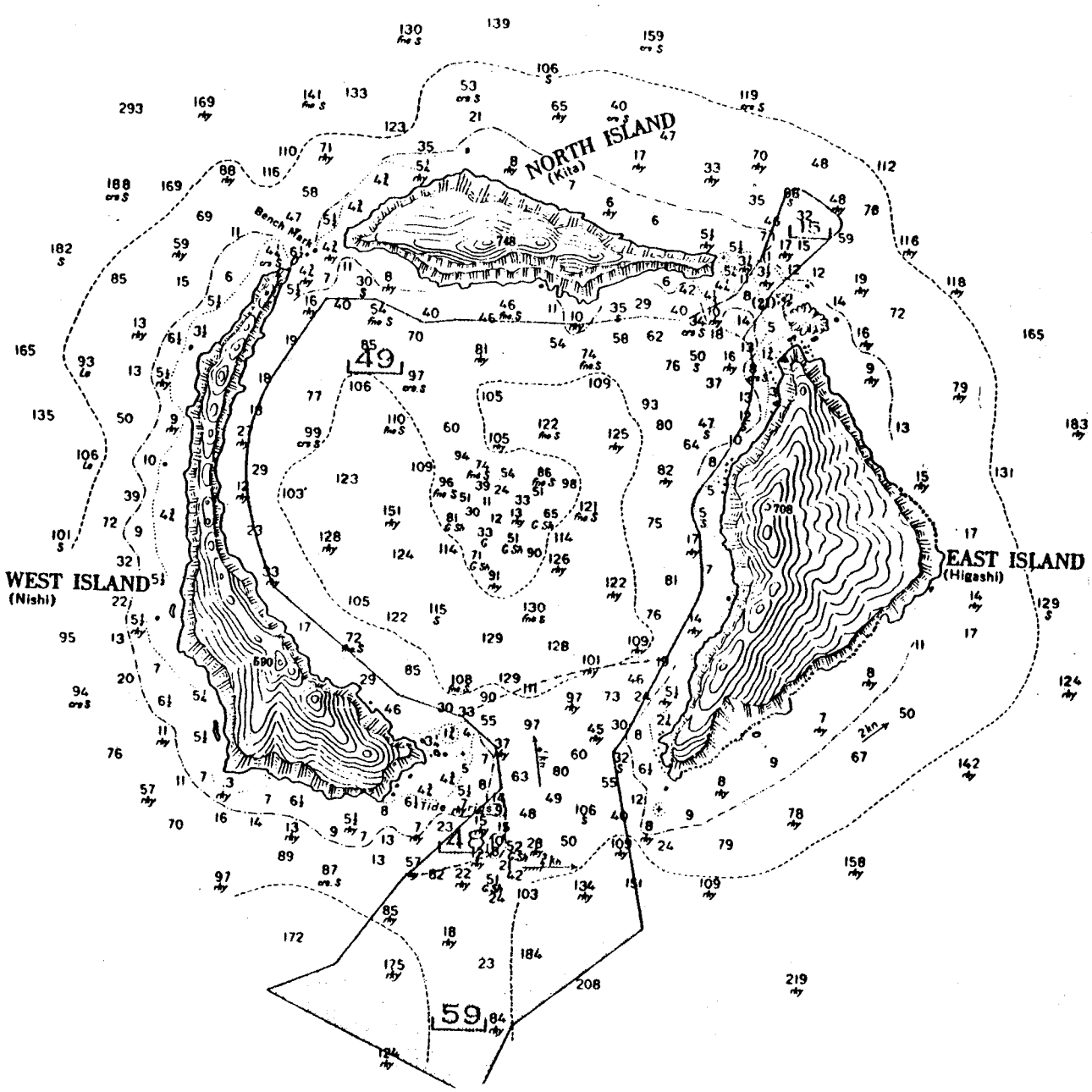



Figure 26.--Index map of Maug.

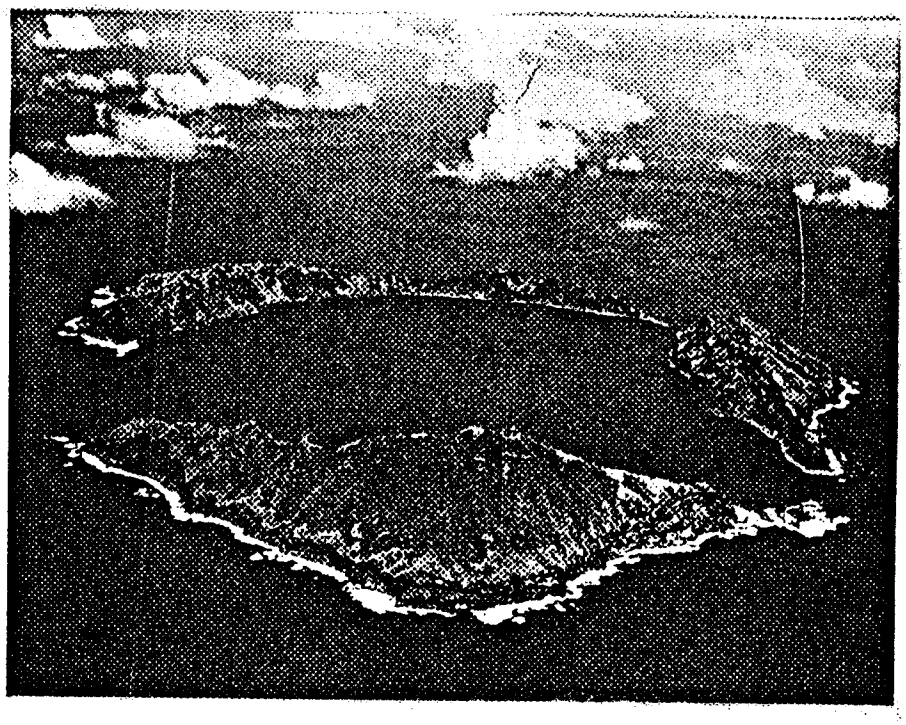


Figure 27.--Aerial photograph of Maug from the east.

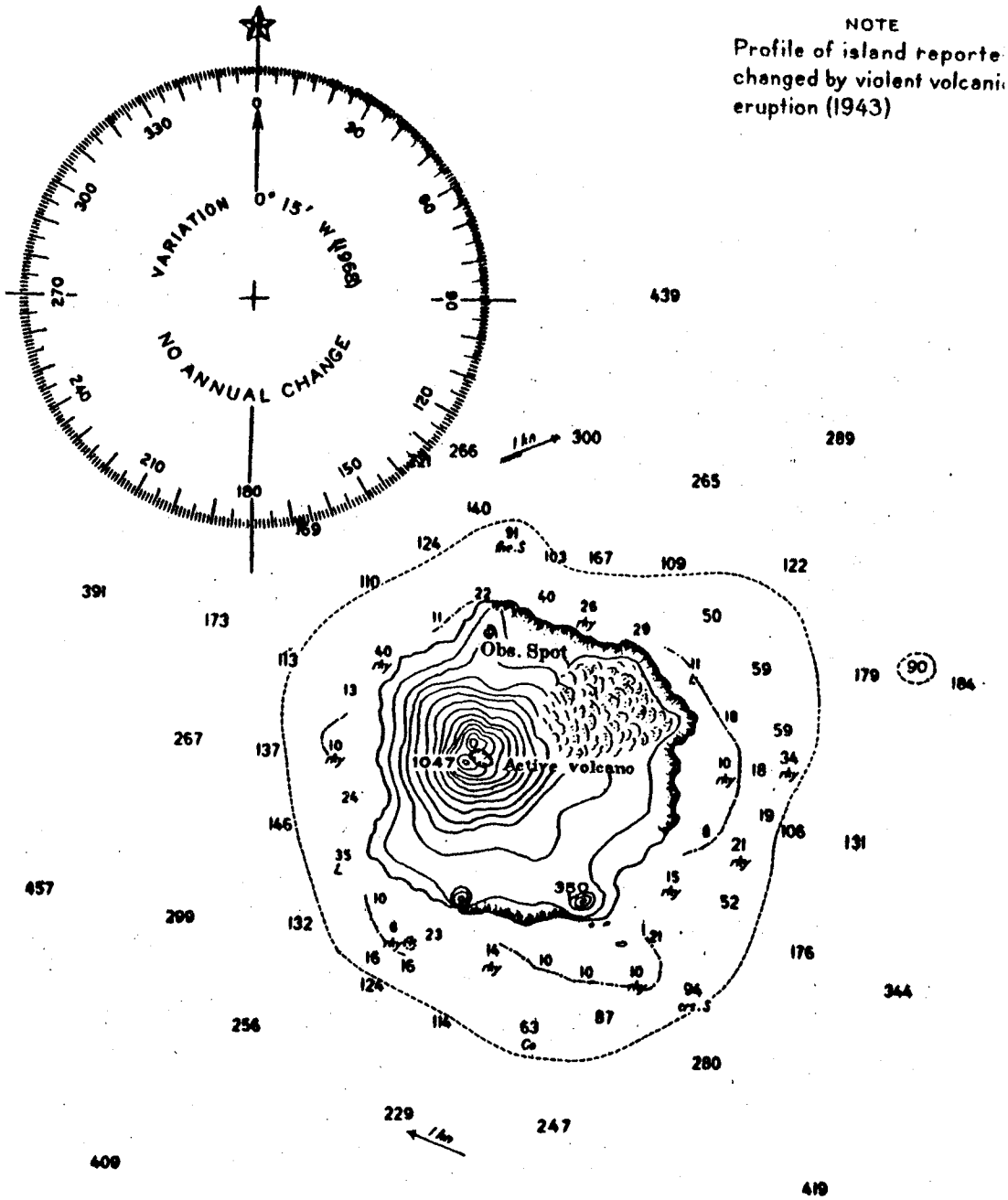



Figure 28.--Index map of Uracas (or Farallon de Pajaros).

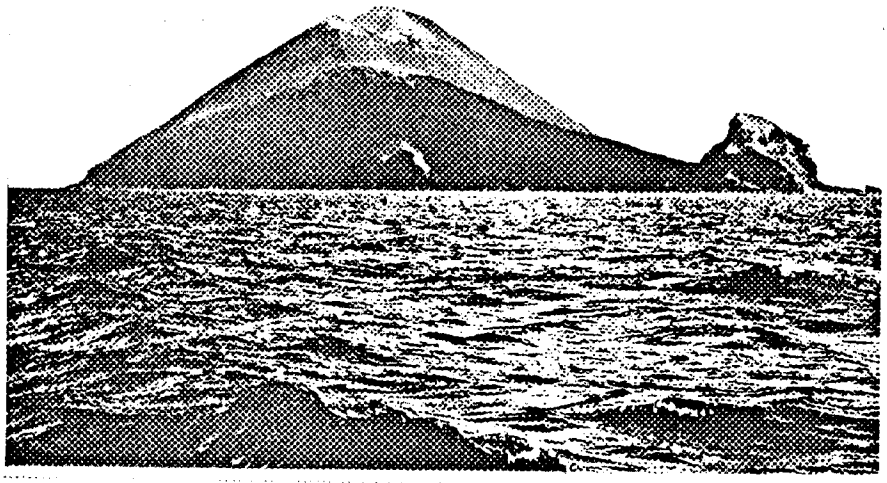


Figure 29.--Profile of Uracas from the west.

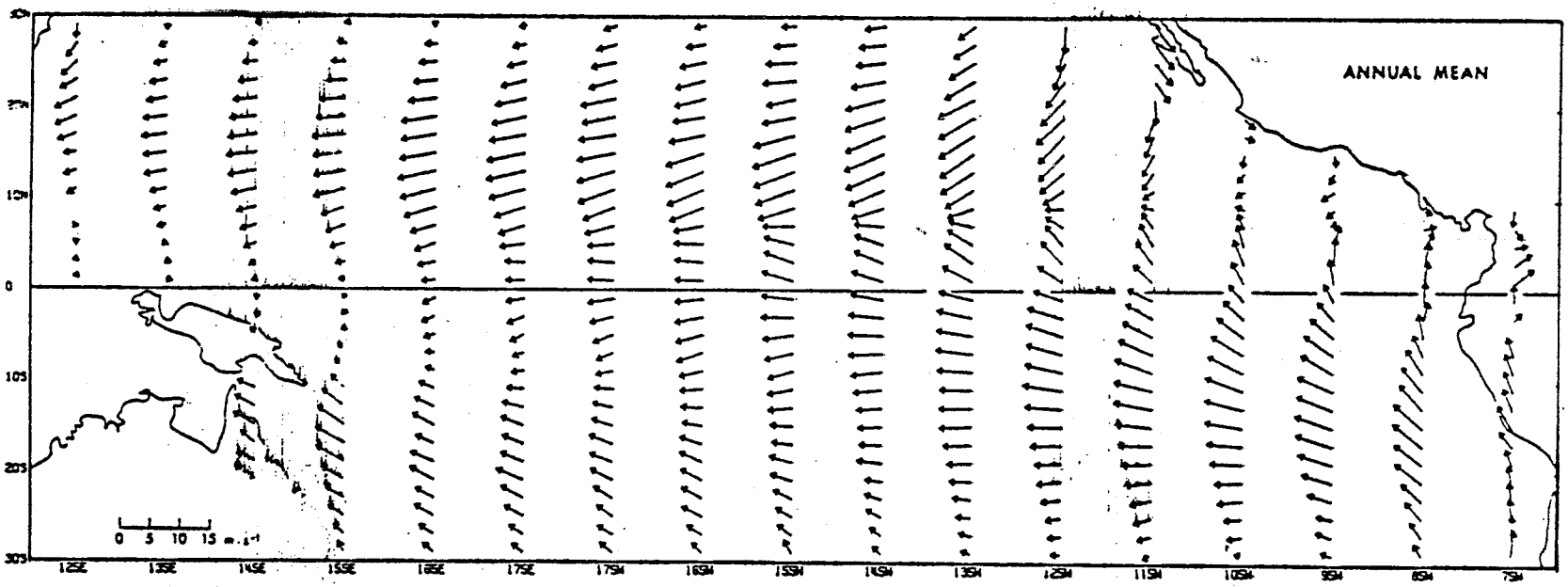



Figure 30.--Annual mean surface wind velocity (from Wyrtki and Meyers 1975).

Symbols shown on charts 3 to 7

Prevailing winds move with the arrows
Direction and frequency:

81 percent or more

61 to 80 percent

41 to 60 percent

25 to 40 percent

Average velocity:

indicates predominance of Beaufort 0–3 (0 to 10 knots), indicates stronger winds, Beaufort 4 (11 to 16 knots) and higher, dominant 60% or more of the time.

CHART 3.—February.

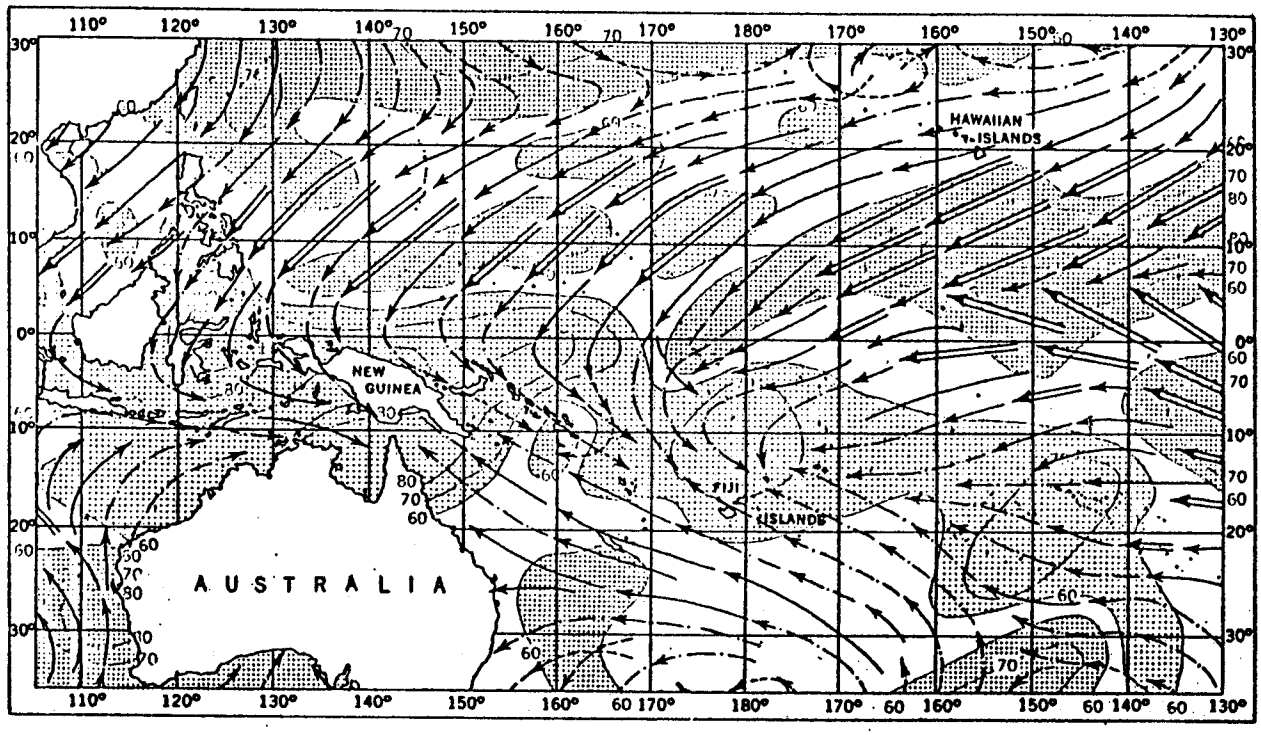



Figure 31.--Average surface wind drift direction, constancy, and force (from U.S. Weather Bureau 1943).

CHART 4.—May.

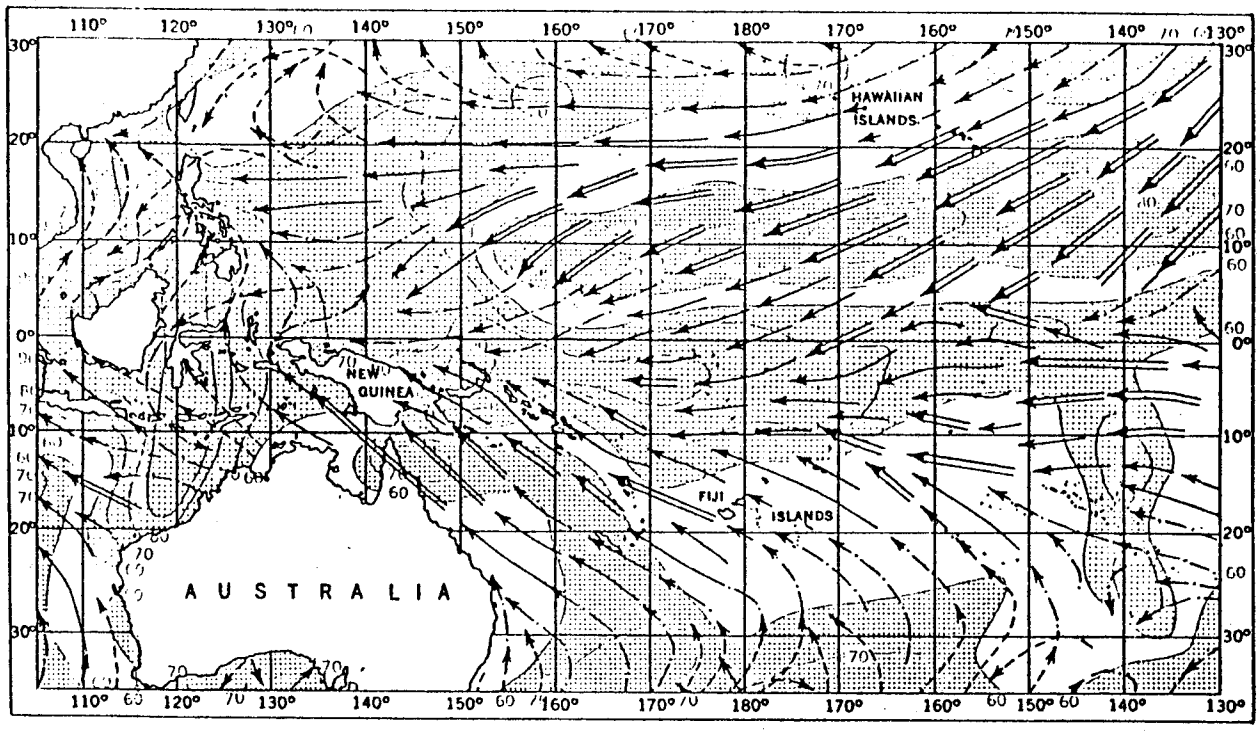



CHART 5.—July.

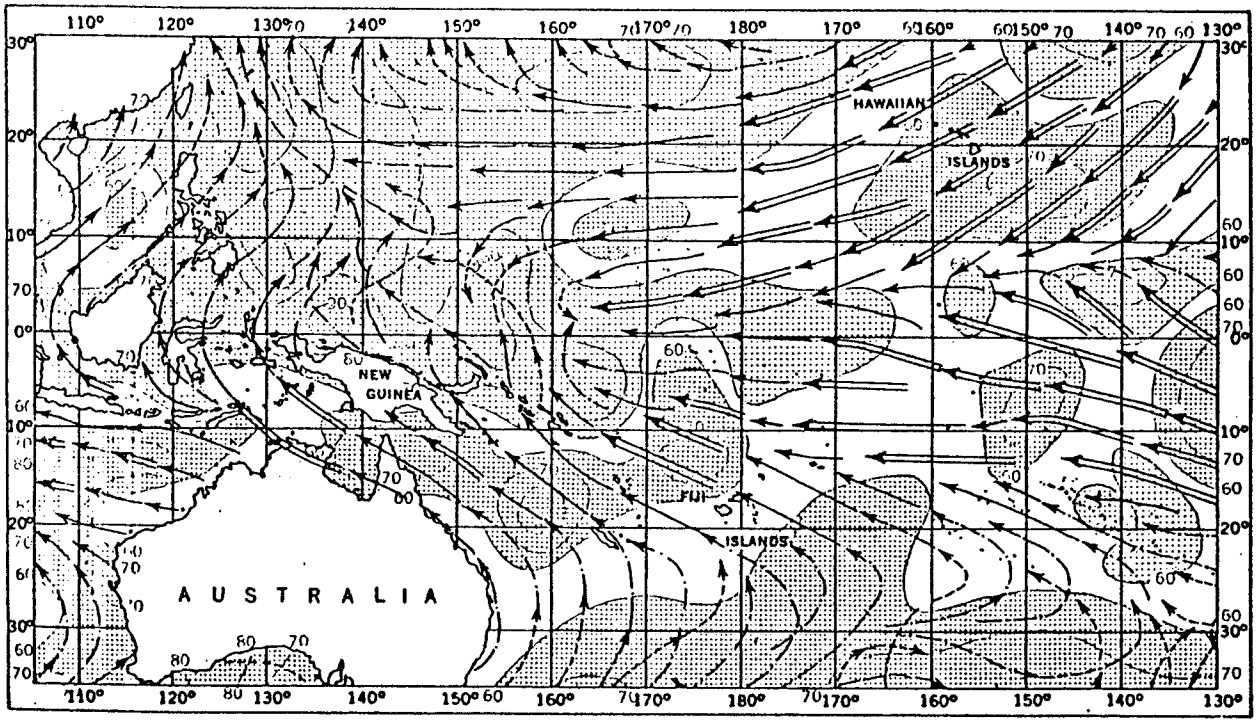



Figure 31 (continued).

CHART 6.—October.

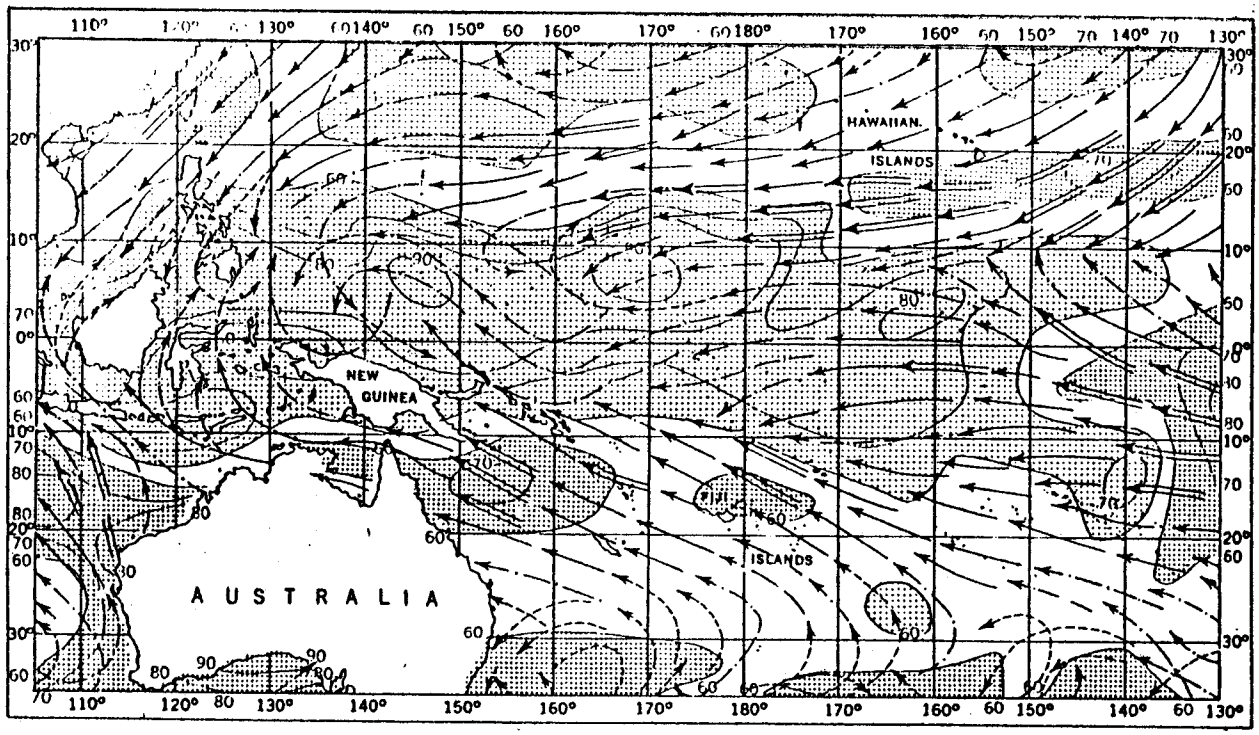



CHART 7.—December.

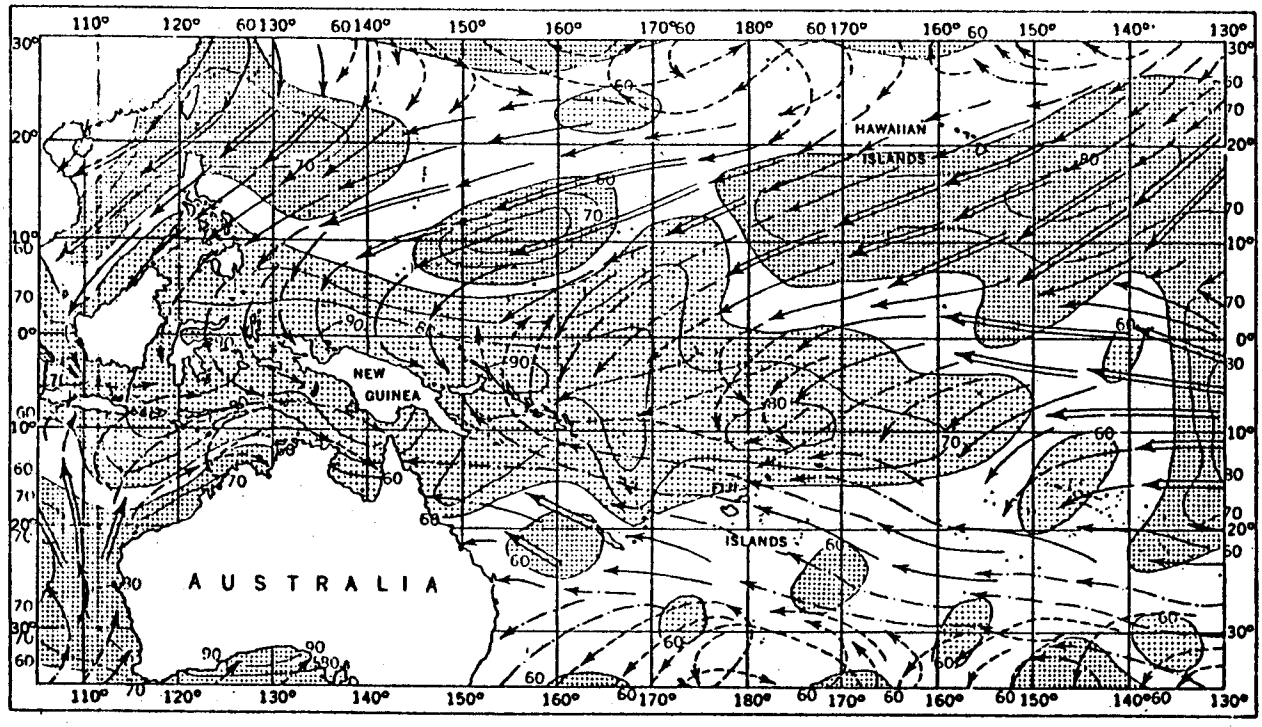



Figure 31 (continued).

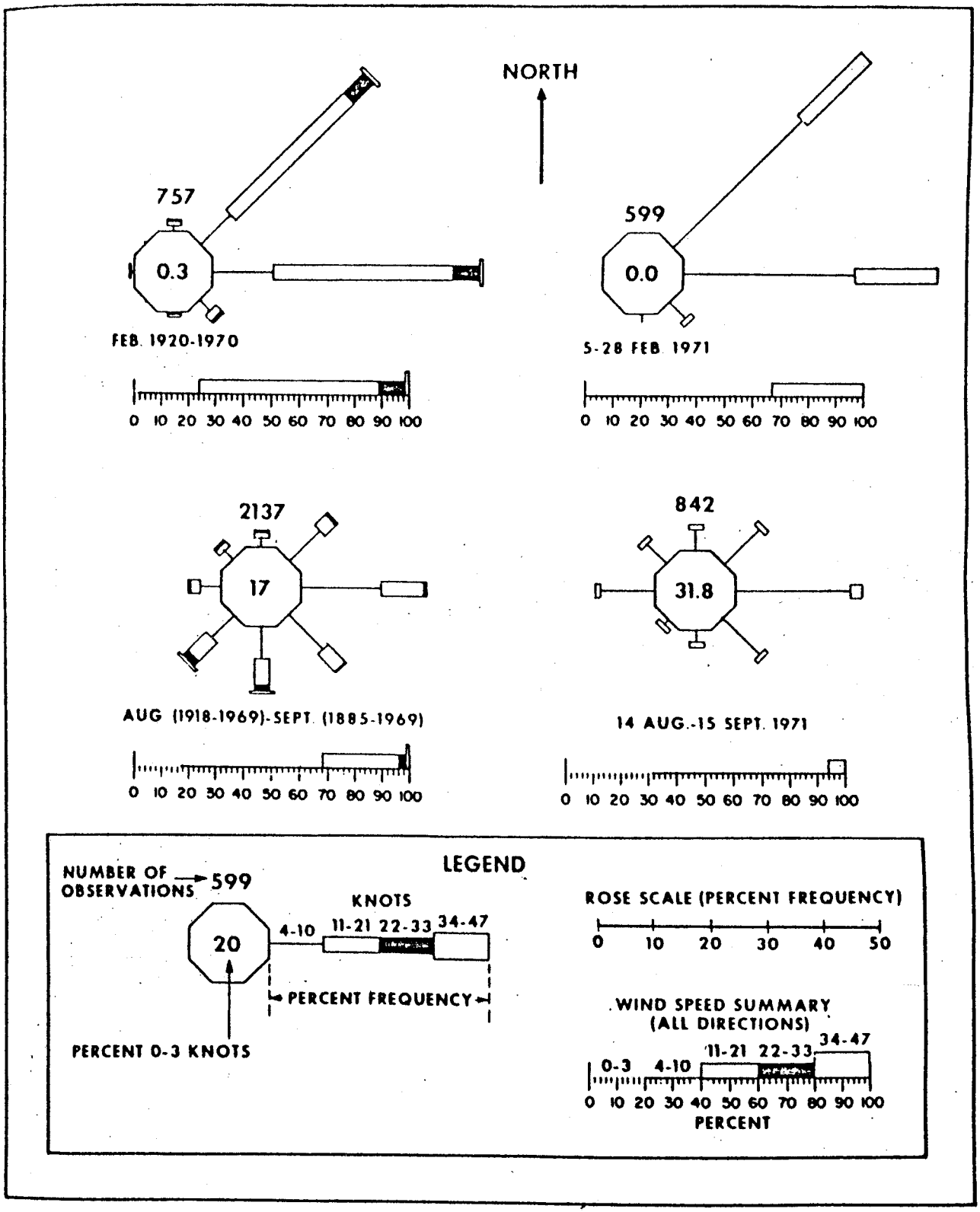



Figure 32.--Wind roses of historical data and 1971 data (from Huddell et al. 1974).

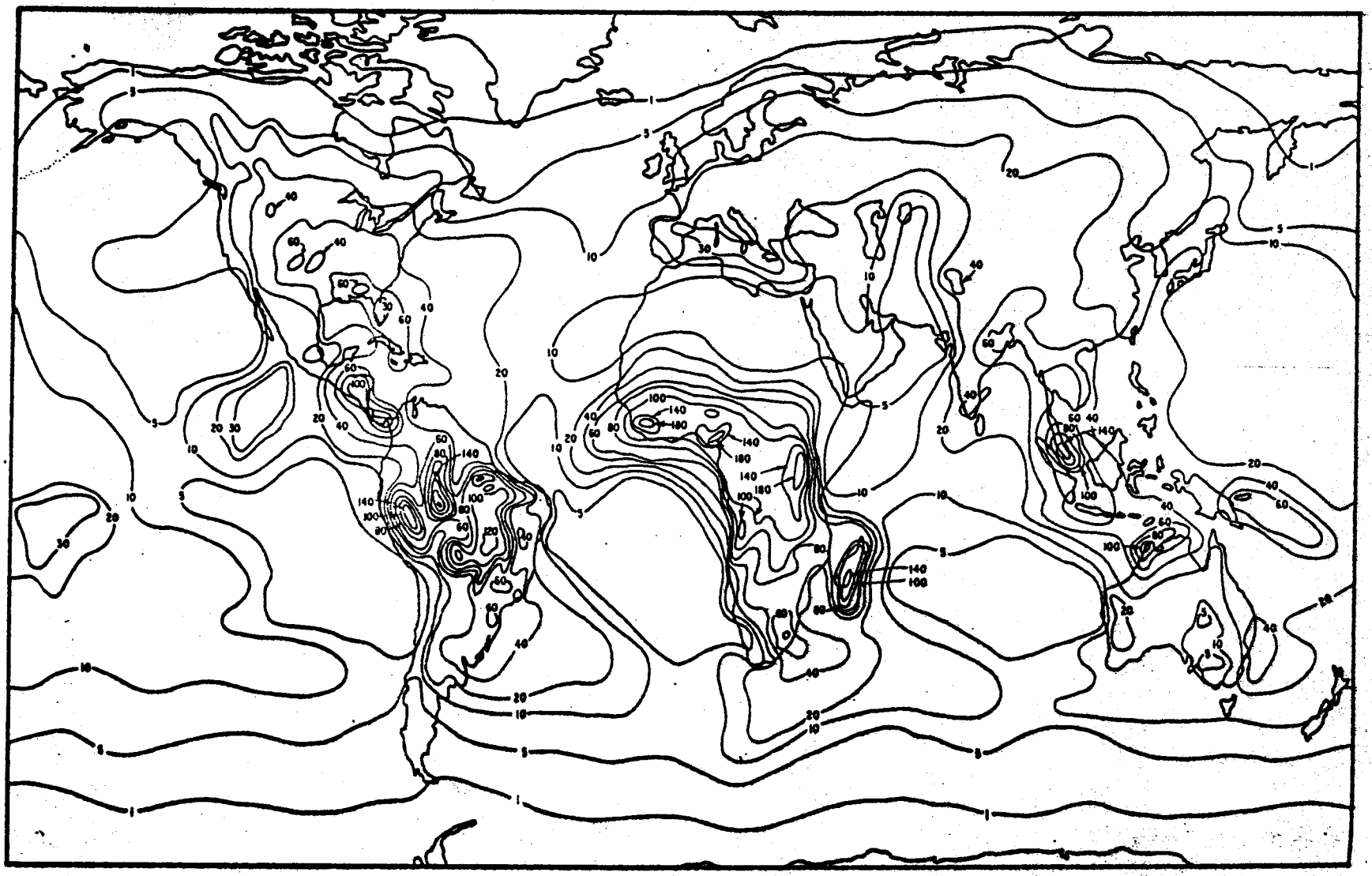


Figure 33.—Mean annual number of thunderstorm days (from Atkinson 1971).

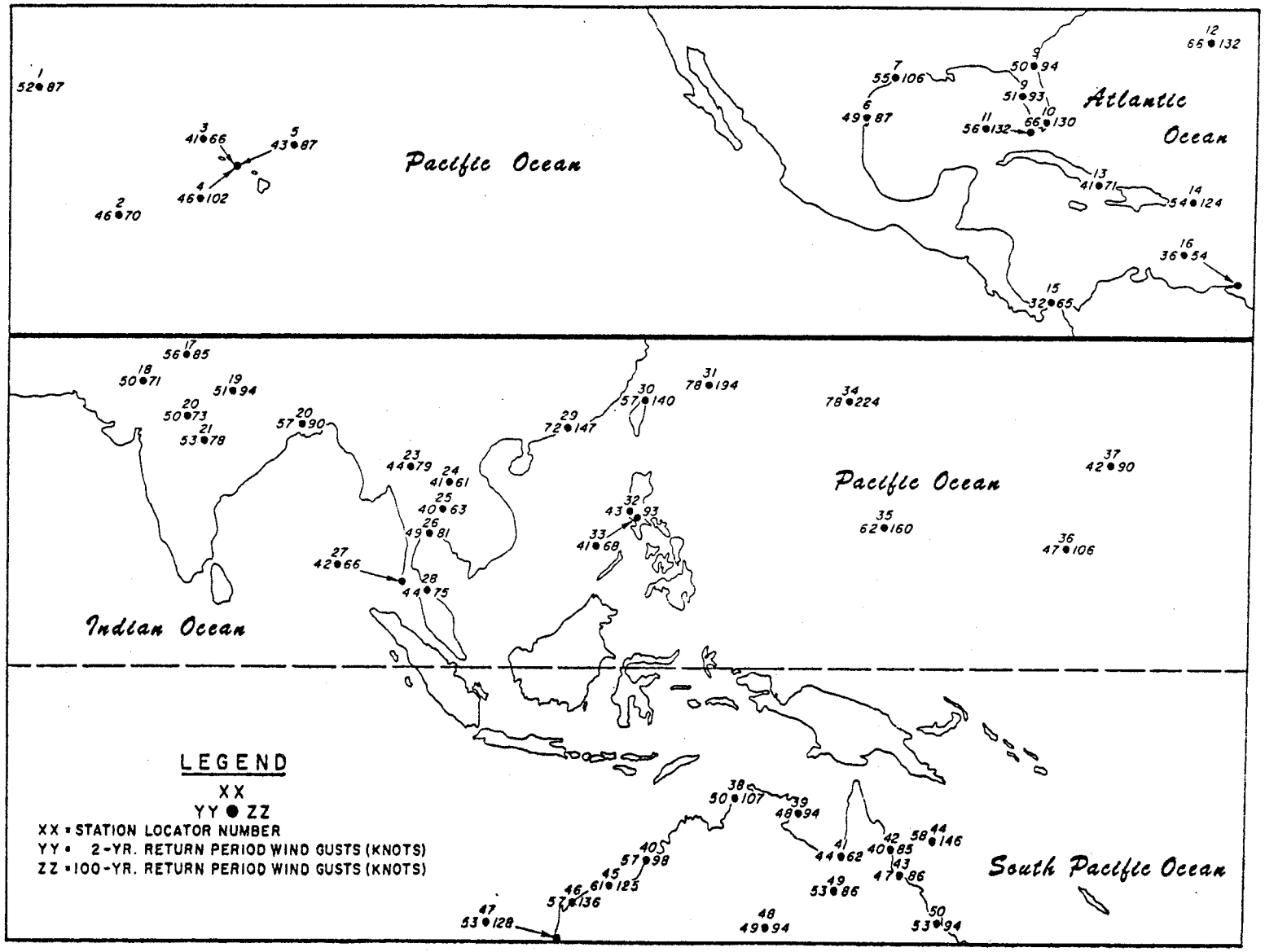



Figure 34.—Expected extreme wind-gusts (knots) for 2-year and 100-year return periods for selected tropical stations (Station 34, Iwo Jima; 35, Andersen Air Force Base, Guam; 36, Enewetak Atoll; 37, Wake Island) (from Atkinson 1971).

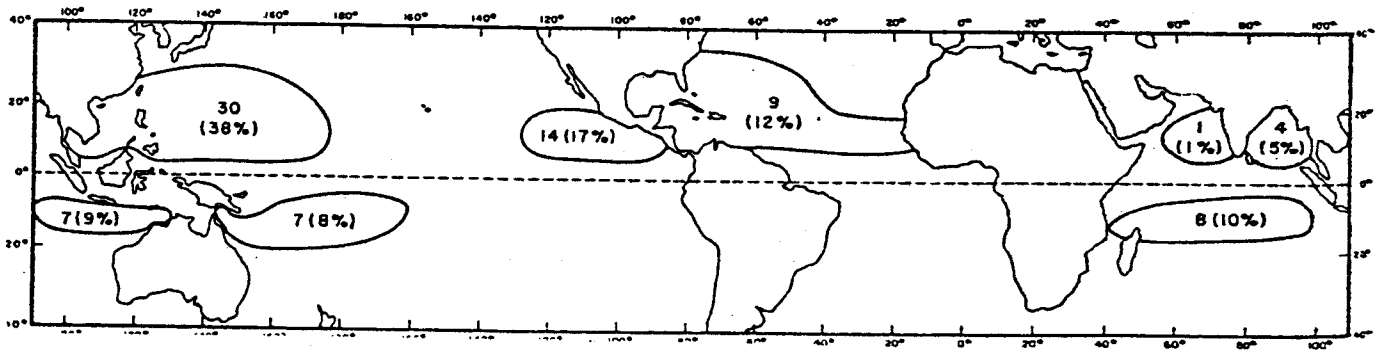



Figure 35.--Average annual number (and percent of global total) of tropical cyclones of tropical-storm or greater intensity in each developed area (from Atkinson 1971).

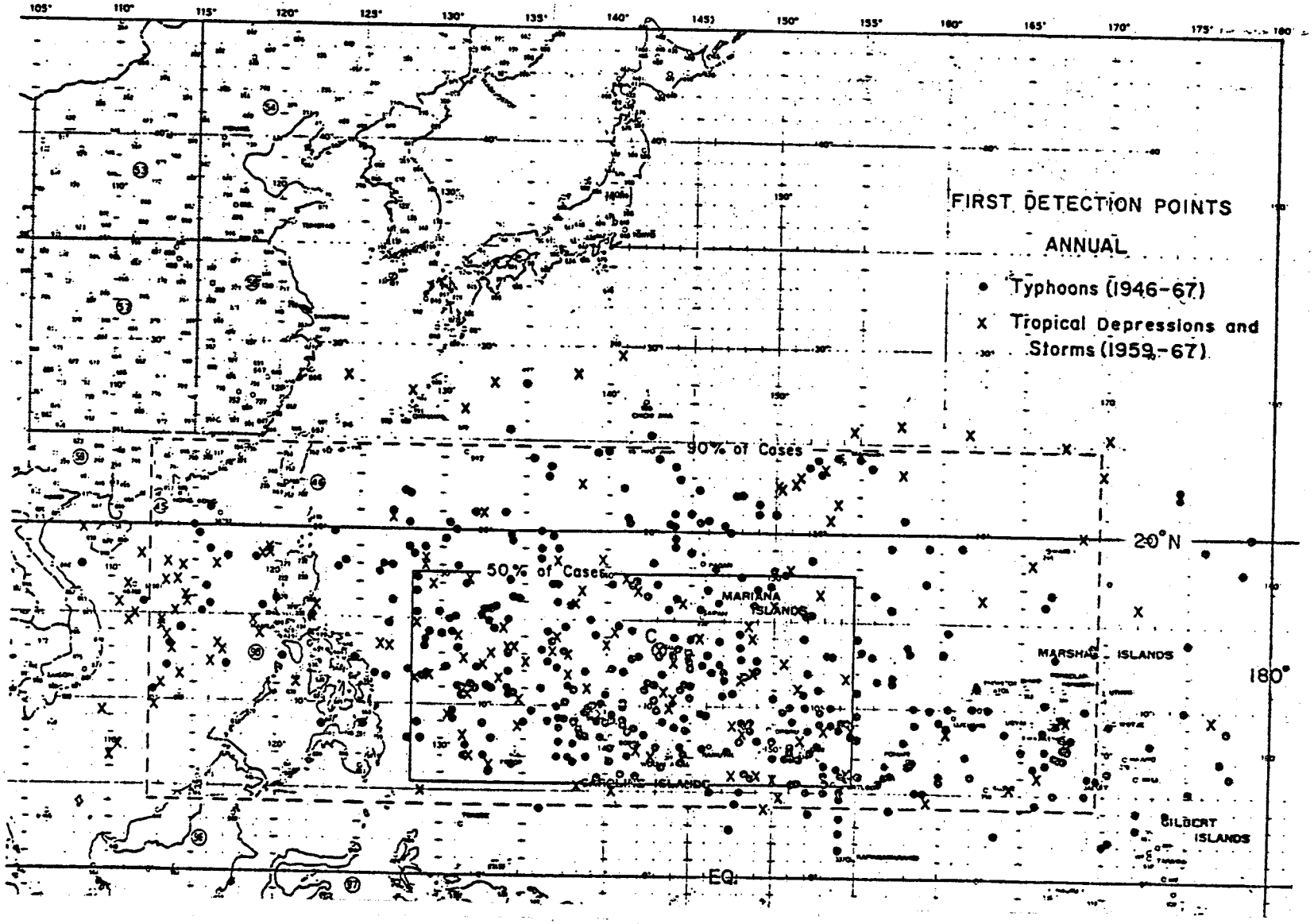



Figure 36.—Initial detection locations of tropical disturbances which later become typhoons (solid dots) for years 1946-67 and tropical storms of depressions (x's) for years 1959-67 (from Gray 1970).

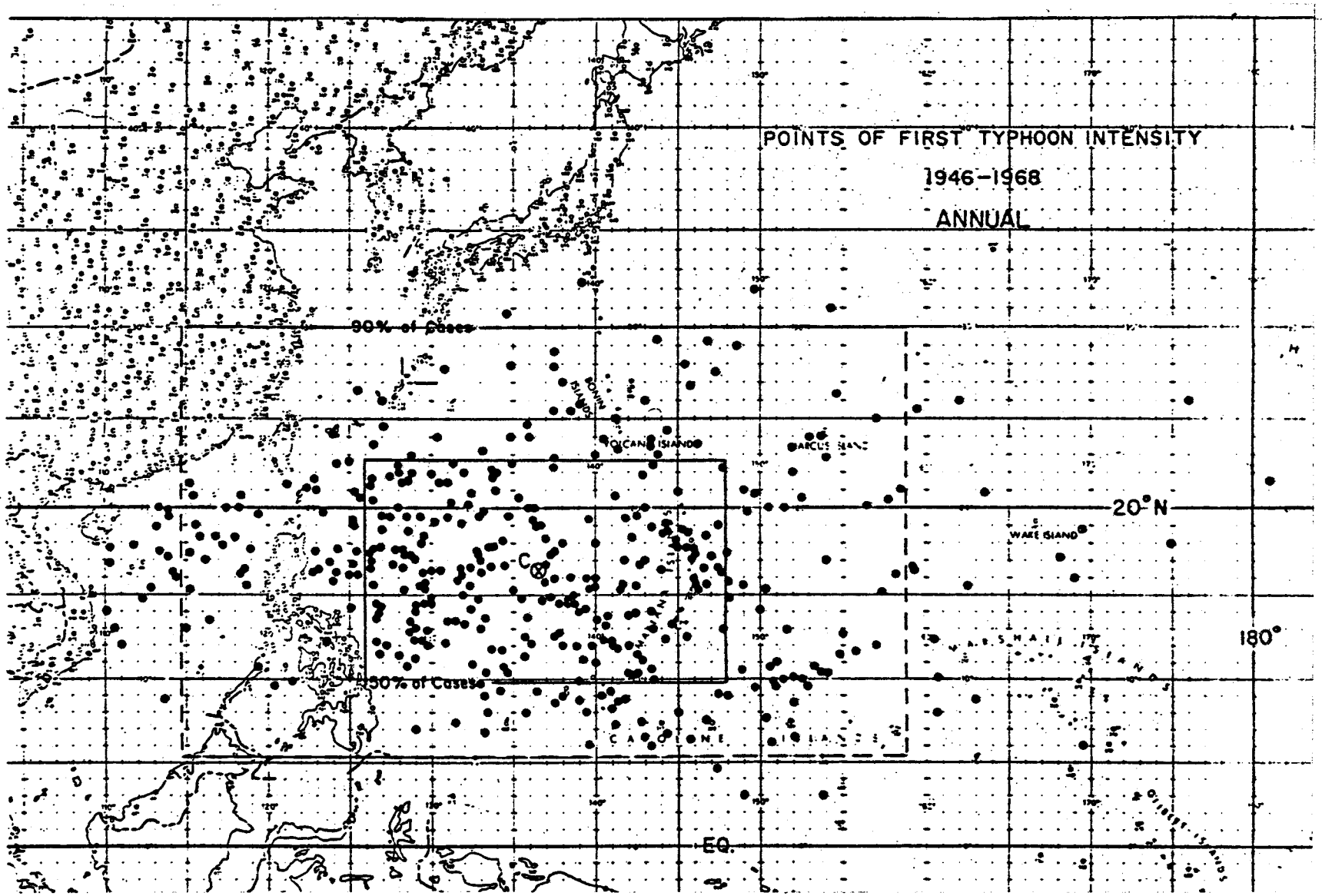



Figure 37.—Location of points where storms first reached typhoon intensity for years 1946-68 (from Gray 1970).

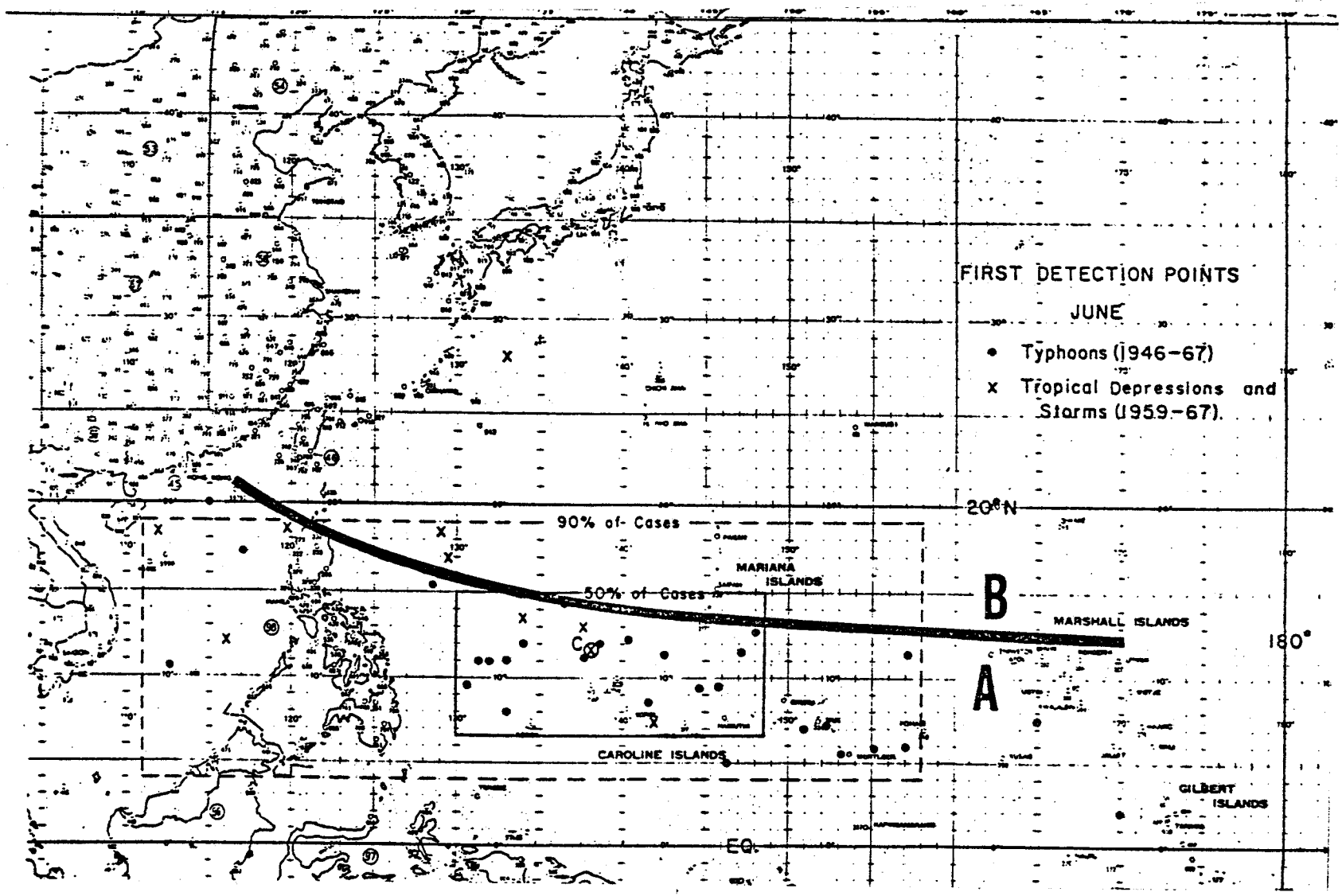



Figure 38.—June initital detection points of tropical systems which later grew to typhoon intensity (solid dots) or to tropical storms or depressions (x's); heavy solid line running west-northwest-east southeast separates probable "B" subtropical type cyclone development from pure tropical "A" type development (from Gray 1970).

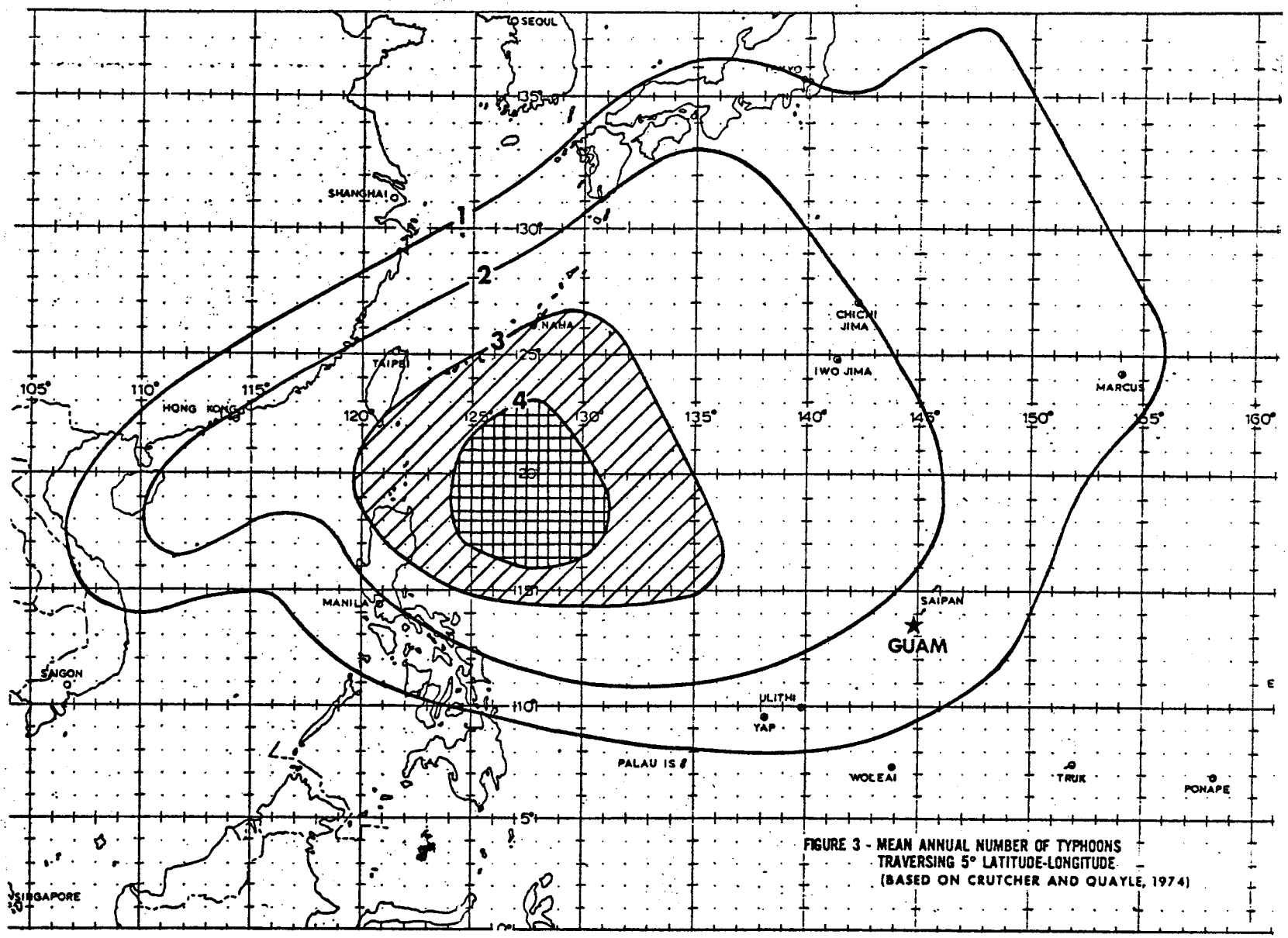



Figure 39.--Mean annual number of typhoons traversing 5° latitude-longitude (from Holliday 1975).

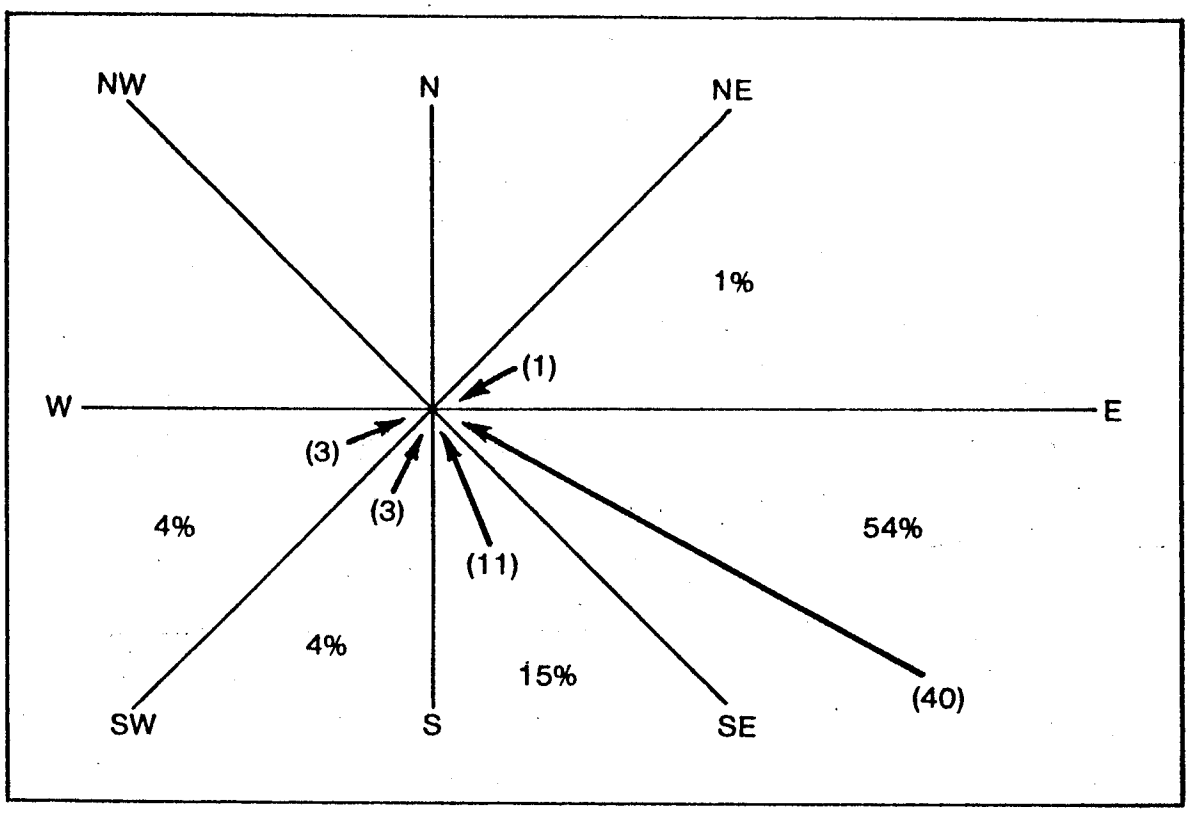



Figure 40.--Direction of approach of tropical cyclones (34 kt) to Guam. Length of each line represents number of occasions on which cyclones approach from each octant of the compass, "The remainder of the storms (22%) displayed loops and stalls at their closest point of approach, or performed major deviations in track making it difficult to assume a uniform direction of motion." (from Holliday 1975).

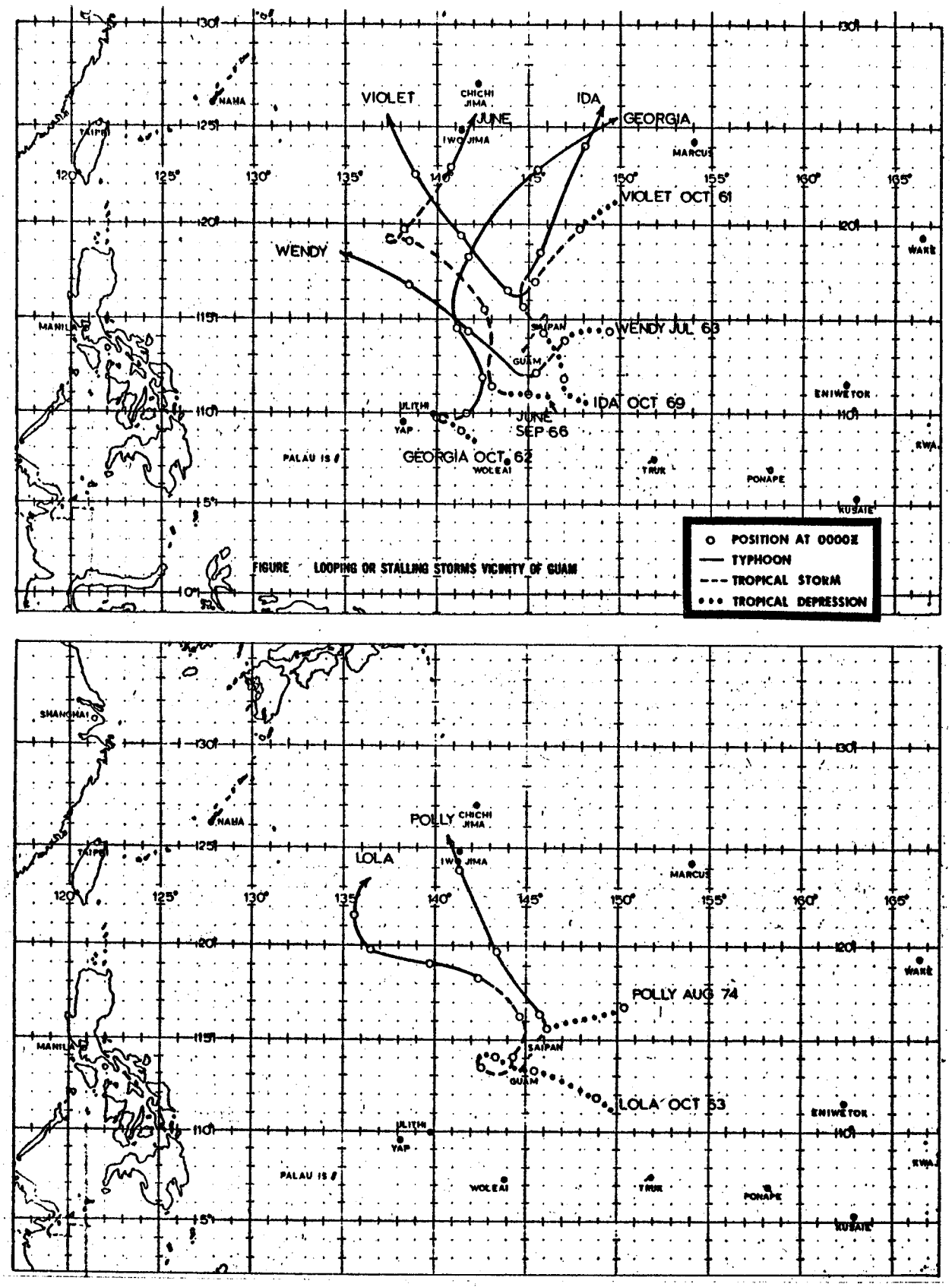



Figure 41.--Looping or stalling storms in the vicinity of Guam (from Holliday 1975).

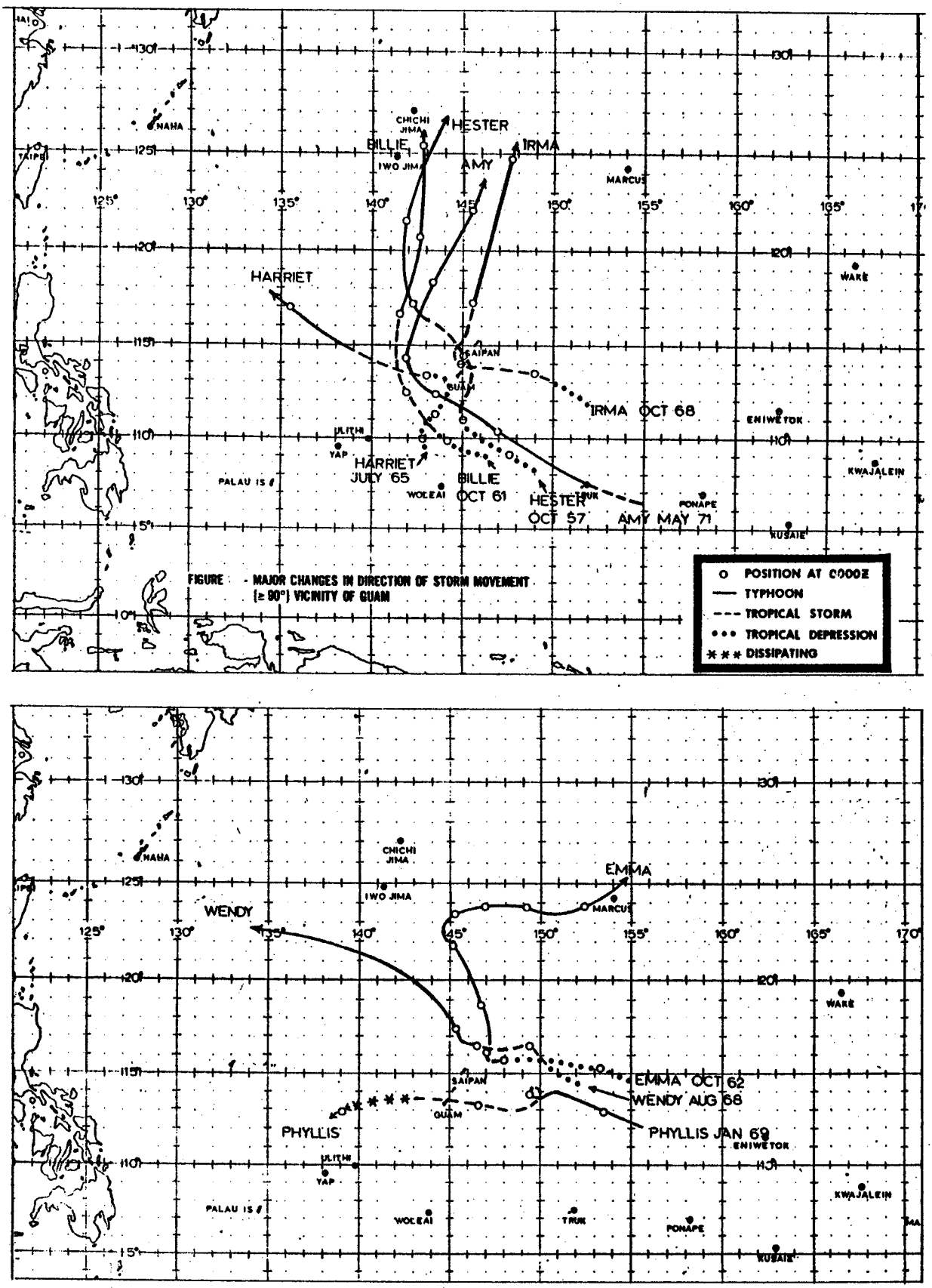



Figure 42.--Major changes in direction of storm movement (≥90°) of Guam (from Holliday 1975).

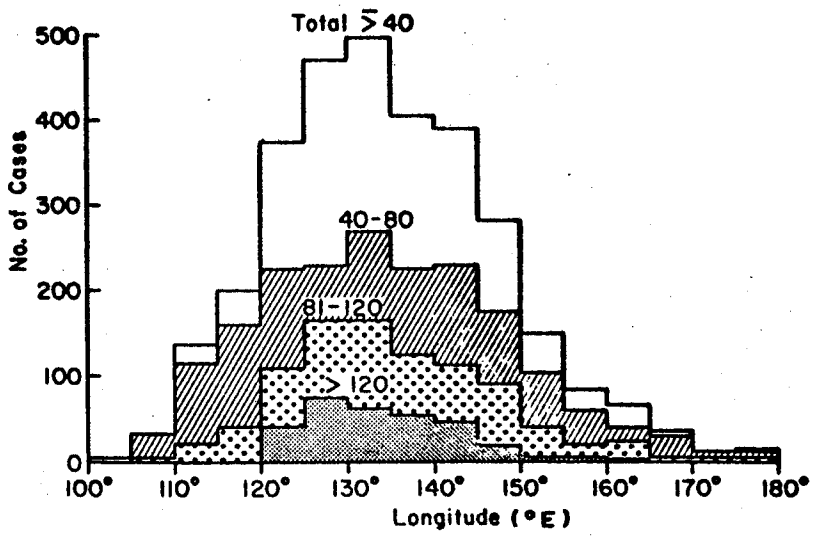



Figure 43.--Maximum sustained winds equal to or greater than 40 knots and in 40-80, 81-120, and greater than 120 knot ranges versus longitude for typhoons occurring during the years 1953-68; the number of cases consists of all reconnaissance aircraft observations which were taken at least 6 hours apart; most reports are near the cyclone center (from Gray 1970).

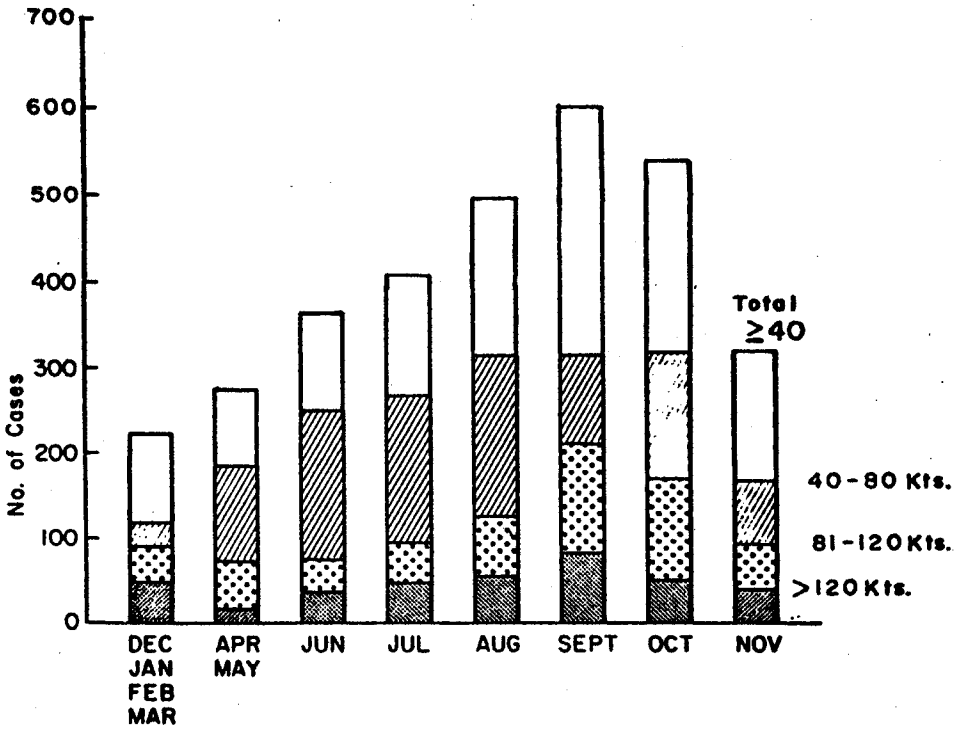



Figure 44.--Maximum sustained winds equal to or greater than 40 knots and in 40-80, 81-120, and greater than 120 knot ranges versus month for typhoons occurring during the years 1953-68; the number of cases consists of all reconnaissance aircraft observations which were taken at least 6 hours apart; most reports are near the cyclone center (from Gray 1970).

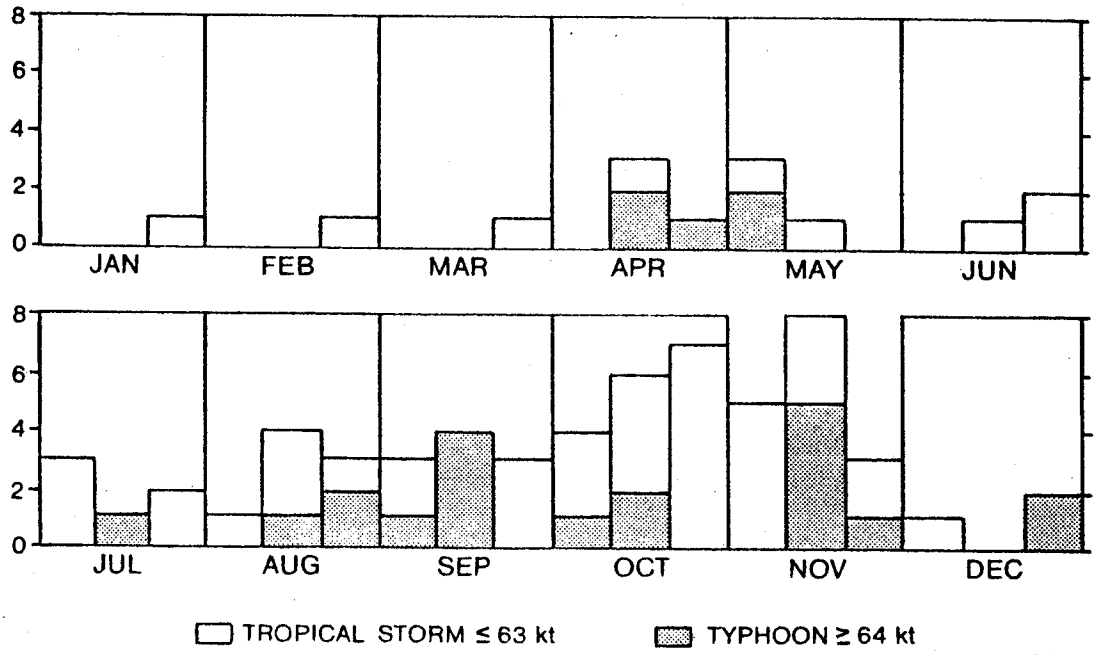



Figure 45.--Monthly occurrence (1948-75) of tropical storm/typhoon passage within 180 nautical miles of Guam by 10-day interval (31-day months have last 11 days included in last 10-day period) (from Holliday 1975).

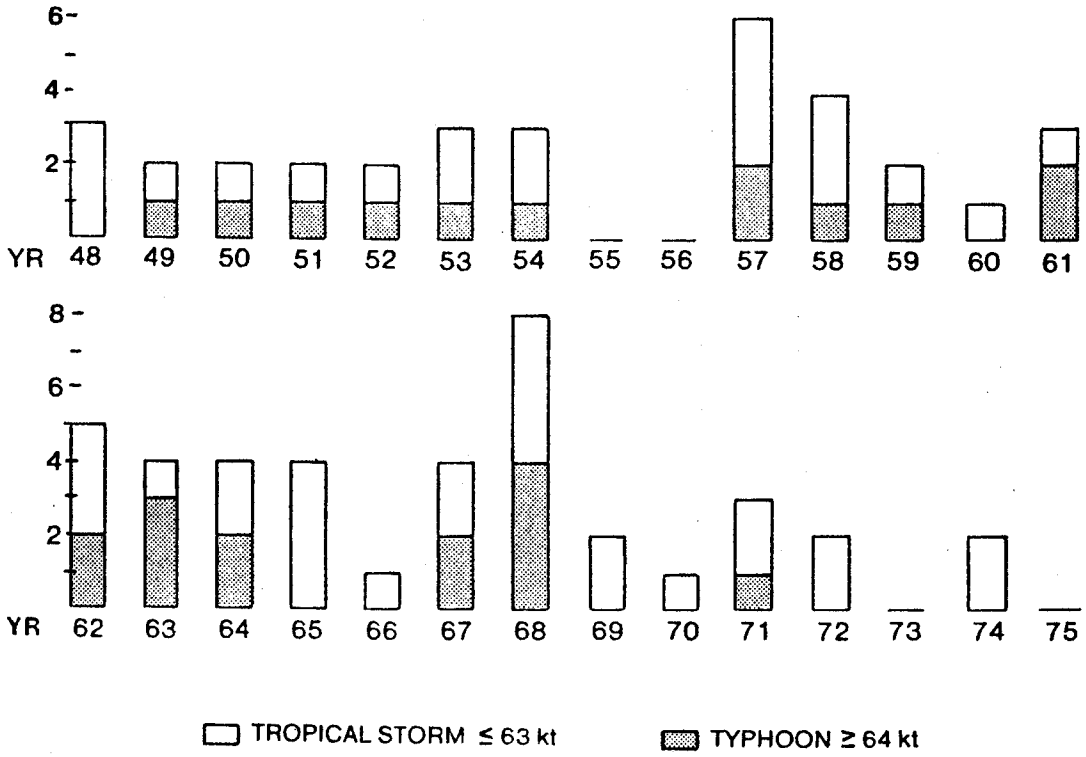



Figure 46.--Yearly frequency (1948-75) of tropical storm/typhoon passage ≥180 nautical miles of Guam (from Holliday 1975).

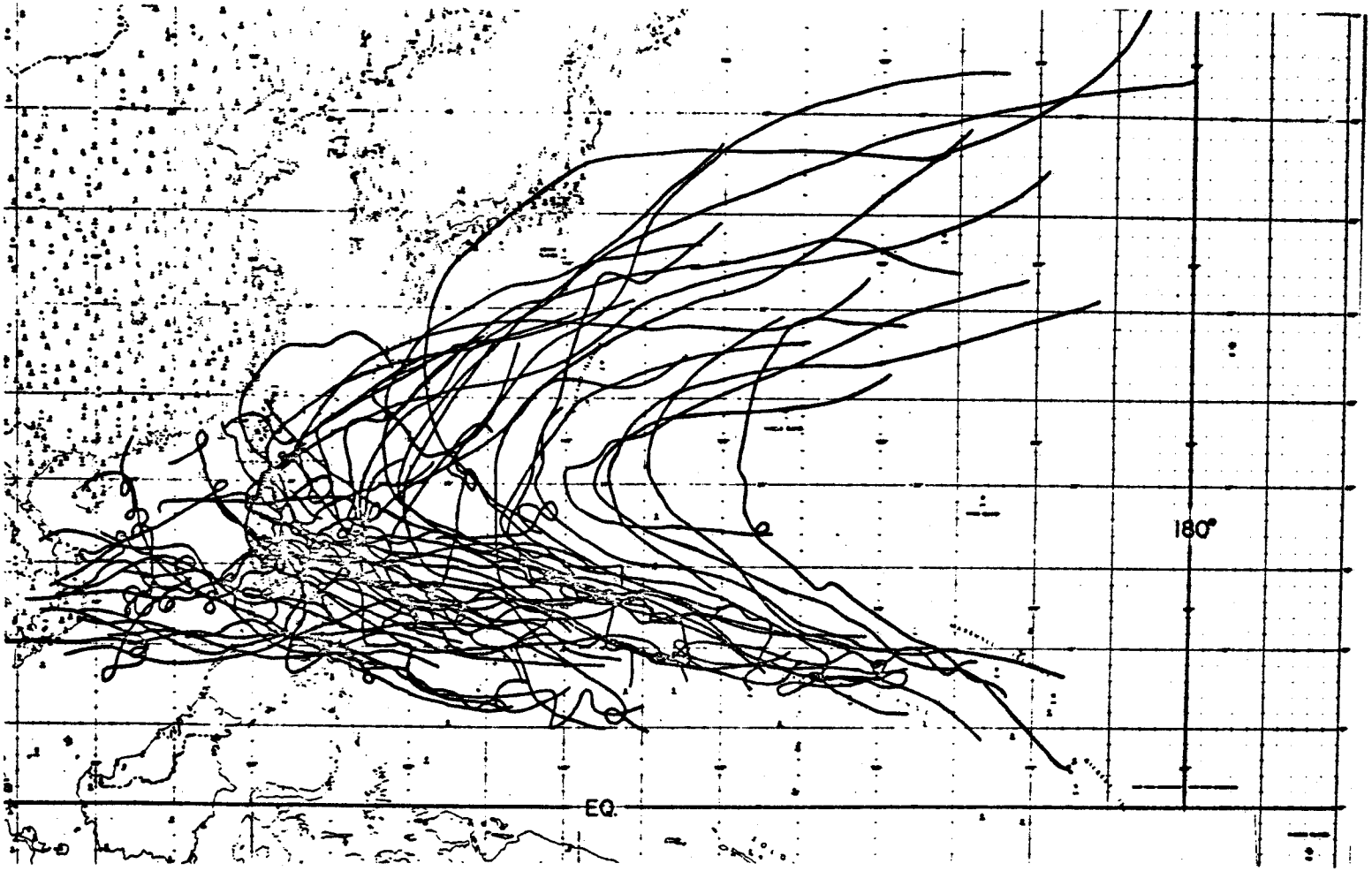



Figure 47.--November tracks of tropical cyclones which at some time were typhoons during the years 1946-69; tropical cyclones have been placed into monthly categories according to the median date of their existence (from Gray 1970).

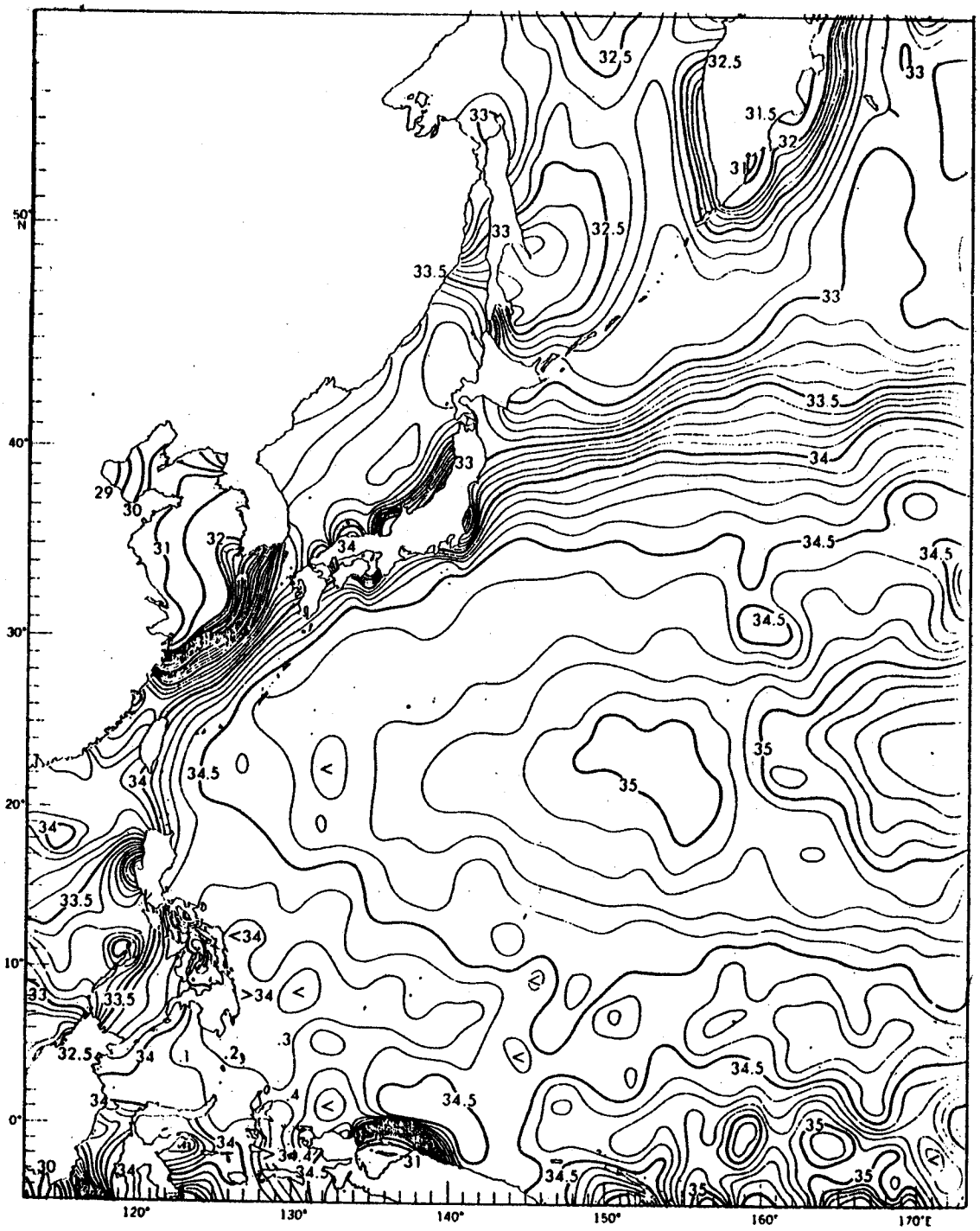



Figure 48.--Annual mean salinities at the surface (from Robinson 1976).

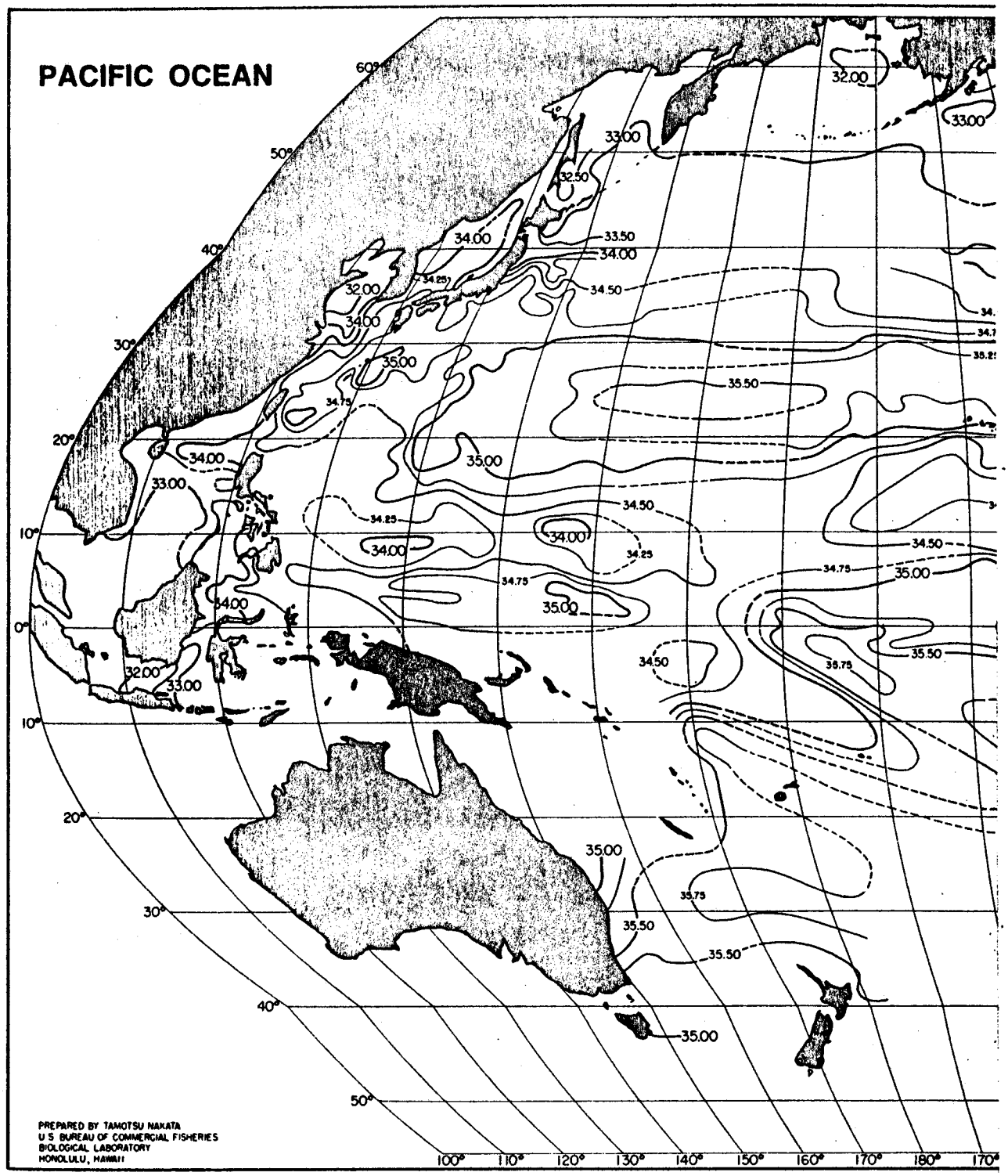



Figure 49.-- Salinity (ppt) at 10 meters, first quarter (from Barkley 1968).

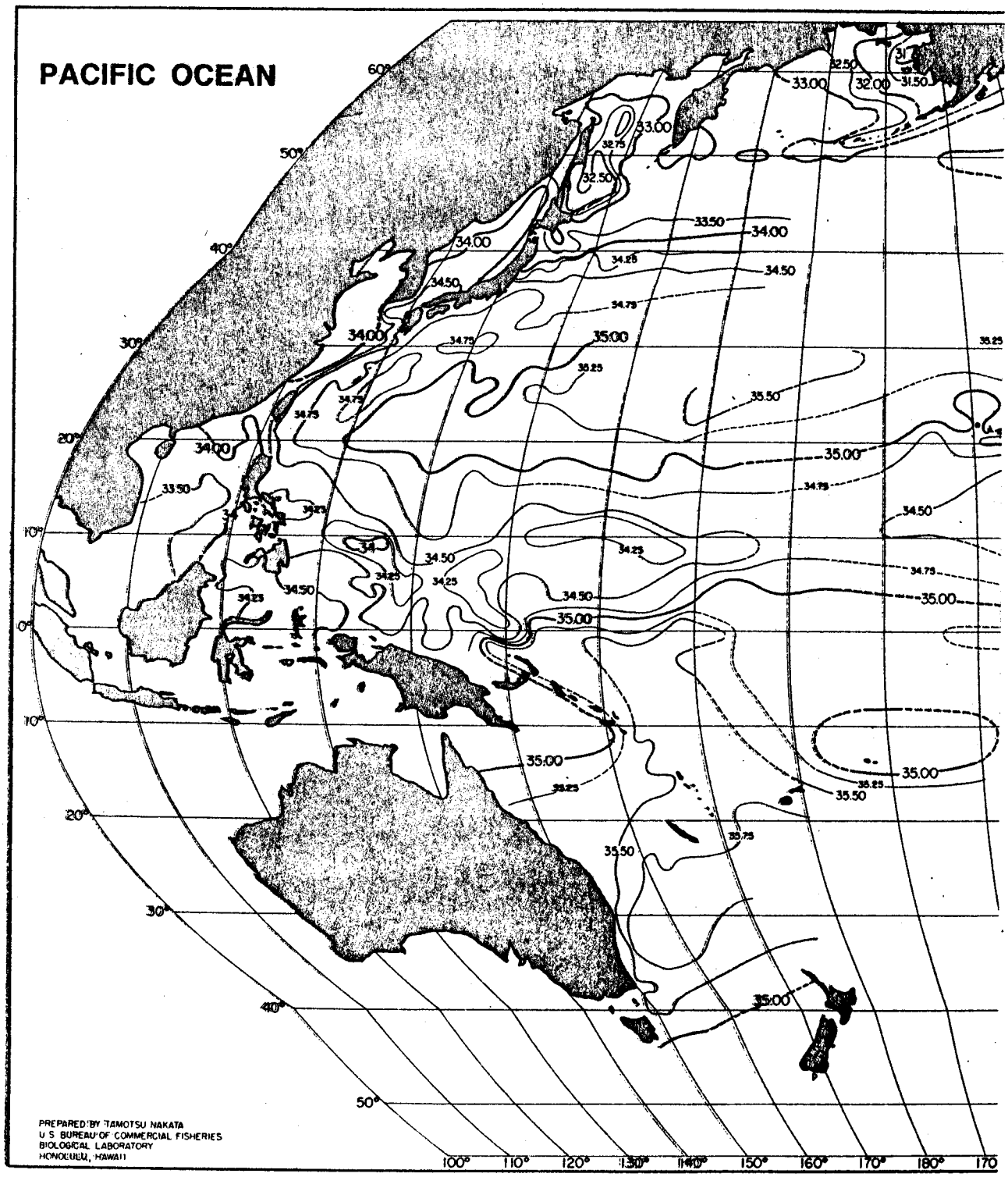



Figure 50.--Salinity (ppt) at 10 meters, second quarter (from Barkley 1968).

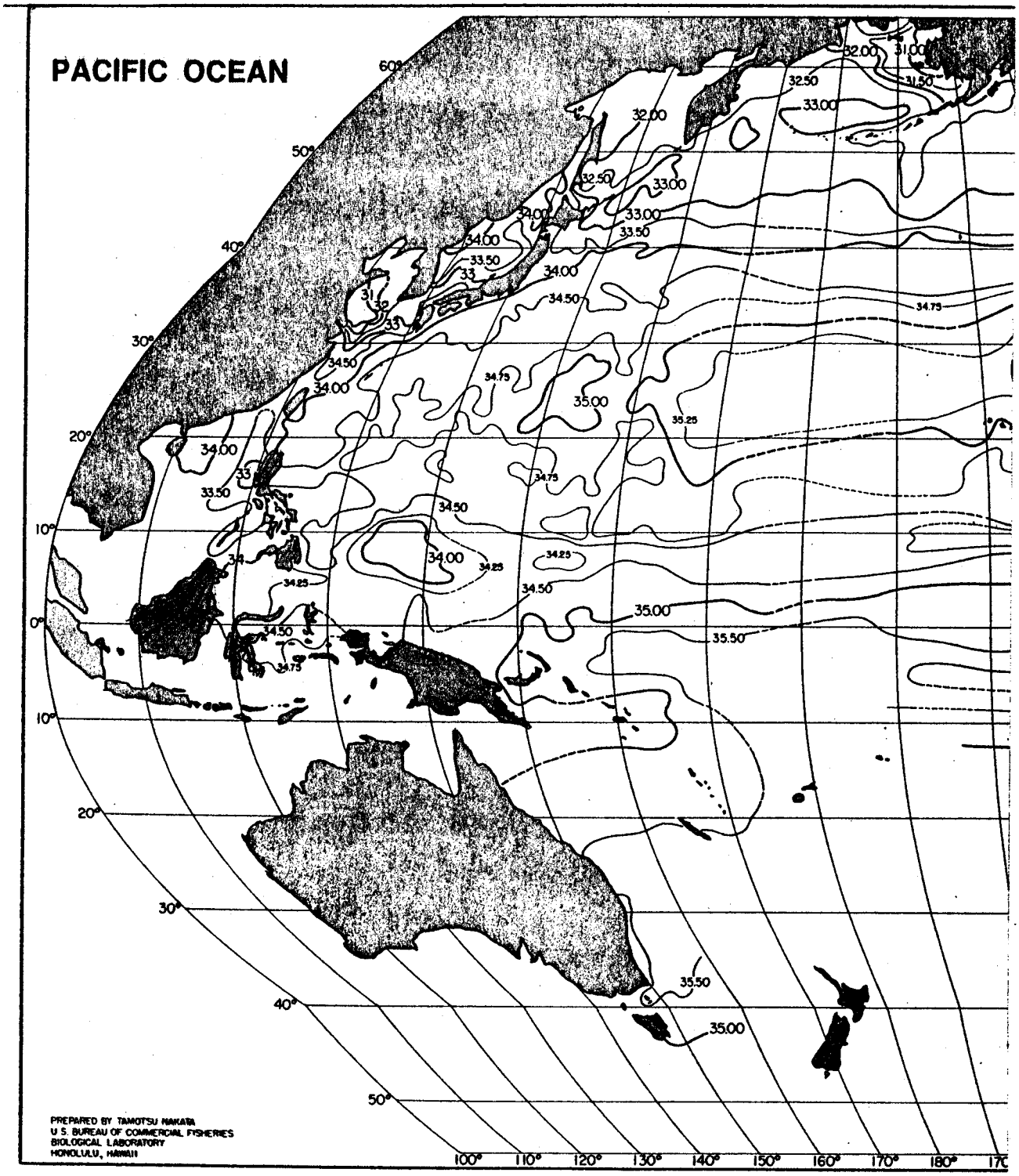



Figure 51.--Salinity (ppt) at 10 meters, third quarter (from Barkely 1968).

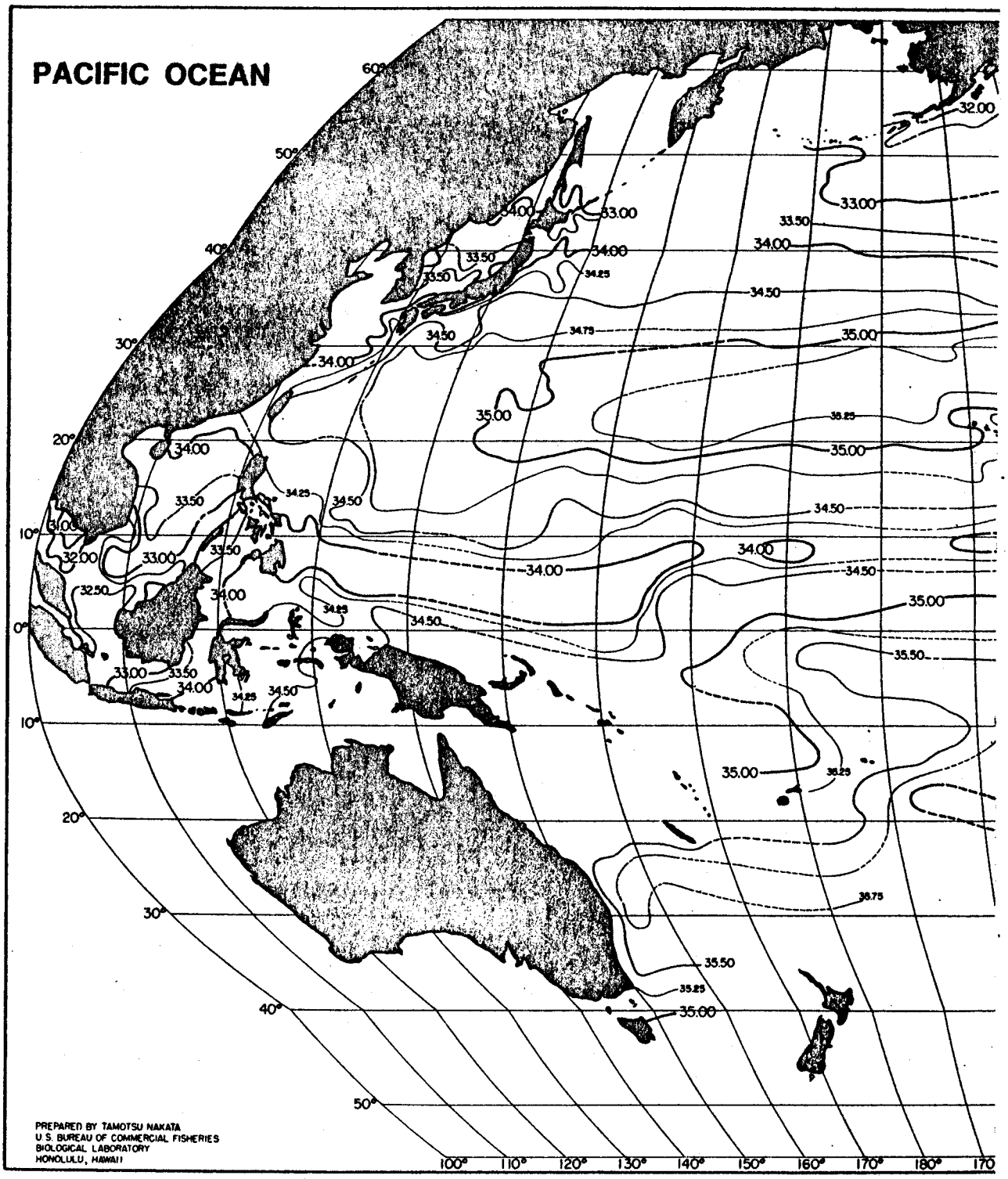



Figure 52.-- Salinity (ppt) at 10 meters, fourth quarter (from Barkley 1968).

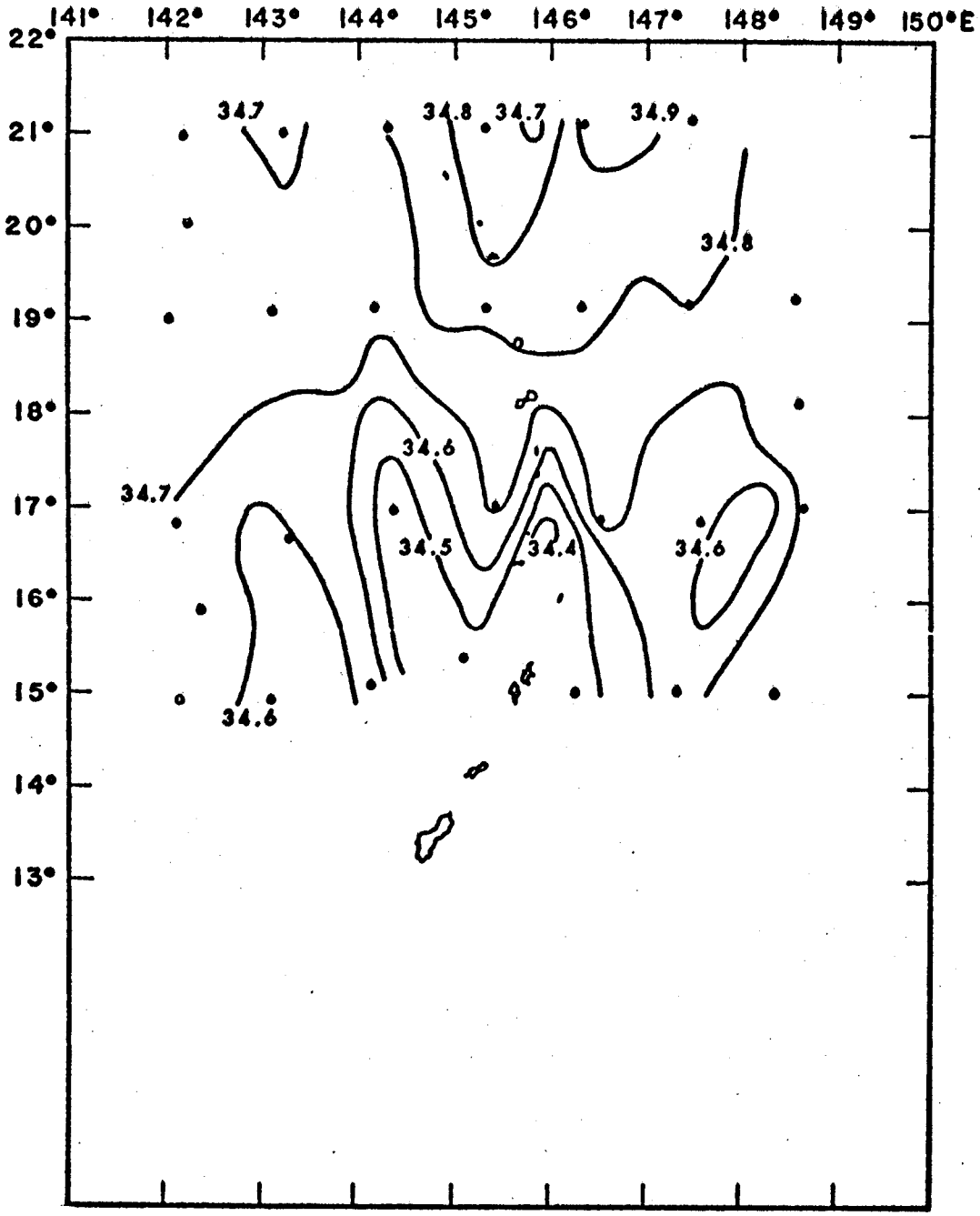



Figure 53.--Surface salinity (21 April-2 May 1971) (from deWitt 1972).

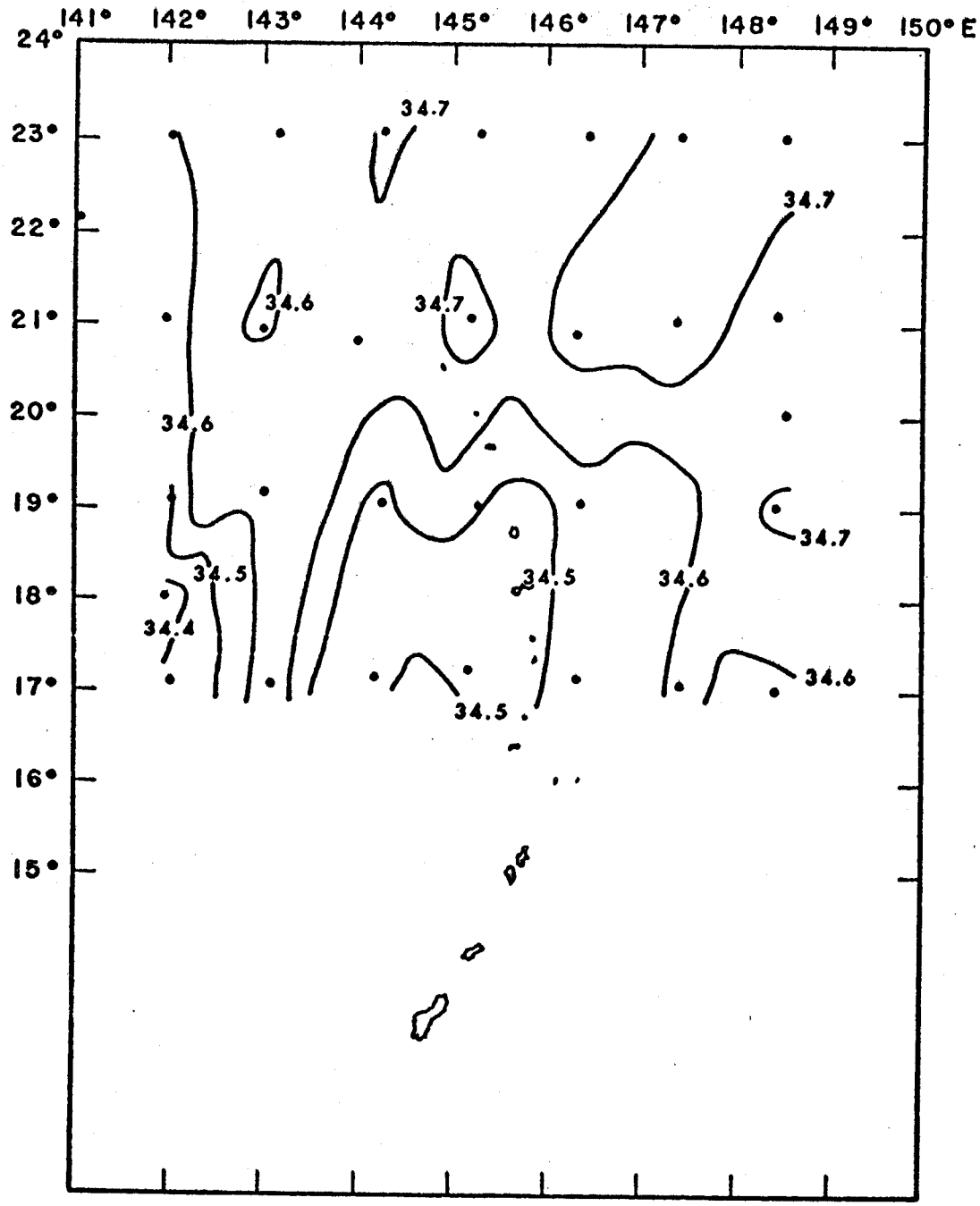



Figure 54.--Surface salinity (2-12 November 1971) (from deWitt 1972).

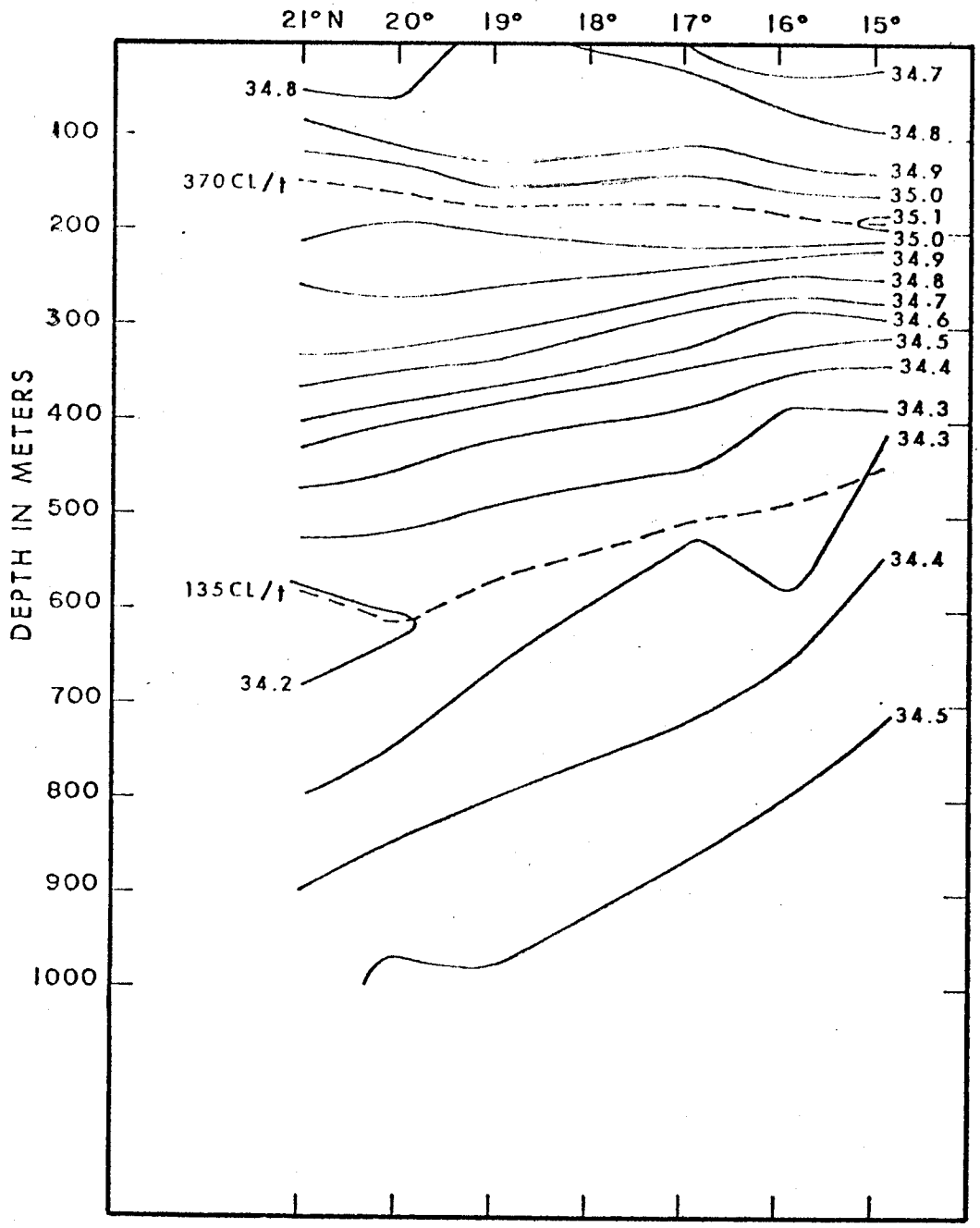



Figure 55.--Salinity in per mil along 142°E, 21 April-2 May 1971 (dashed lines represent the depths of the 370 and 135 cl/t isopleths (from deWitt 1972).

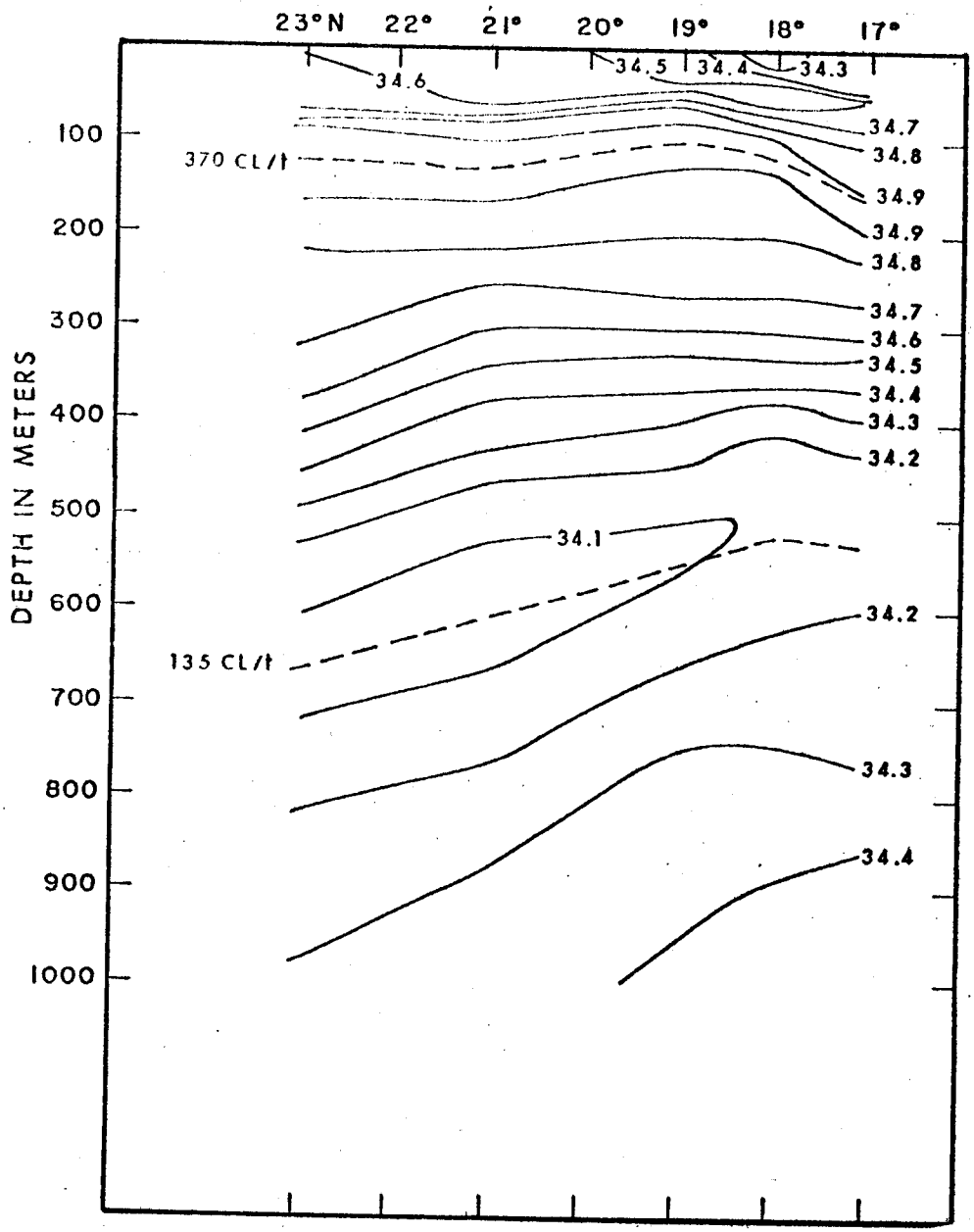



Figure 56.--Salinity in per mil along 142°E, 2-12 November 1971 (dashed lines represent the depths of the 370 and 135 cl/t isopleths) (from deWitt 1972).

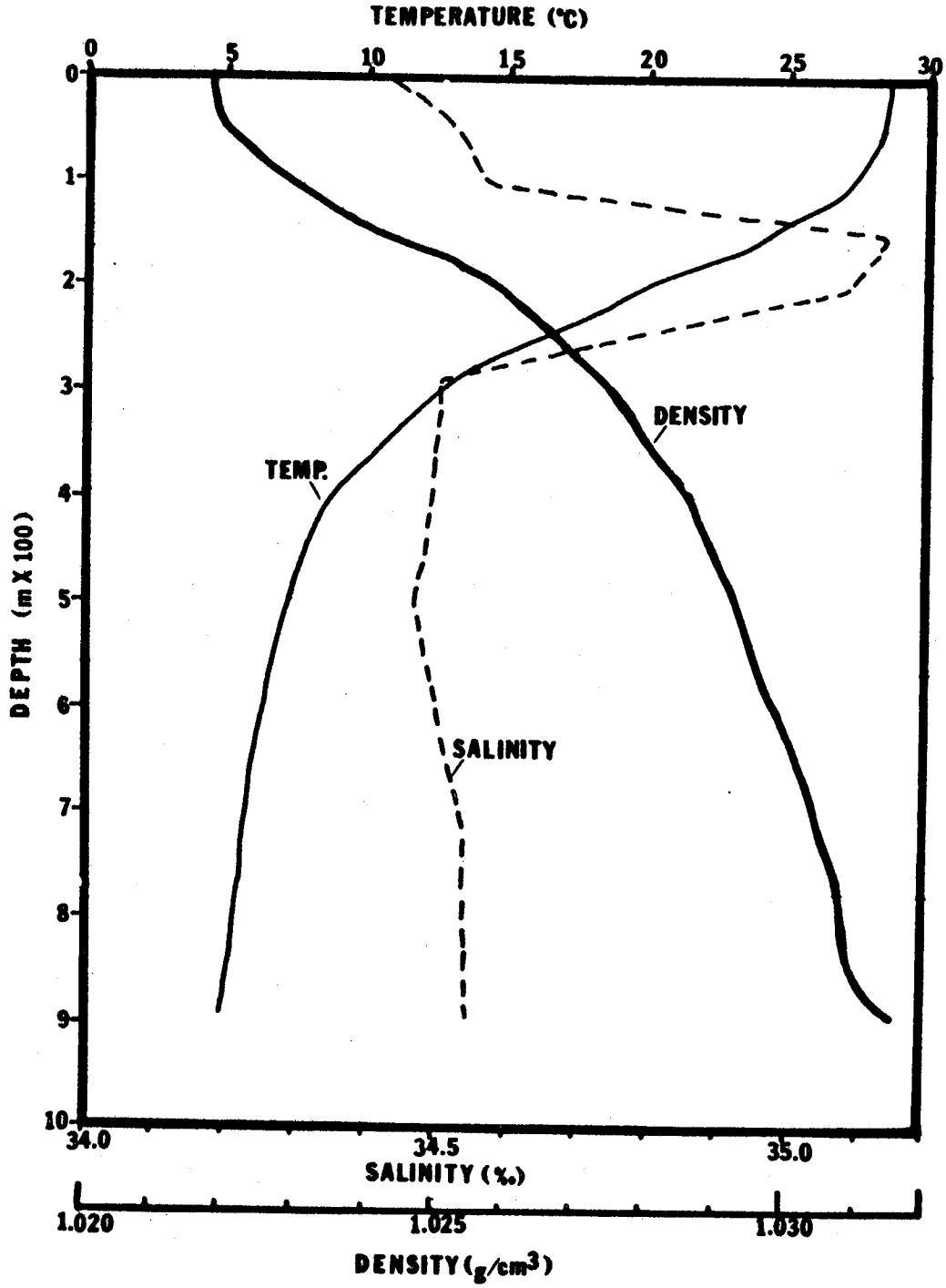



Figure 57.--Mean temperature, salinity, and density profiles in the vicinity of Cabras Island, Luminao Reef, and Glass Breakwater (February 1978-February 1979) (from Lassuy 1979).

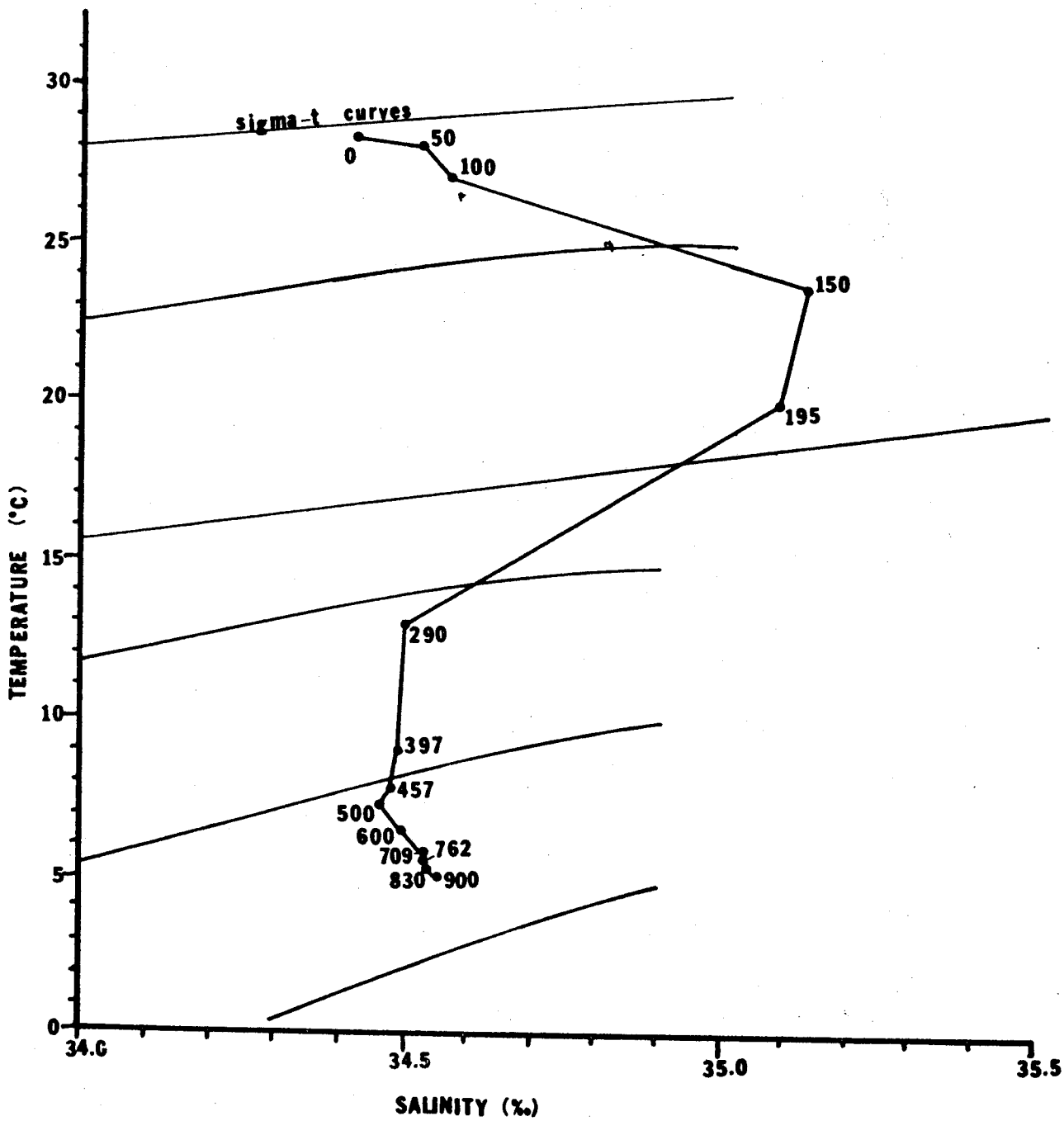



Figure 58.--T-S diagram for the vicinity of the proposed OTEC site at Guam (based on mean temperature and salinity data, February 1978-February 1979) (from Lassuy 1979).

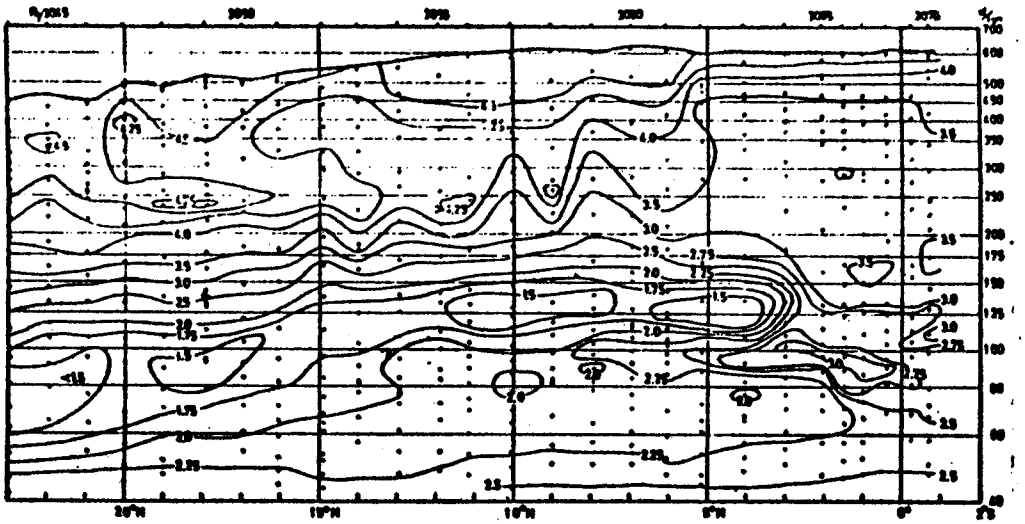


Figure 59.--Meridional section of oxygen content against thermosteric anomaly in logarithmic scale in the equatorial current system at 137°E in January 1967 (from Masuzawa 1967).

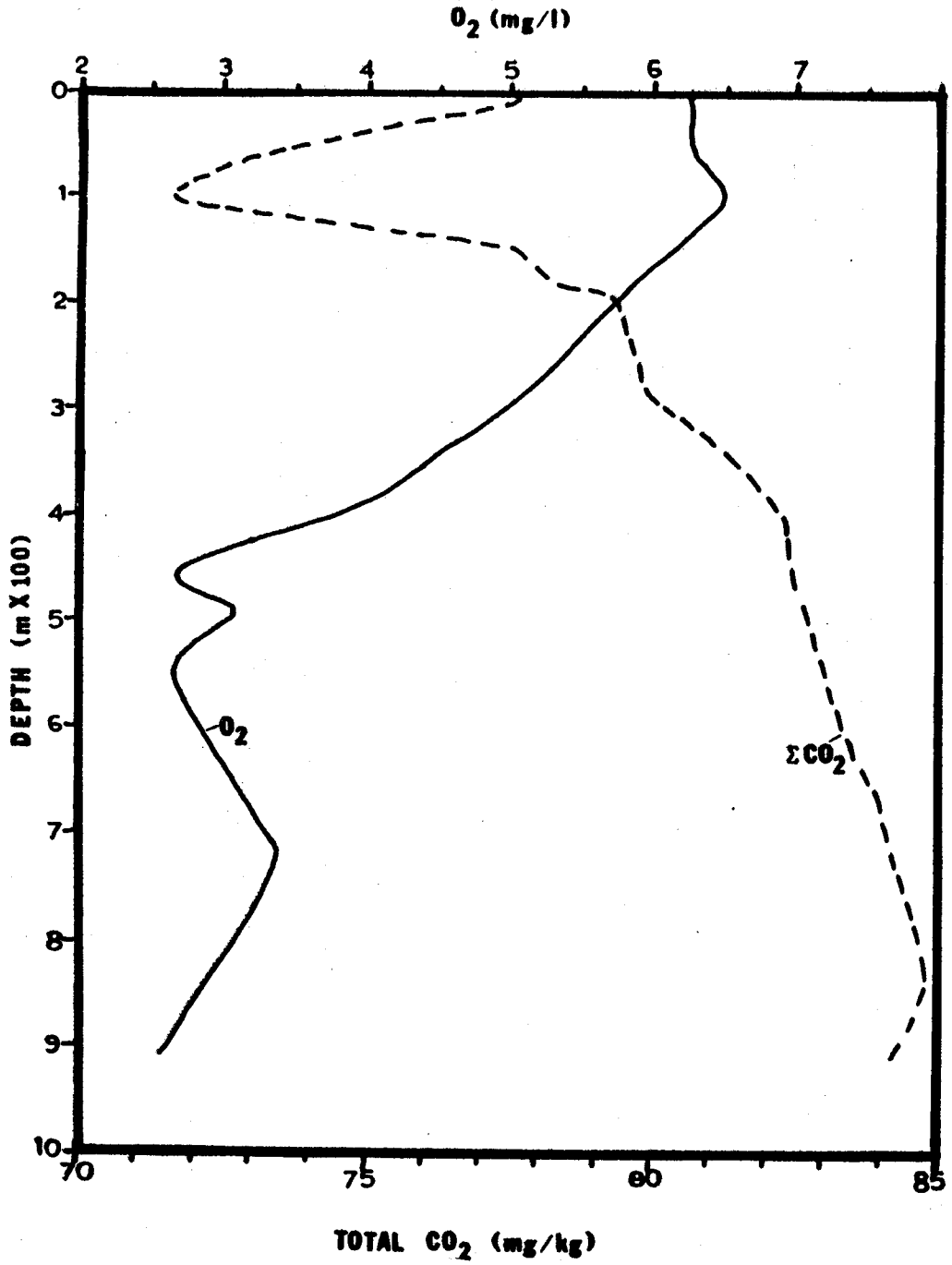



Figure 60.--Mean dissolved oxygen and total carbon dioxide profiles in the vicinity of Cabras Island, Luminao Reef, and Glass Breakwater, Guam (February 1978-February 1979) (from Lassuy 1979).

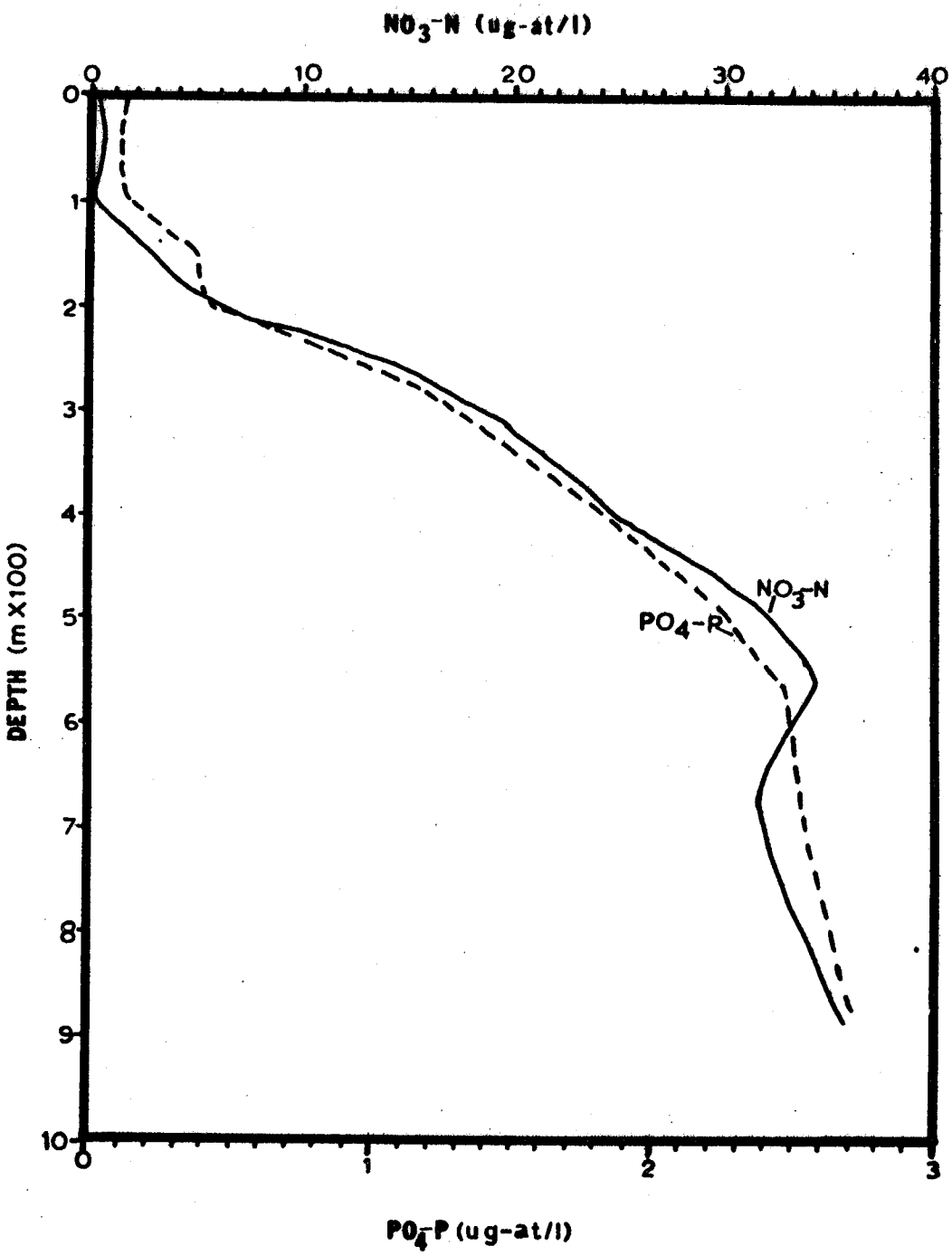



Figure 61.--Mean nitrate-nitrite and reactive phosphate profiles in the vicinity of Cabras Island, Luminao Reef, and Glass Breakwater (February 1978-February 1979) (from Lassuy 1979).

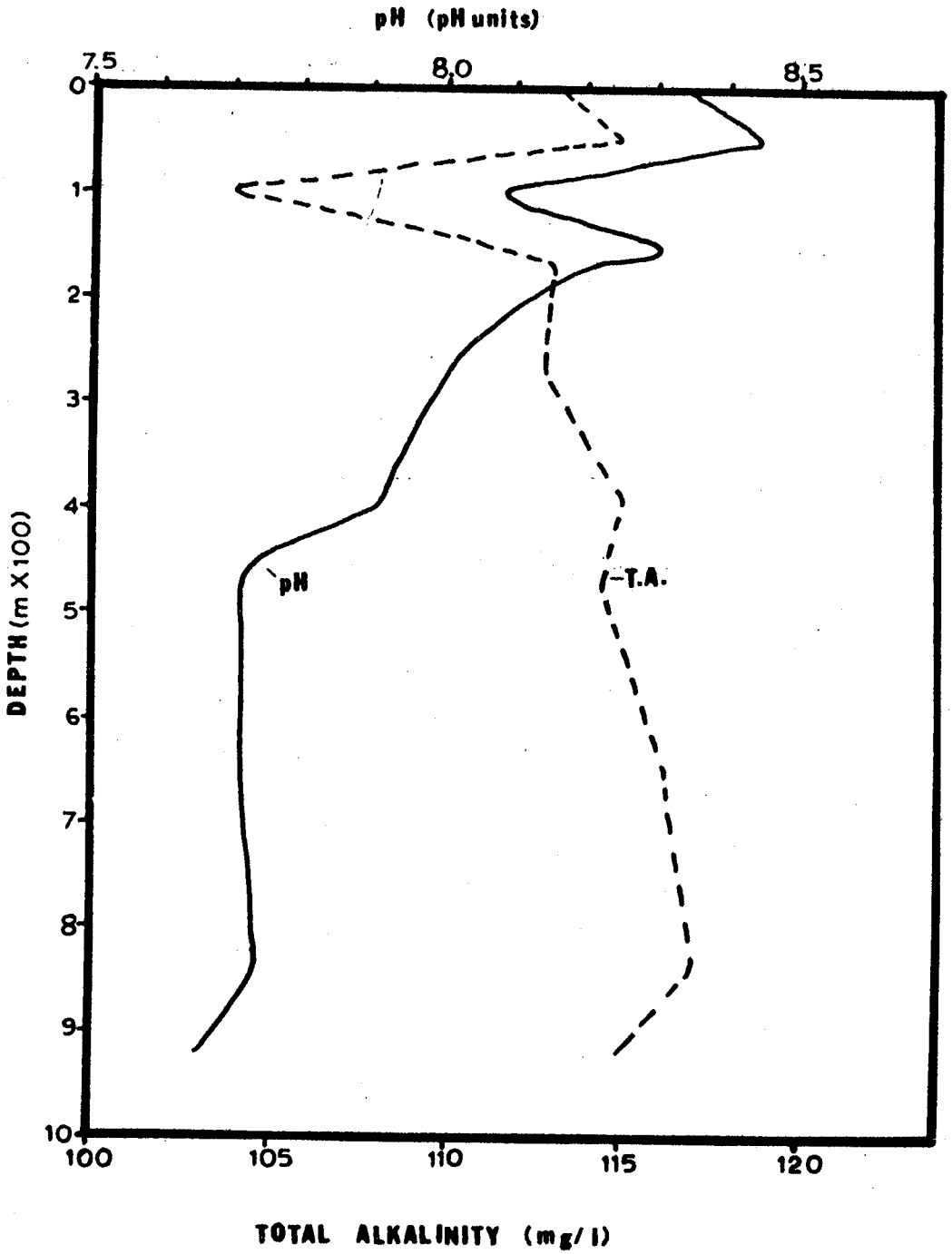



Figure 62.--Mean pH and total alkalinity profiles in the vicinity of Cabras Island, Luminao Reef, and Glass Breakwater (February 1978-February 1979) (from Lassuy 1979).

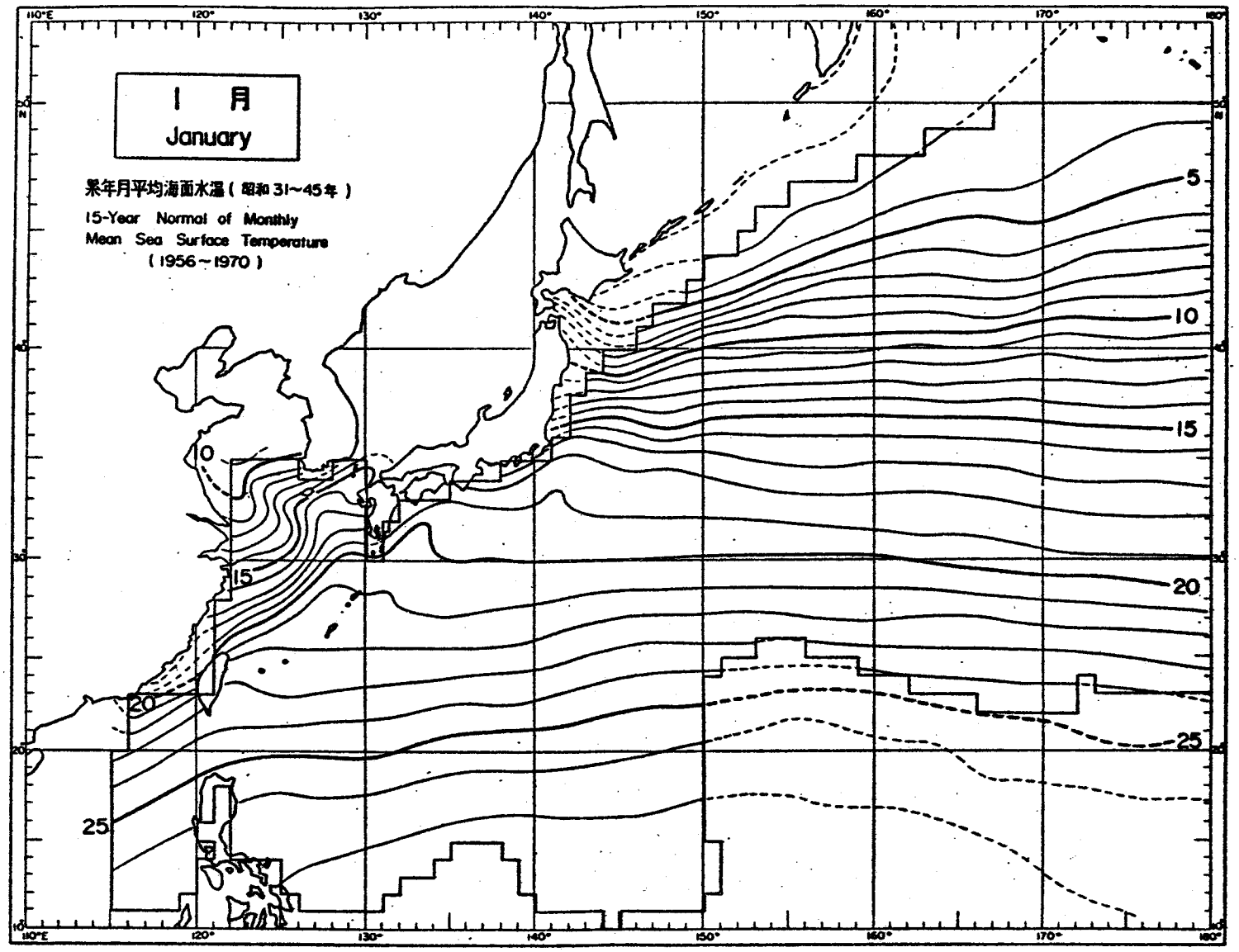



Figure 63.—Sea-surface temperature, January (from Japan Meteorological Agency 1975).

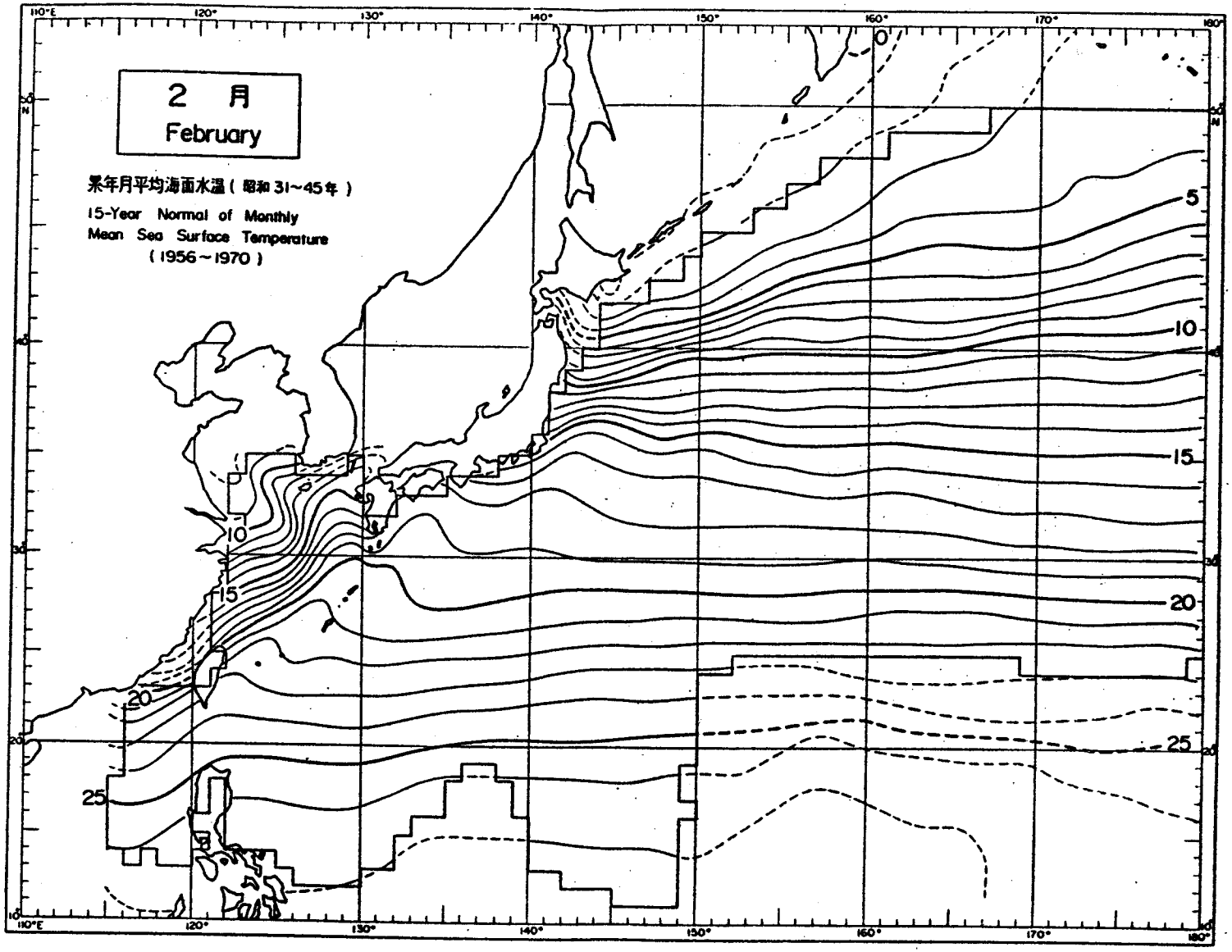



Figure 64.--Sea-surface temperature, February (from Japan Meteorological Agency 1975).

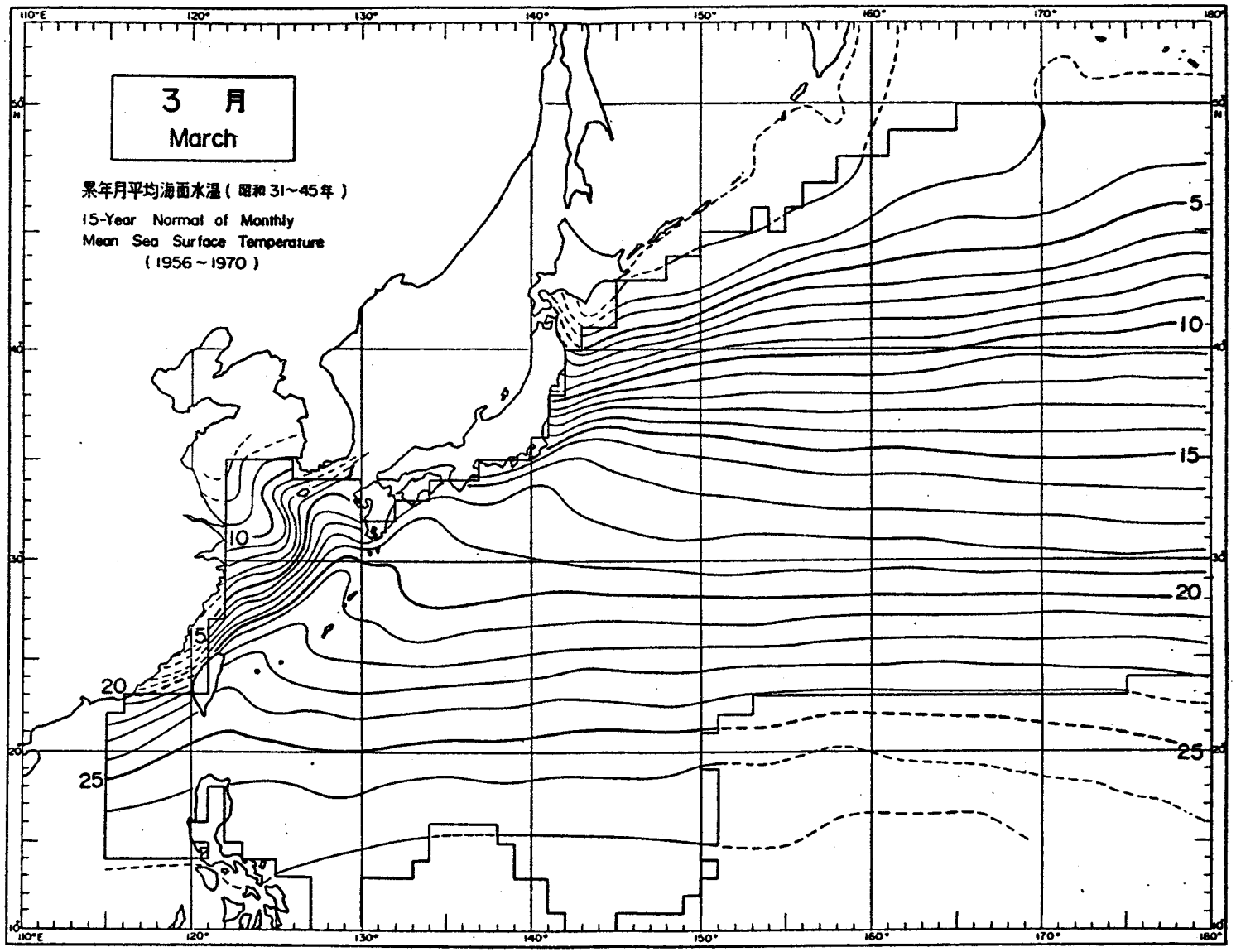



Figure 65.--Sea-surface temperature, March (from Japan Meteorological Agency 1975).

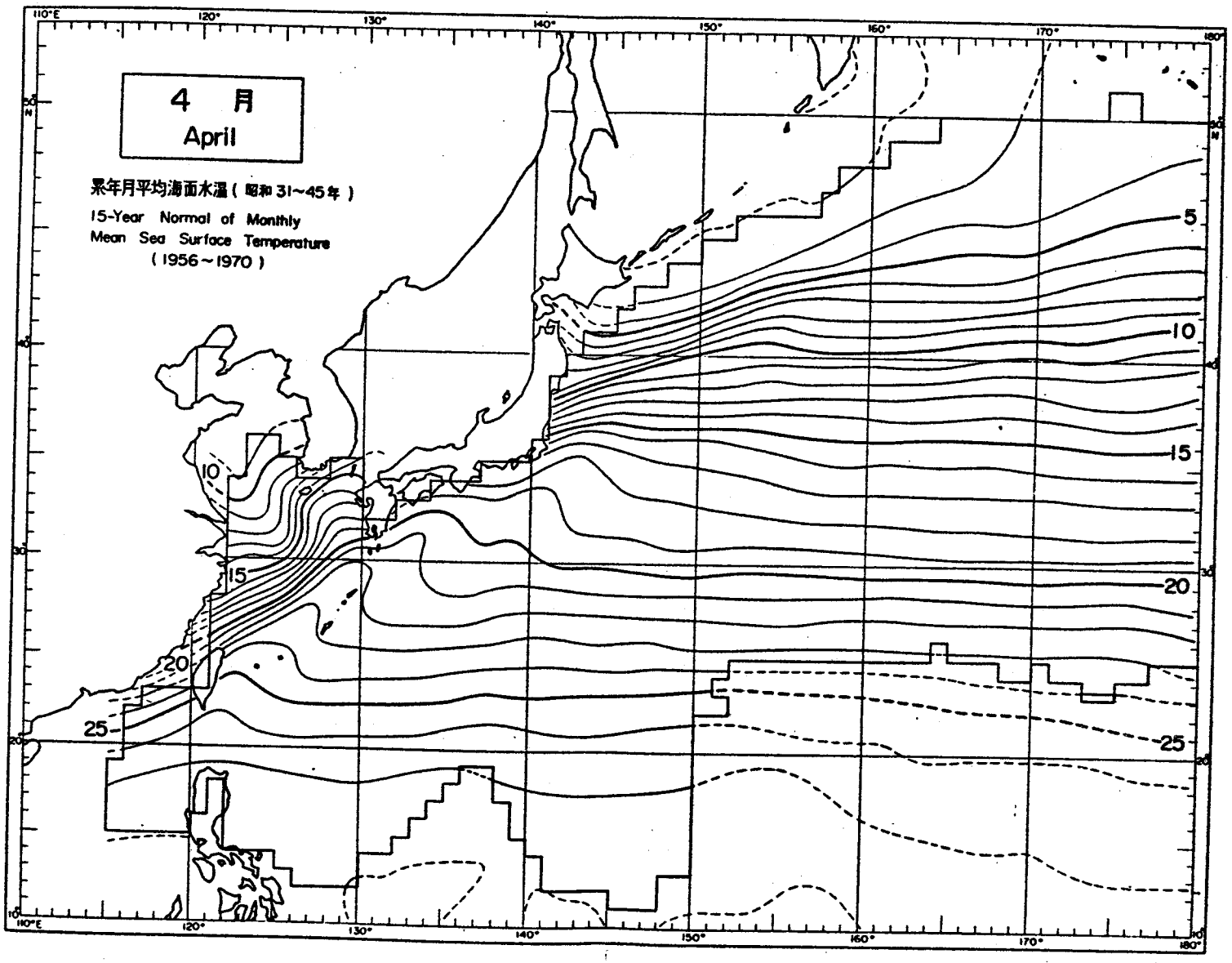



Figure 66.--Sea-surface temperature, April (from Japan Meteorological Agency 1975).

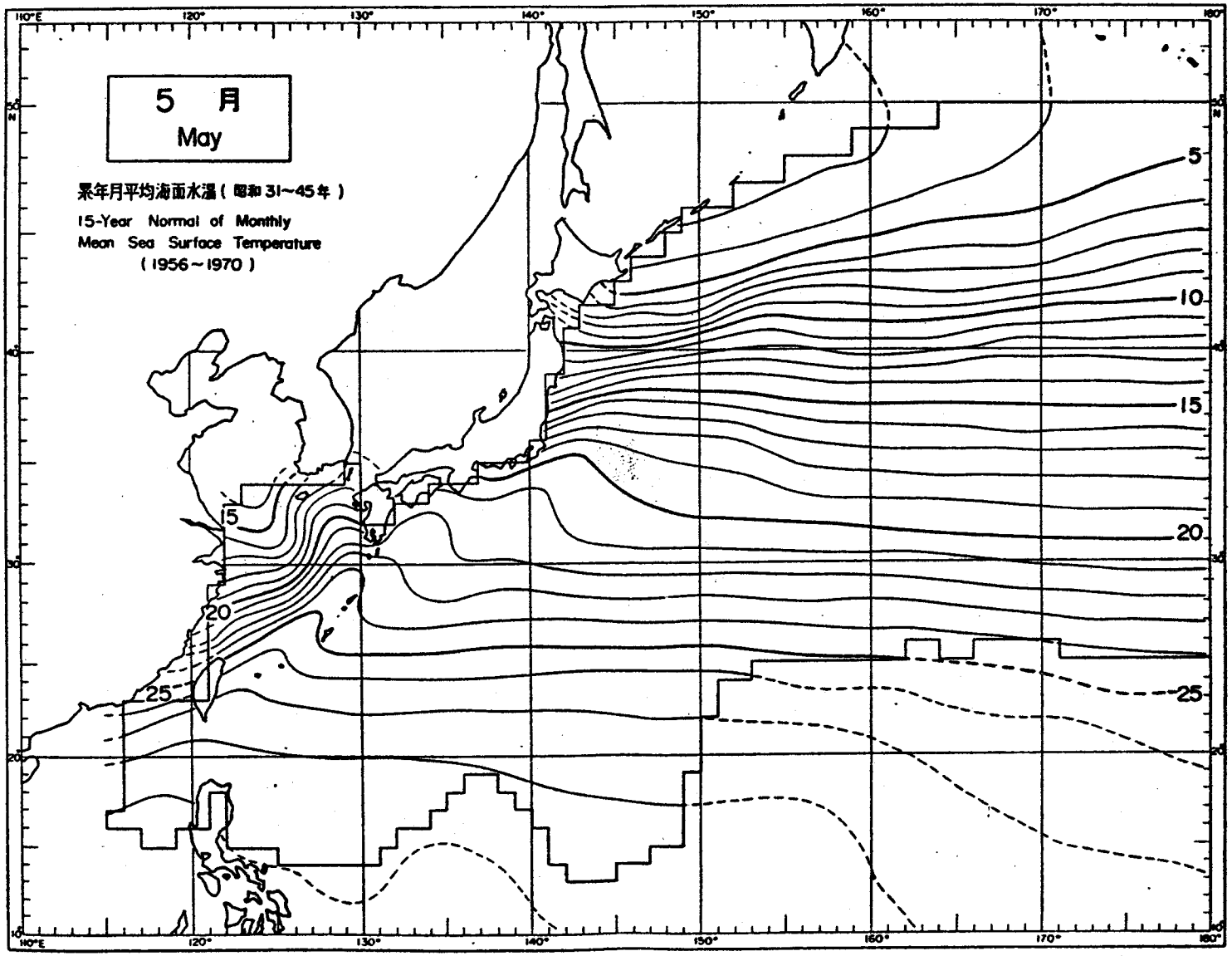



Figure 67.—Sea-surface temperature, May (from Japan Meteorological Agency 1975).

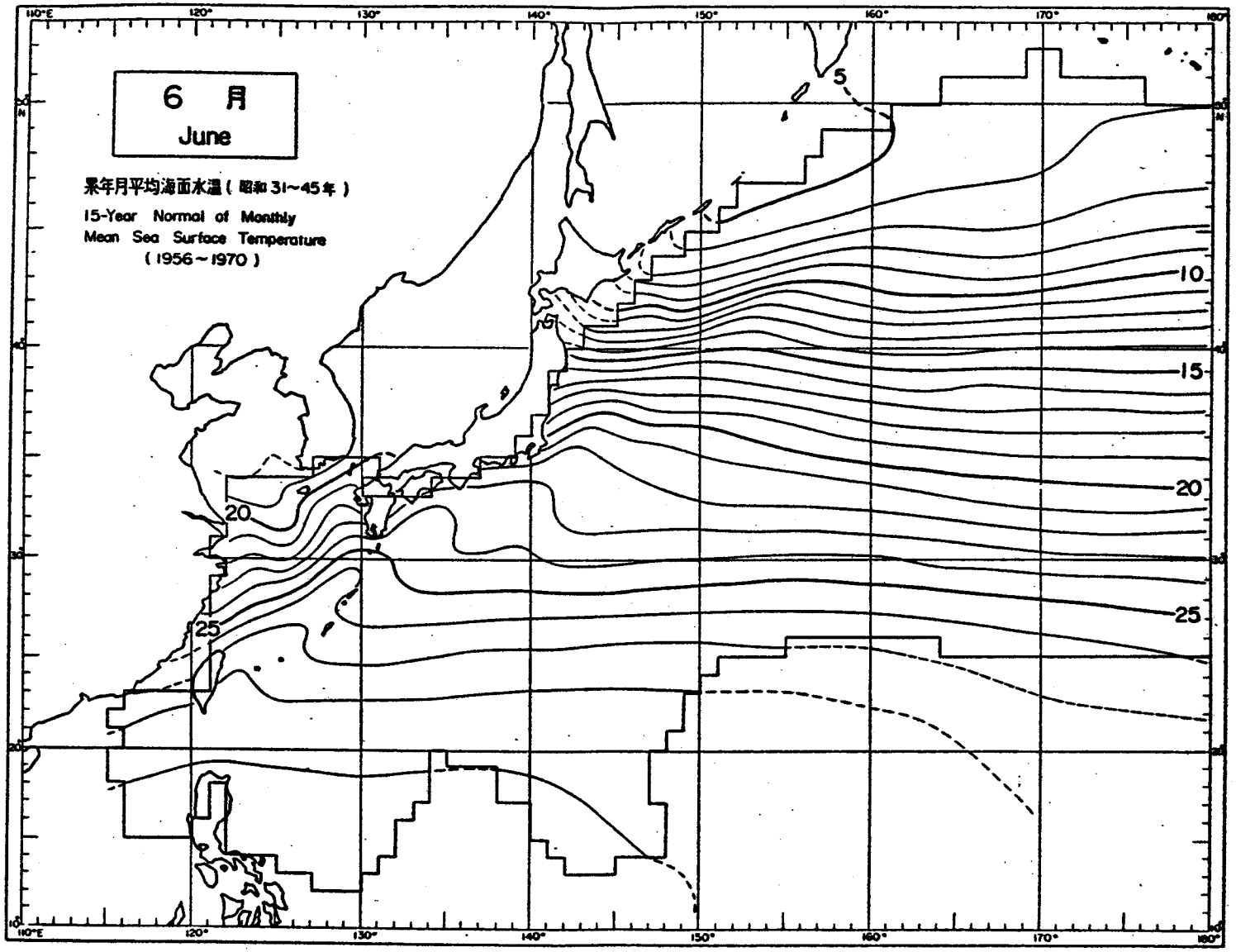



Figure 68.--Sea-surface temperature, June (from Japan Meteorological Agency 1975).

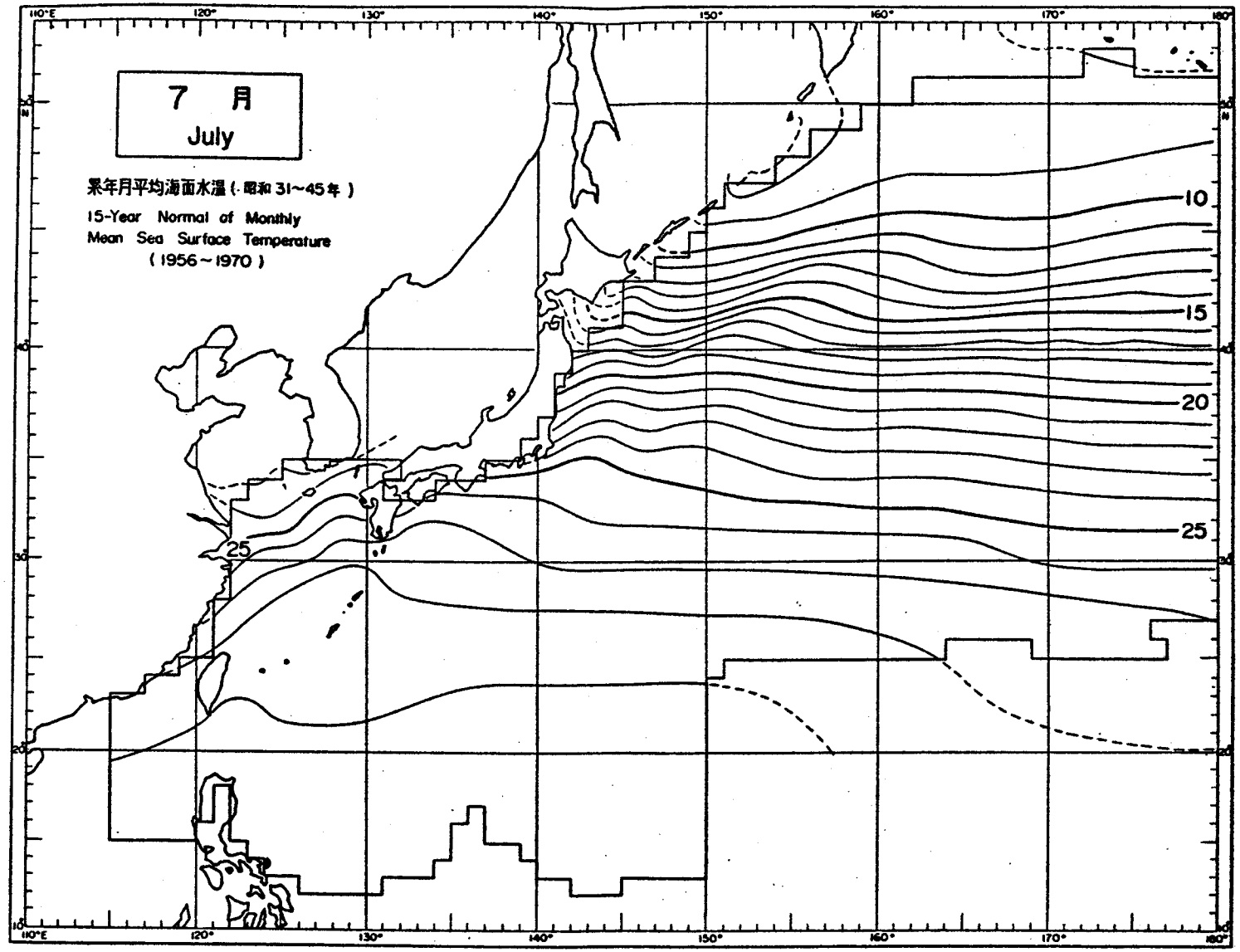



Figure 69.--Sea-surface temperature, July (from Japan Meteorological Agency 1975).

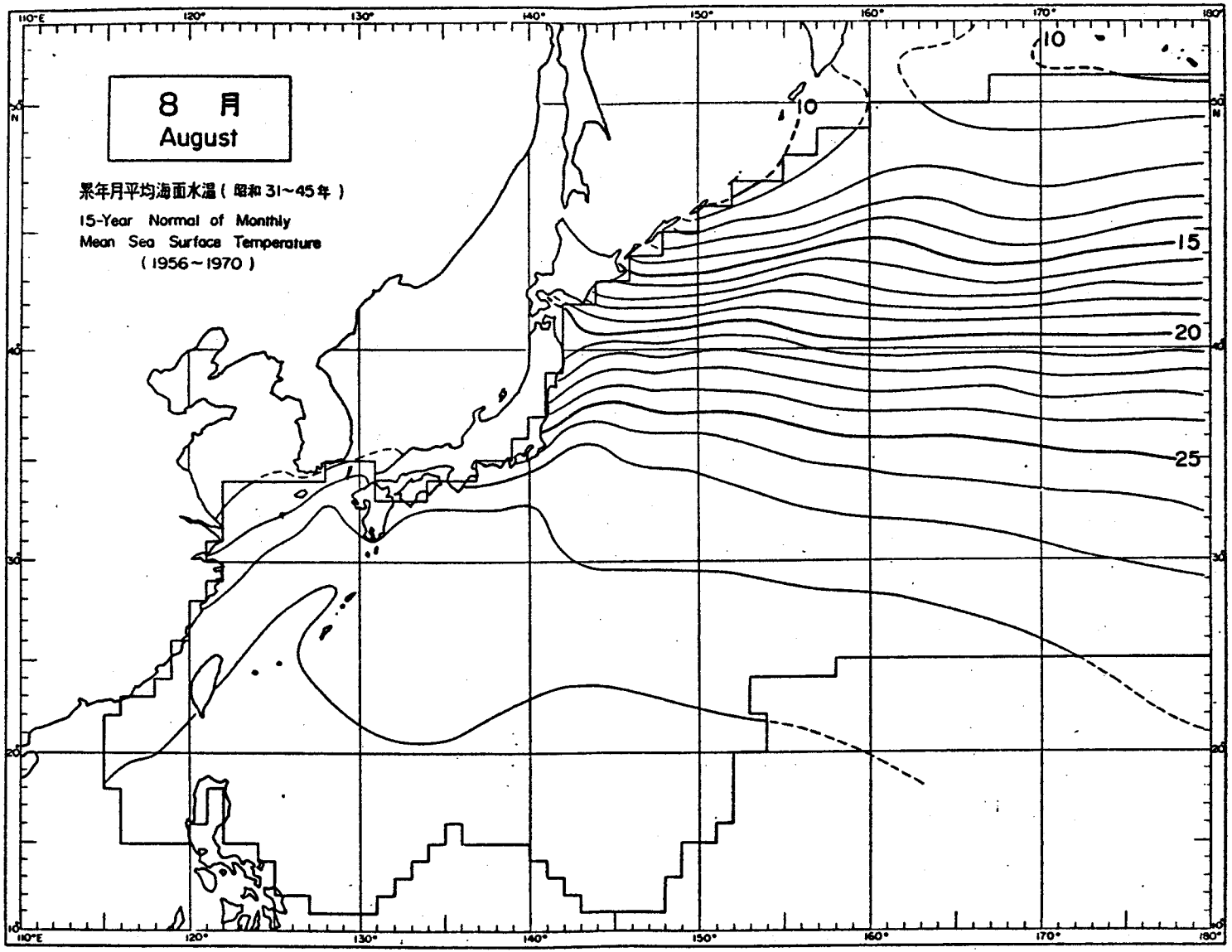



Figure 70.--Sea-surface temperature, August (from Japan Meteorological Agency 1975).

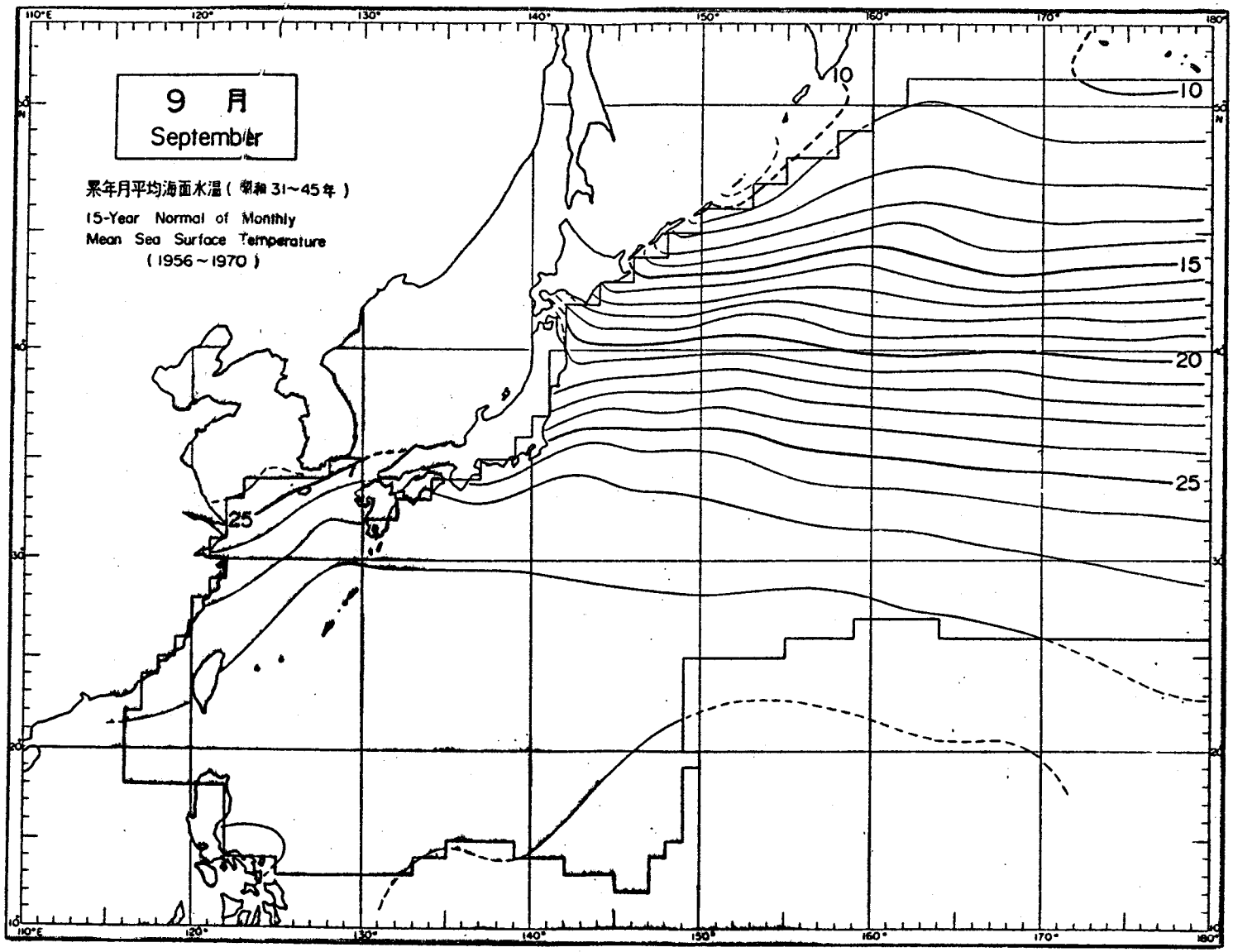



Figure 71.--Sea-surface temperature, September (from Japan Meteorological Agency 1975).

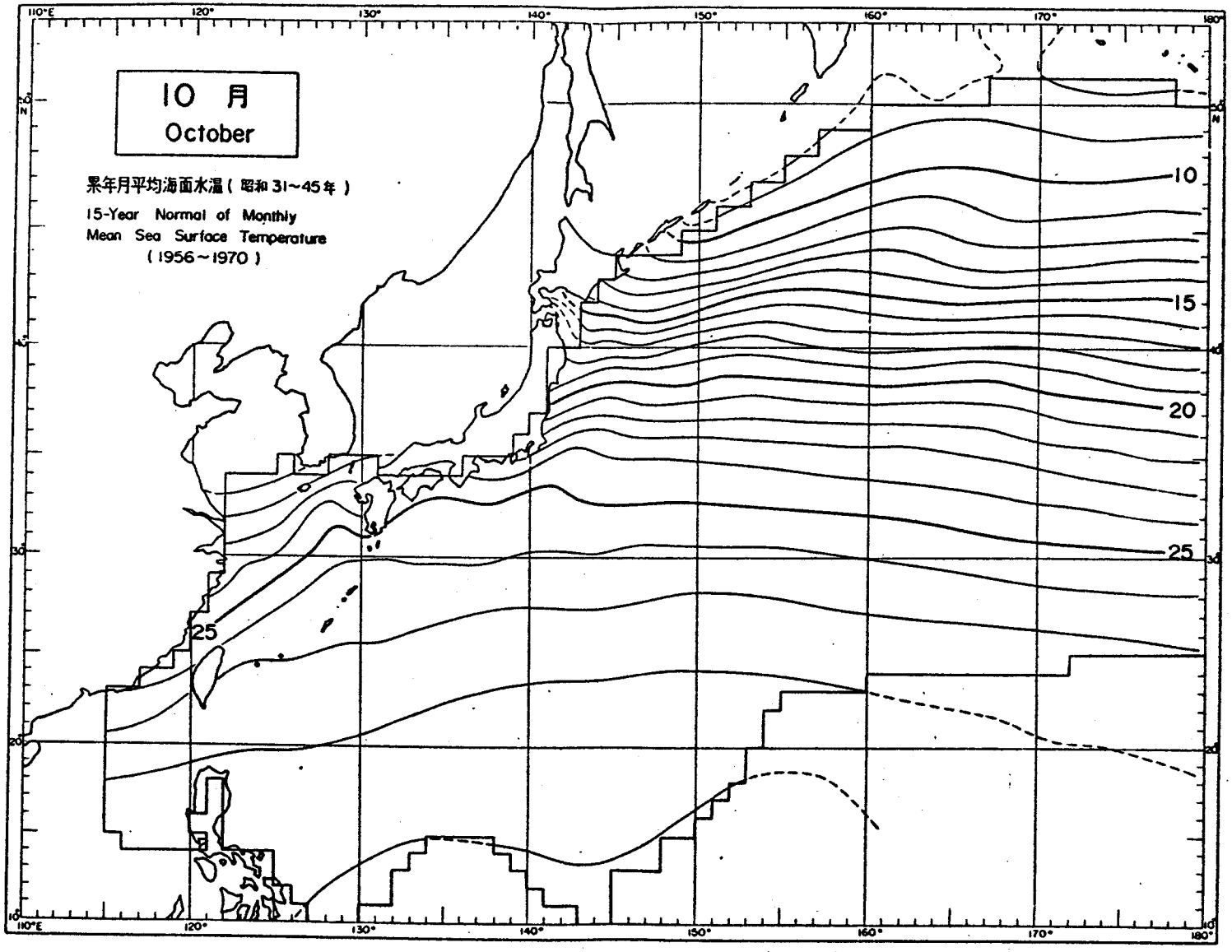



Figure 72.—Sea-surface temperature, October (from Japan Meteorological Agency 1975).

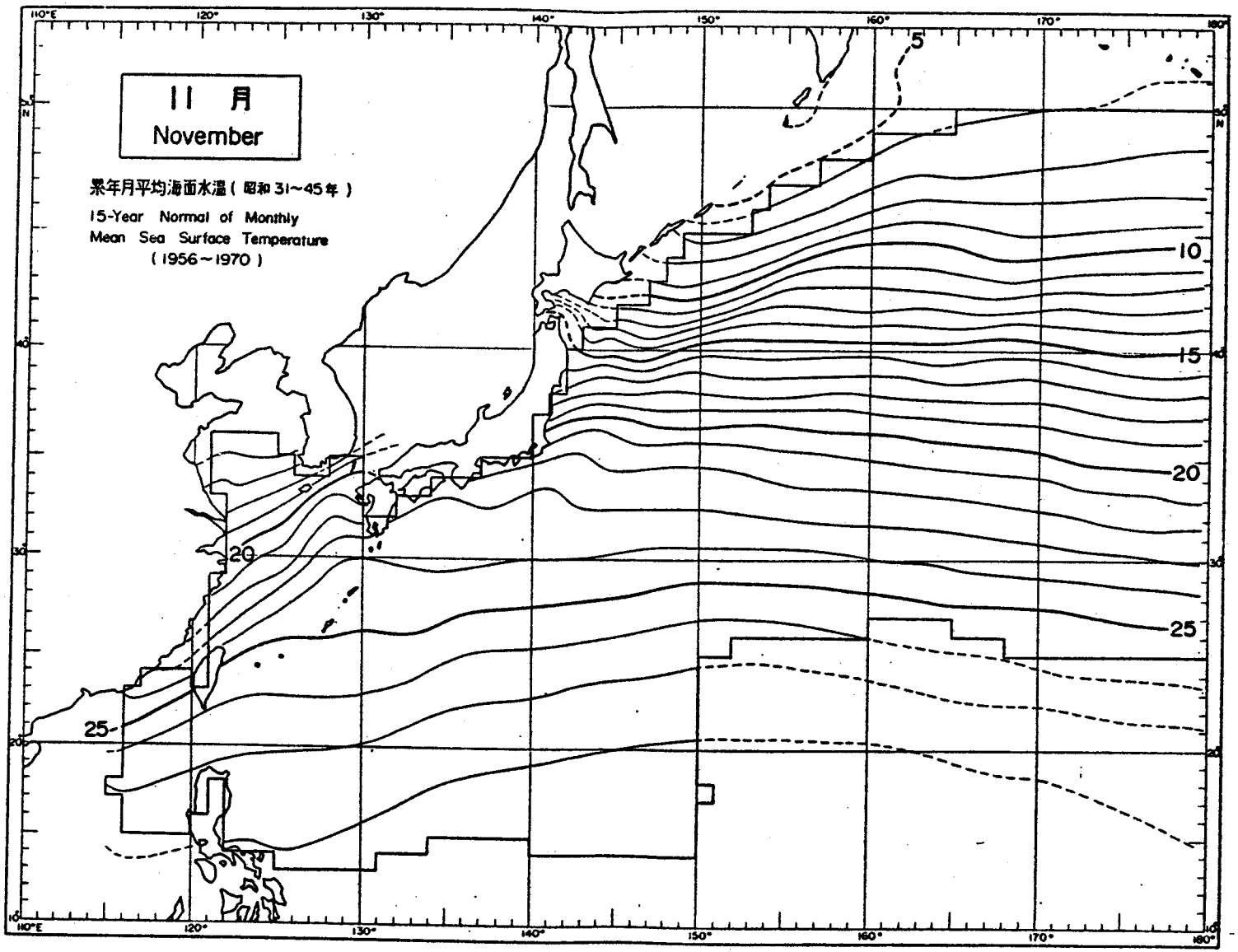



Figure 73.--Sea-surface temperature, November (from Japan Meteorological Agency 1975).

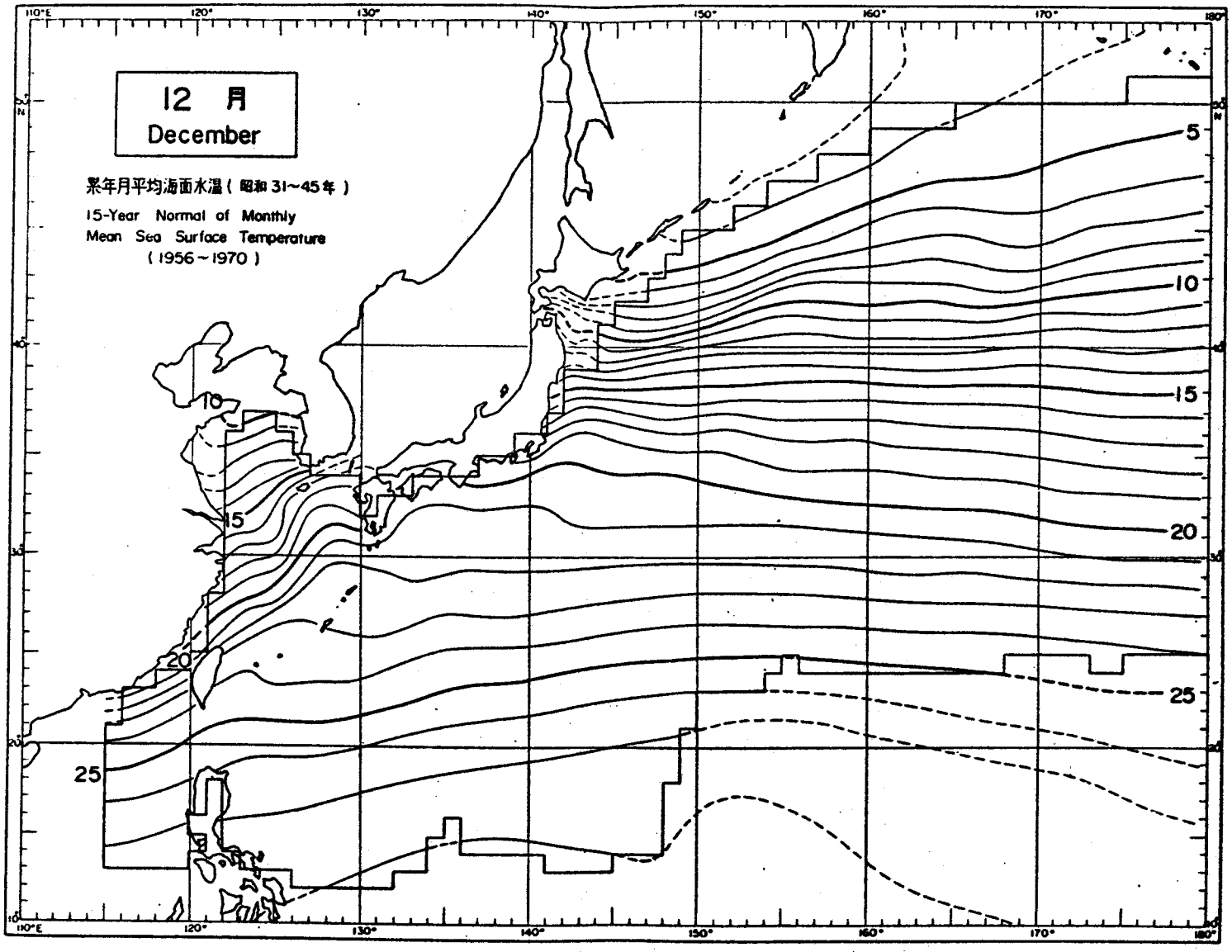



Figure 74.--Sea-surface temperature, December (from Japan Meteorological Agency 1975).

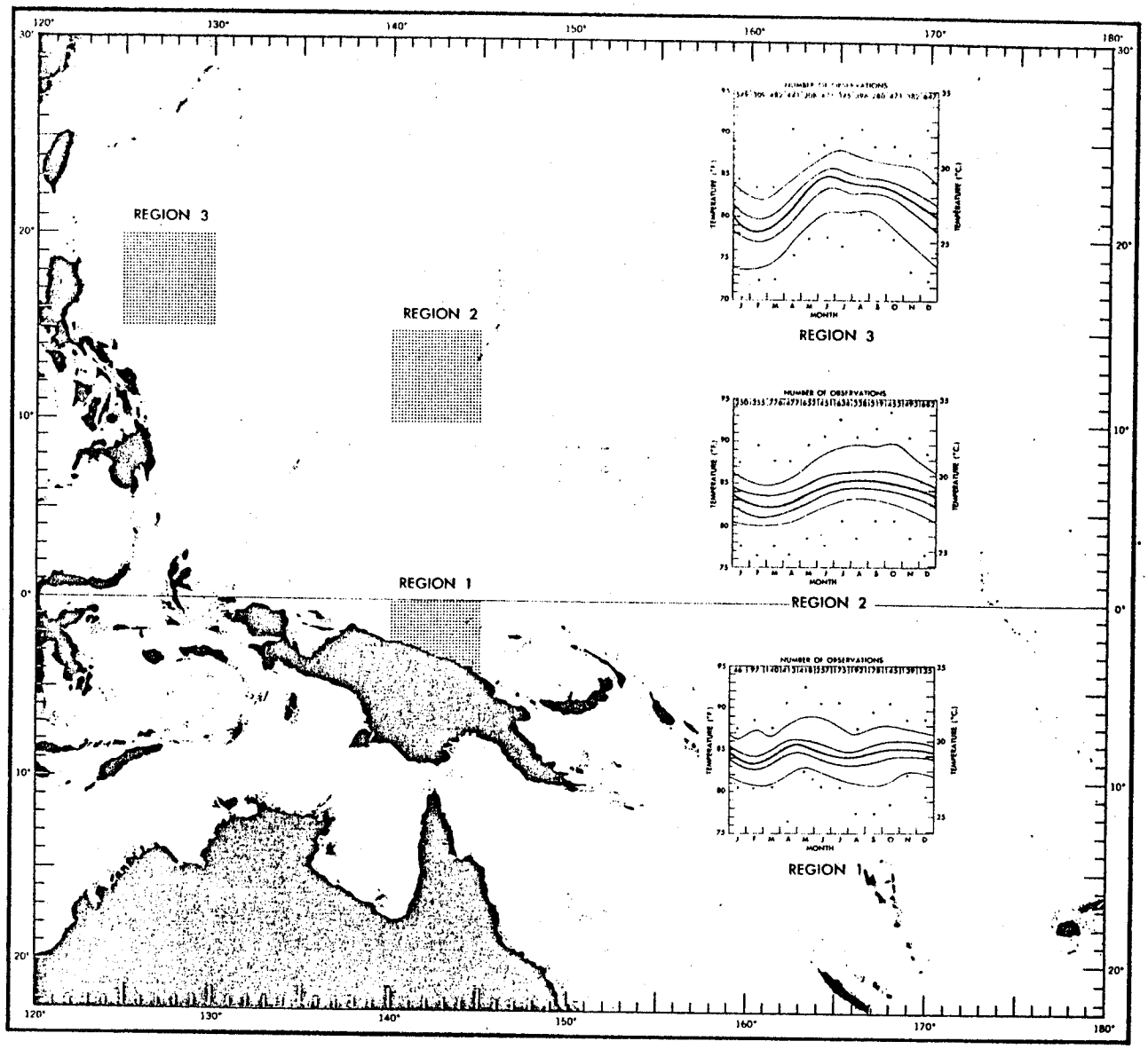



Figure 75.--Monthly variation of sea surface temperature in selected areas (dots represent the absolute extreme value reported; the inner (shaded) and outer (unshaded) envelopes represent 50 and 95 percent of the data observed (from LaViolette 1970).

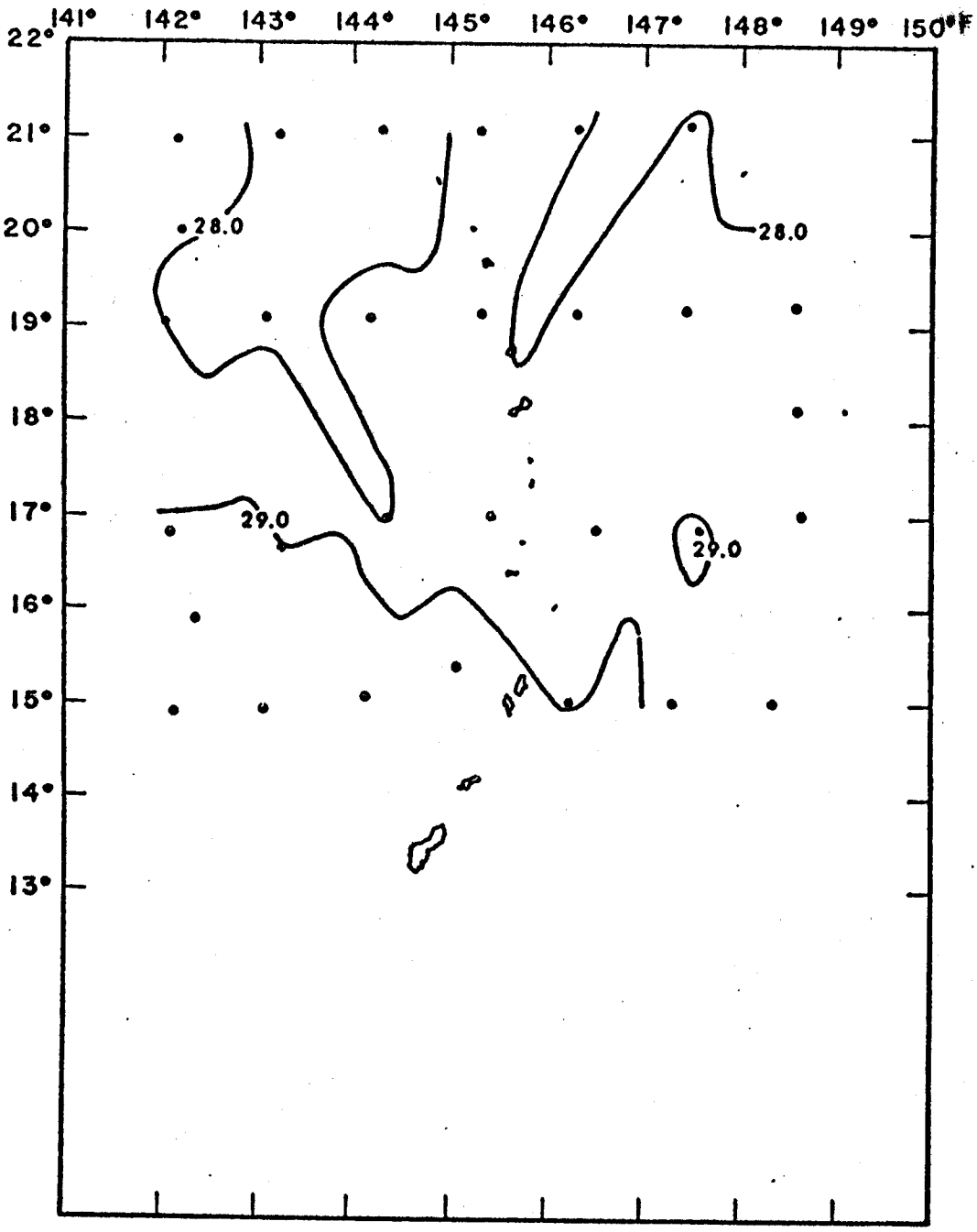



Figure 76.--Sea surface temperature north of Saipan (21 April-2 May 1971) (from deWitt 1972).

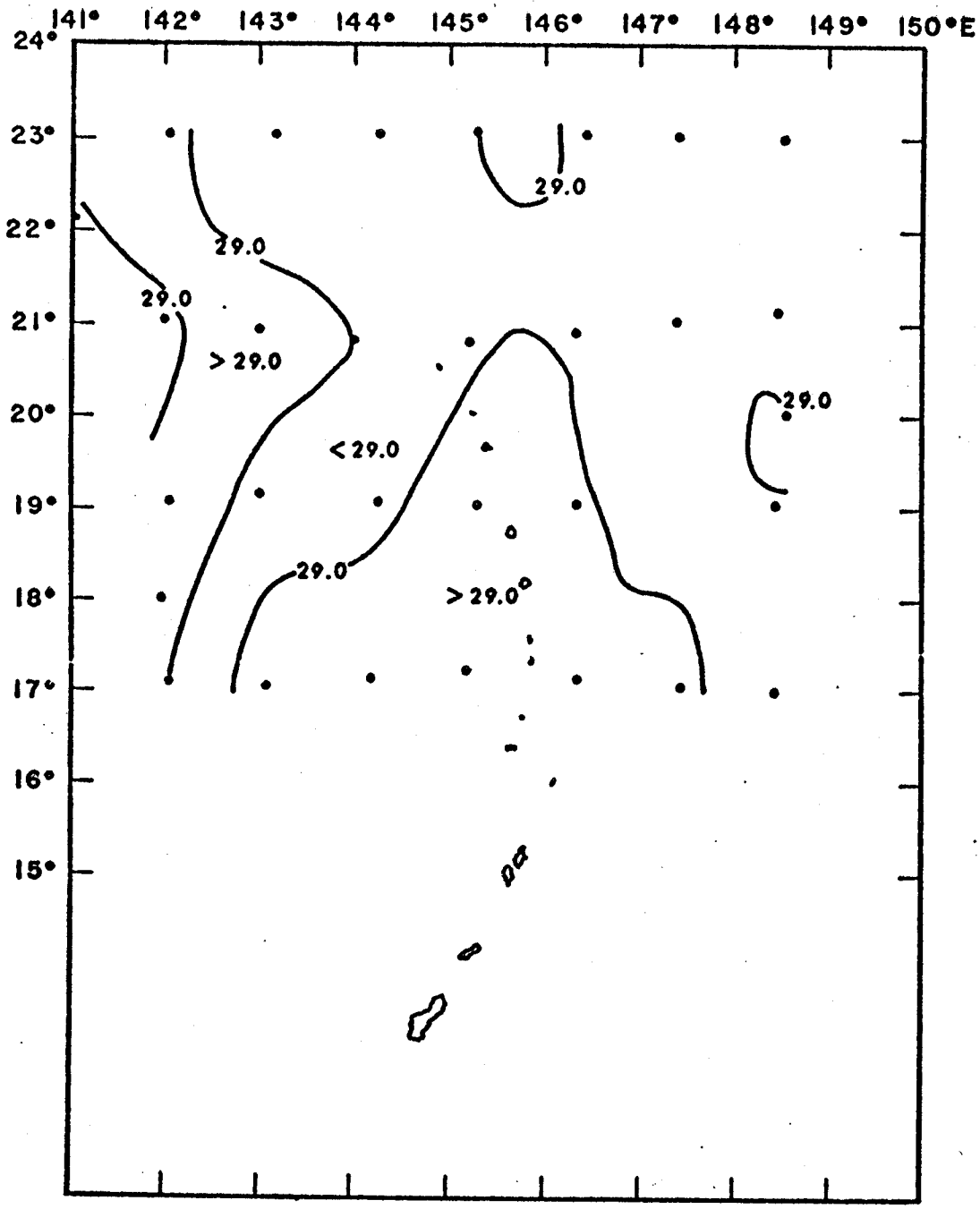



Figure 77.--Sea-surface temperature north of Saipan (2-12 November 1971) (from deWitt 1972).

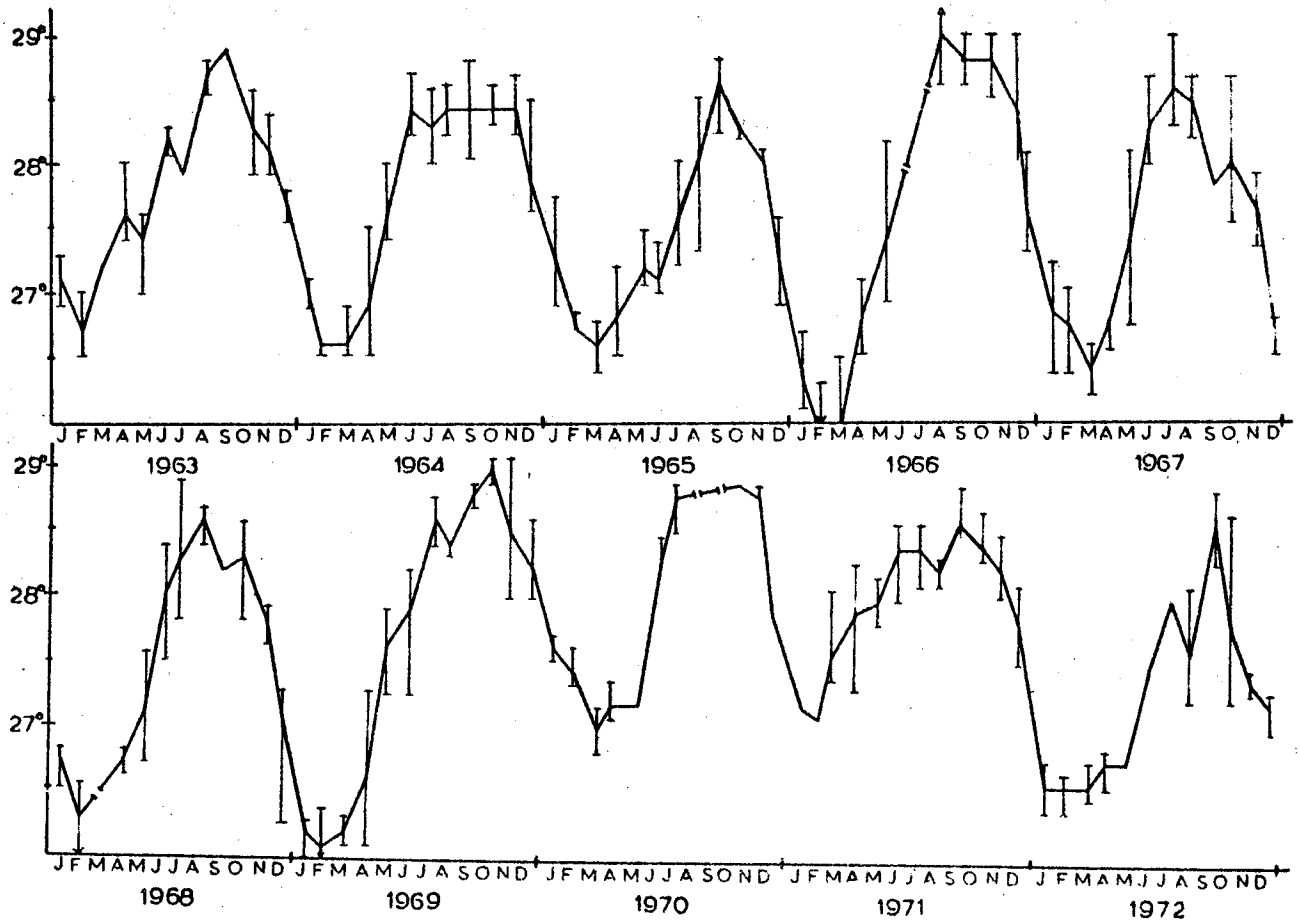



Figure 78.--Plot of mean monthly sea-surface temperatures for a 10-year period at Tanguisson Point, Guam (from Jones et al. 1976).

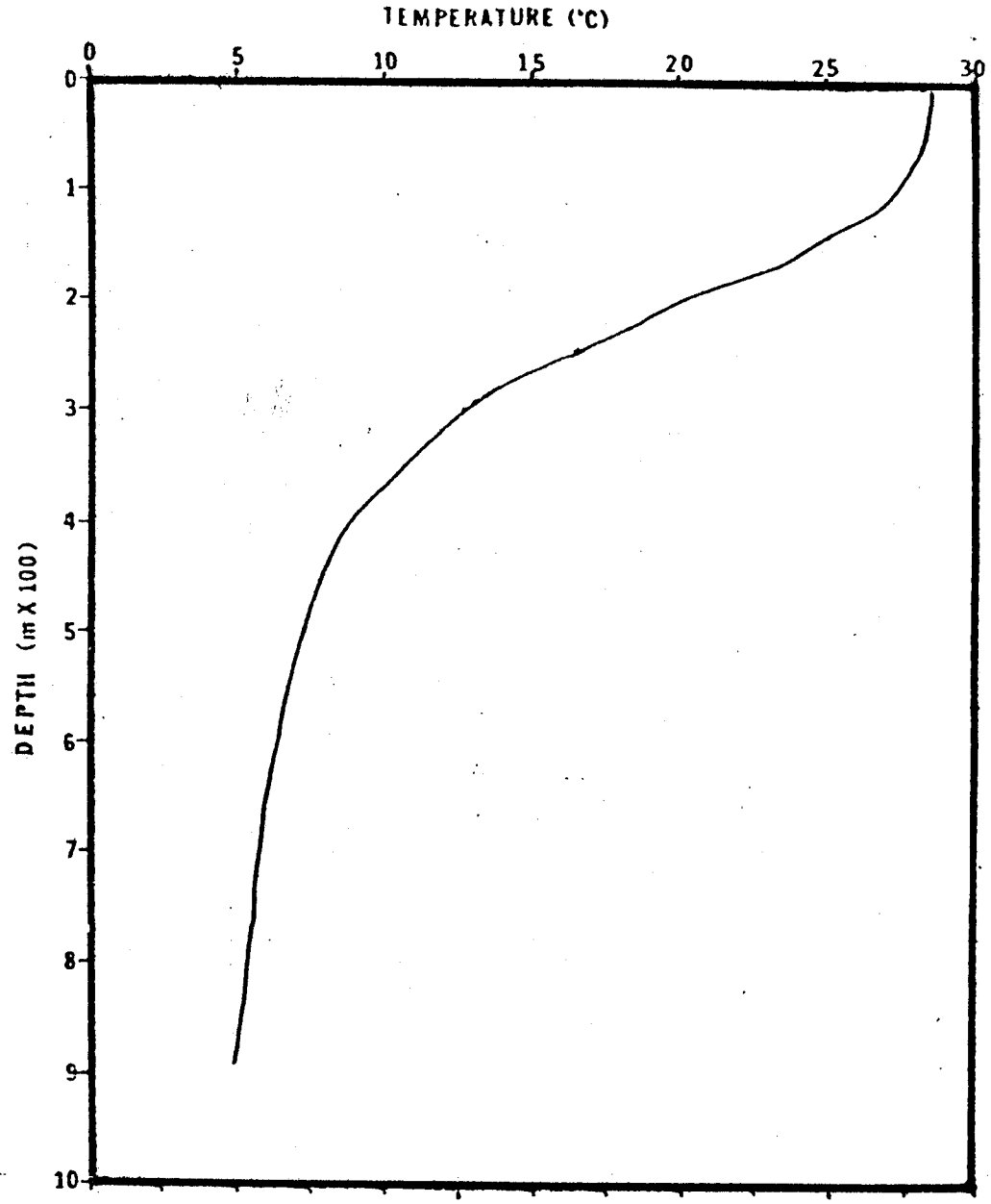



Figure 79.--Mean temperature profile in the vicinity of Cabras Island, Luminao Reef, and Glass Breakwater, Guam (February 1978-February 1979) (from Lassuy 1979).

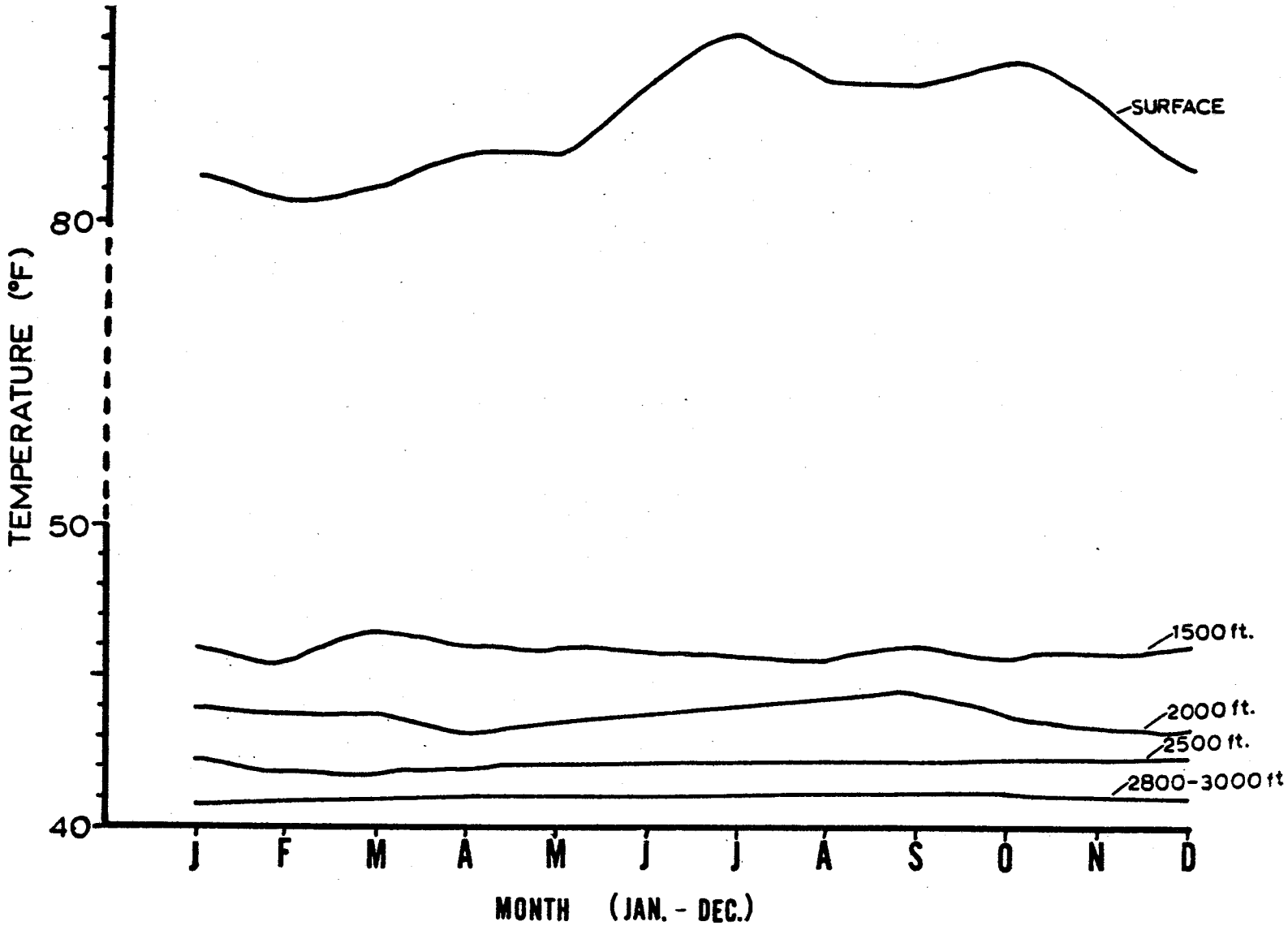



Figure 80.--Mean monthly temperatures for surface, 1500, 2000, 2500, and 2800-3000 feet in the vicinity of Cabras Island, Luminao Reef, and Glass Breakwater, Guam (from Lassuy 1979).

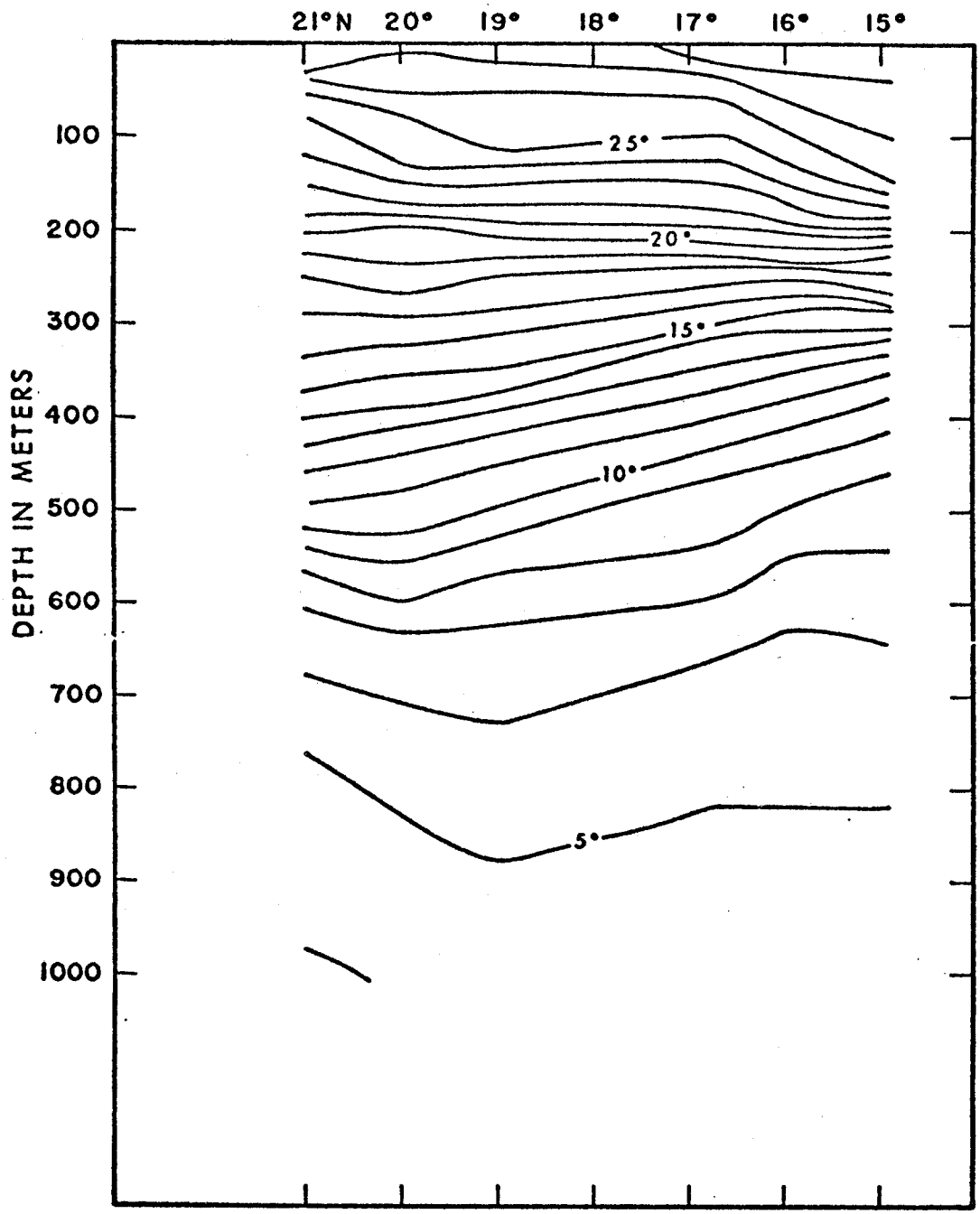



Figure 81.--Temperature along 142°E (21 April-2 May 1971) (from deWitt 1972).

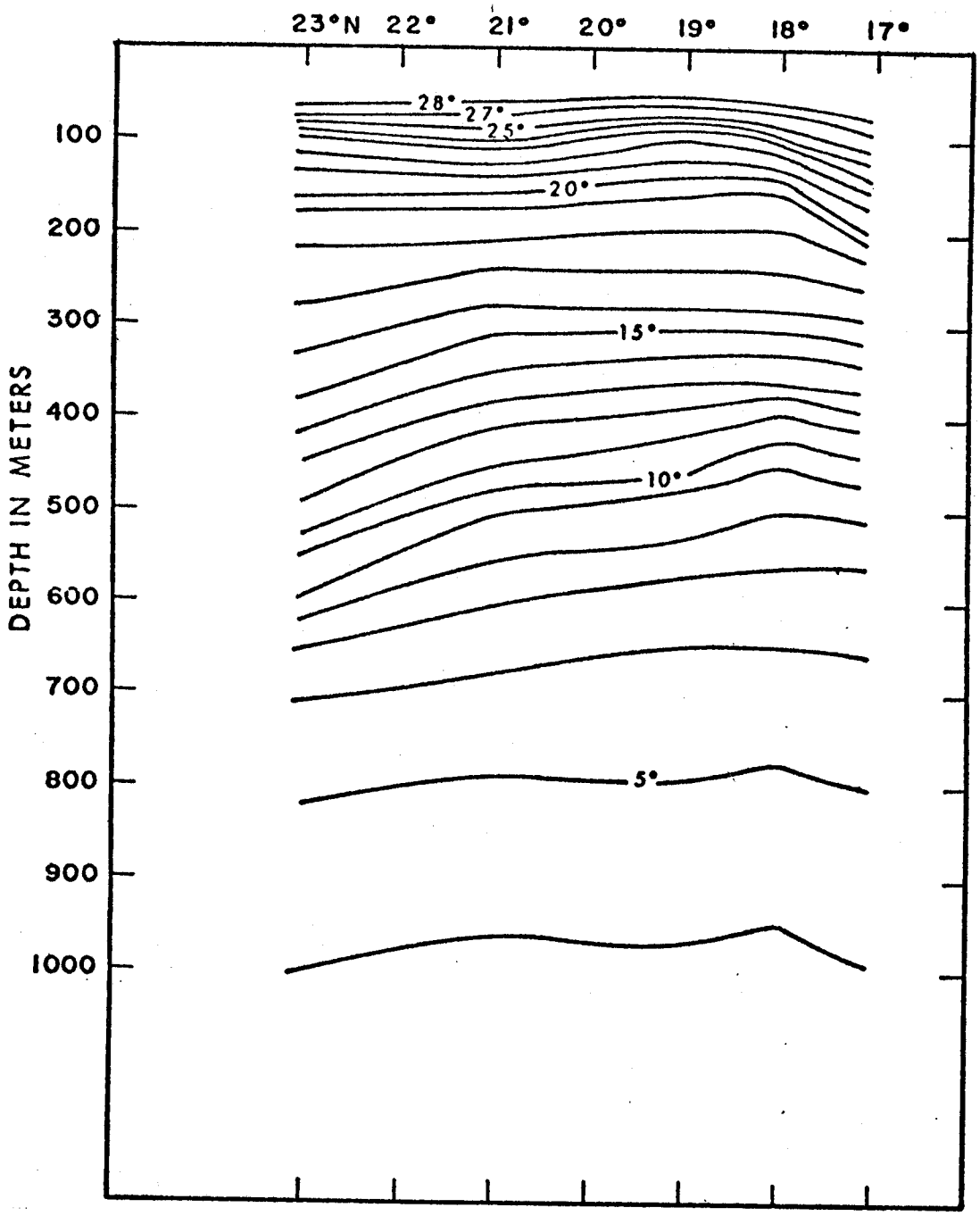



Figure 82.--Temperature along 142°E (1-12 November 1971) (from deWitt 1972).

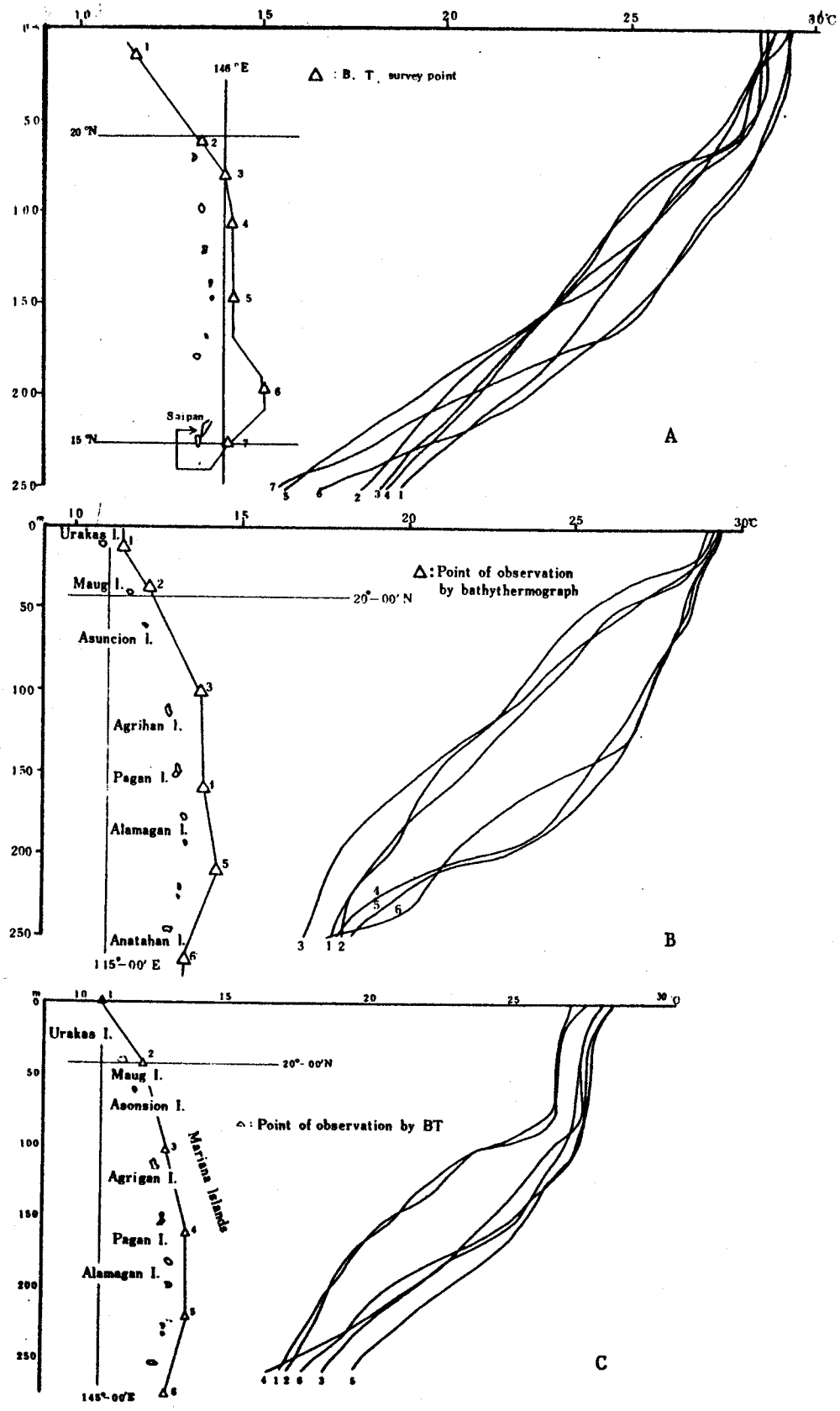



Figure 83.--Vertical distribution of water temperature: A--9-13 July 1974; B--28 May-1 June 1975; C--31 May-2 June 1976 (from JAMARC 1975, 1976, 1977).

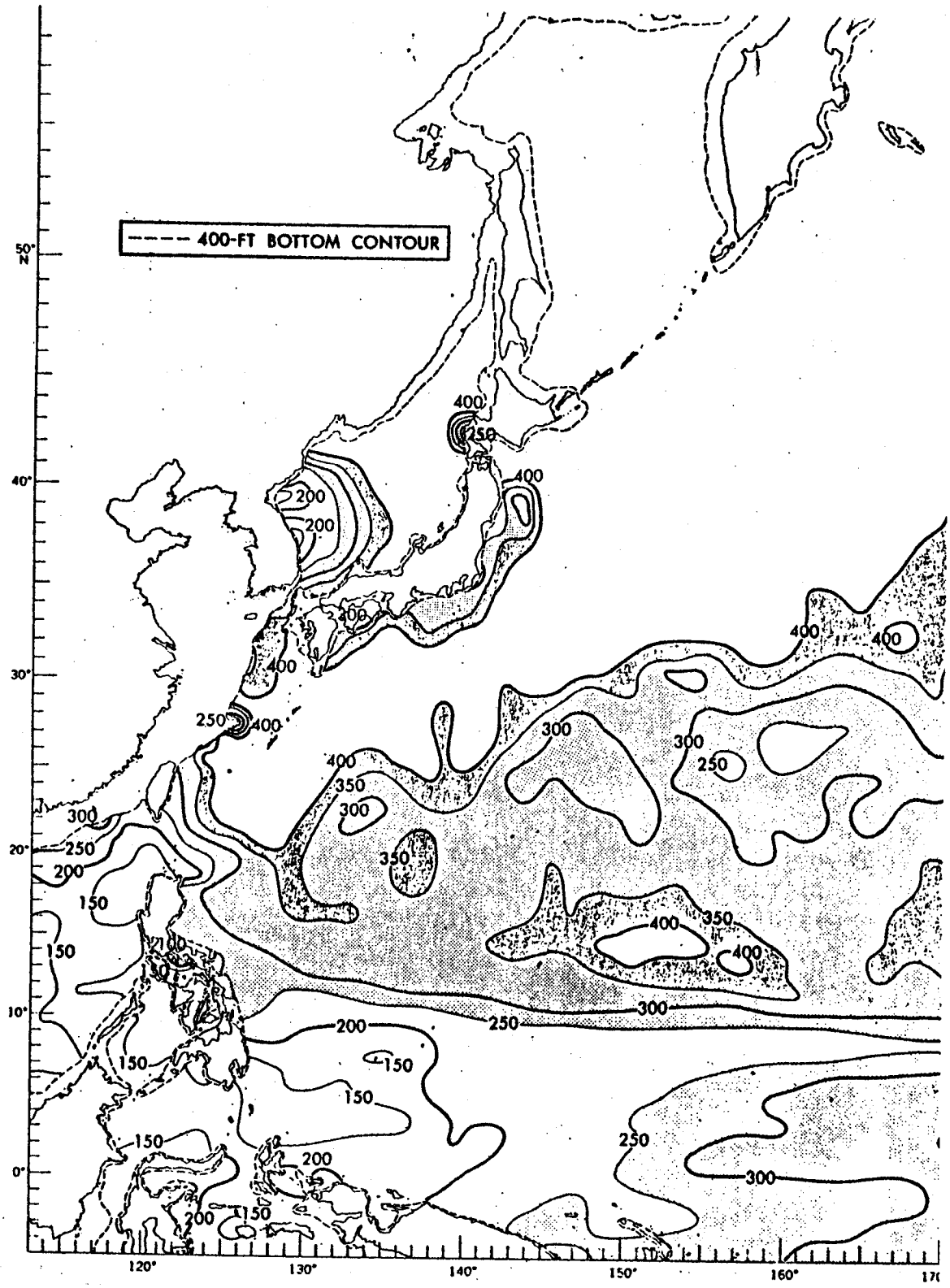



Figure 84.--Mean depth (in feet) to the top of the thermocline, January (from Robinson 1976).

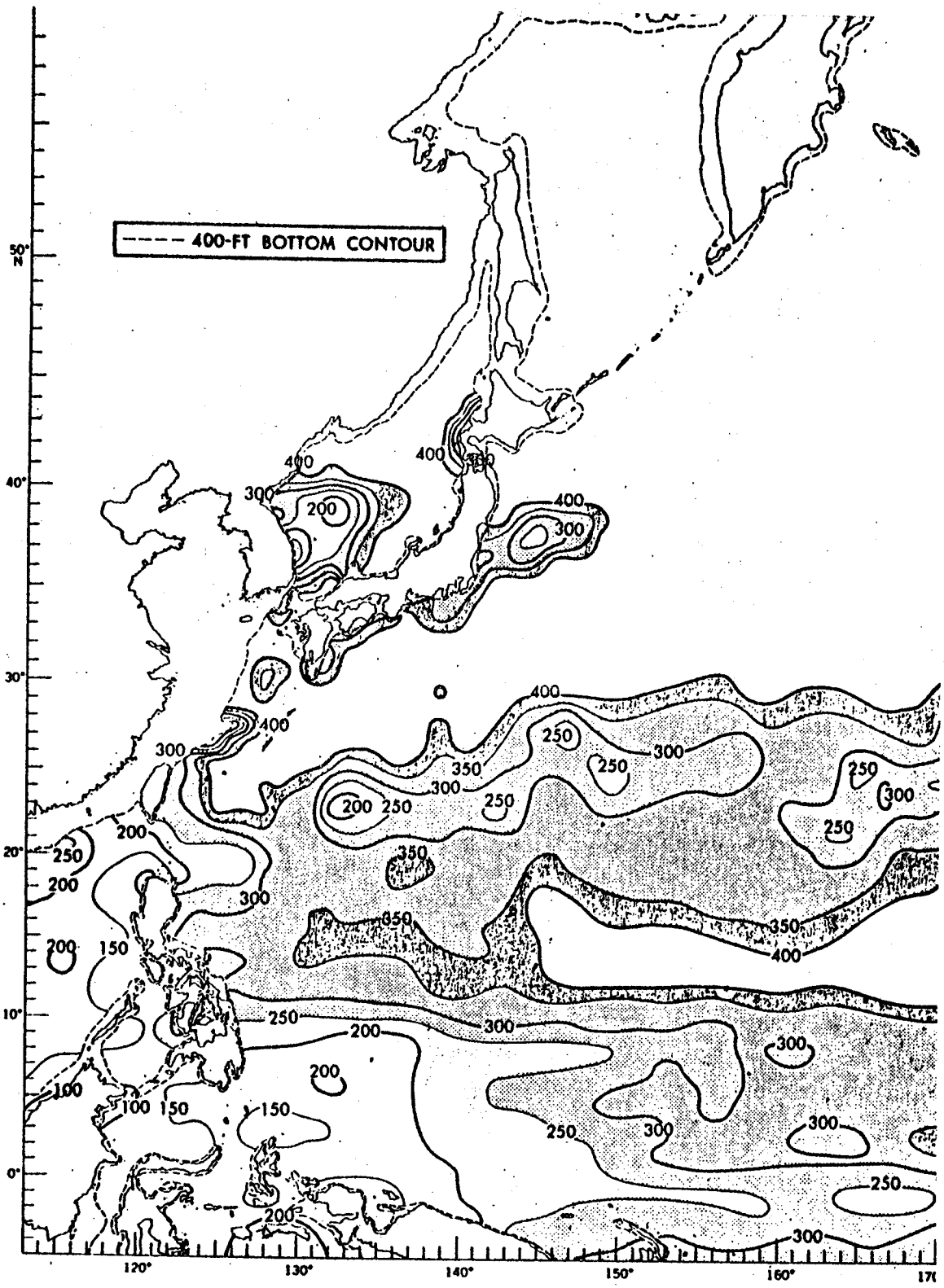



Figure 85.--Mean depth (in feet) to the top of the thermocline, February (from Robinson 1976).

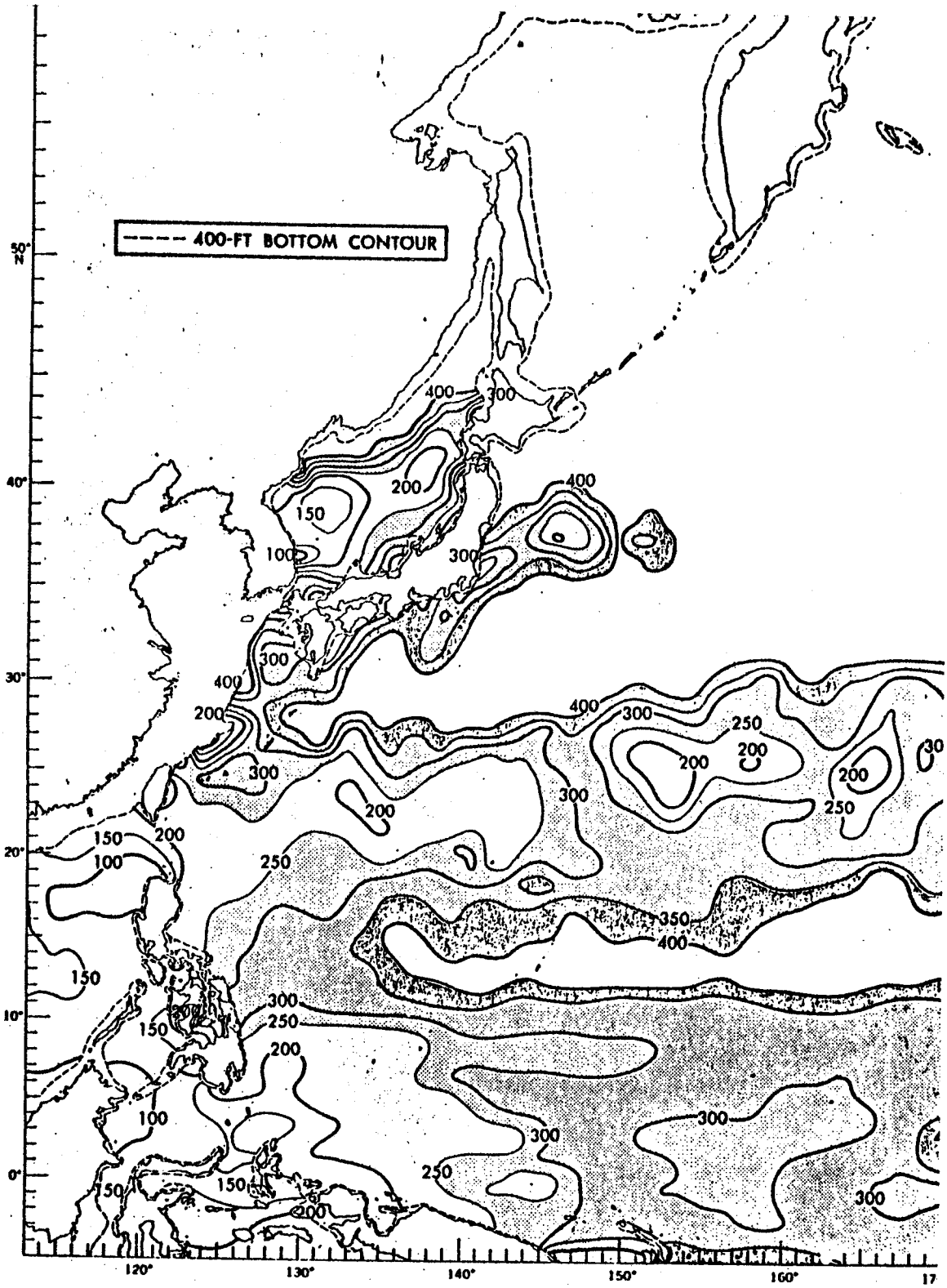



Figure 86.--Mean depth (in feet) to the top of the thermocline, March (from Robinson 1976).

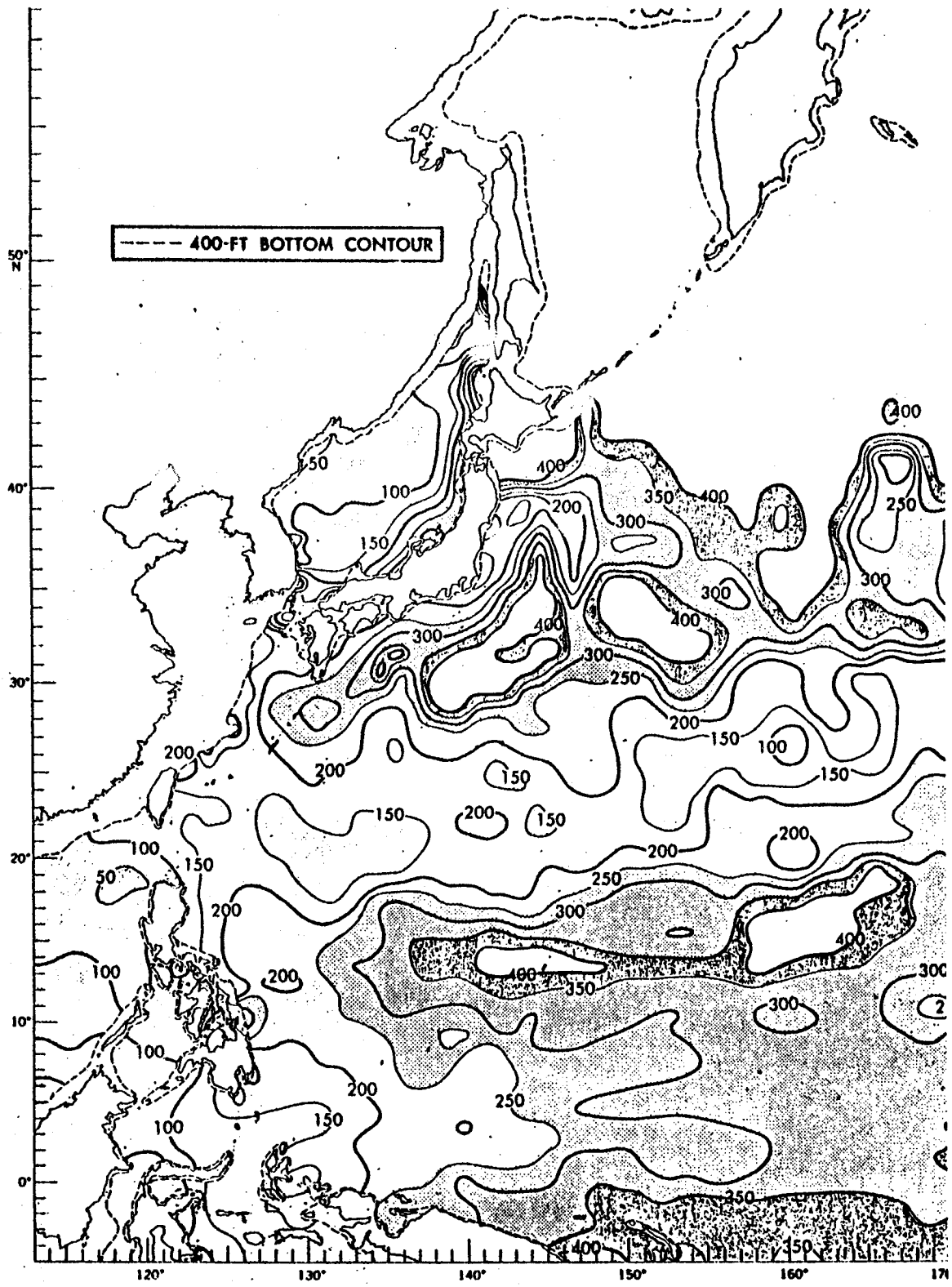



Figure 87.--Mean depth (in feet) to the top of the thermocline, April (from Robinson 1976).

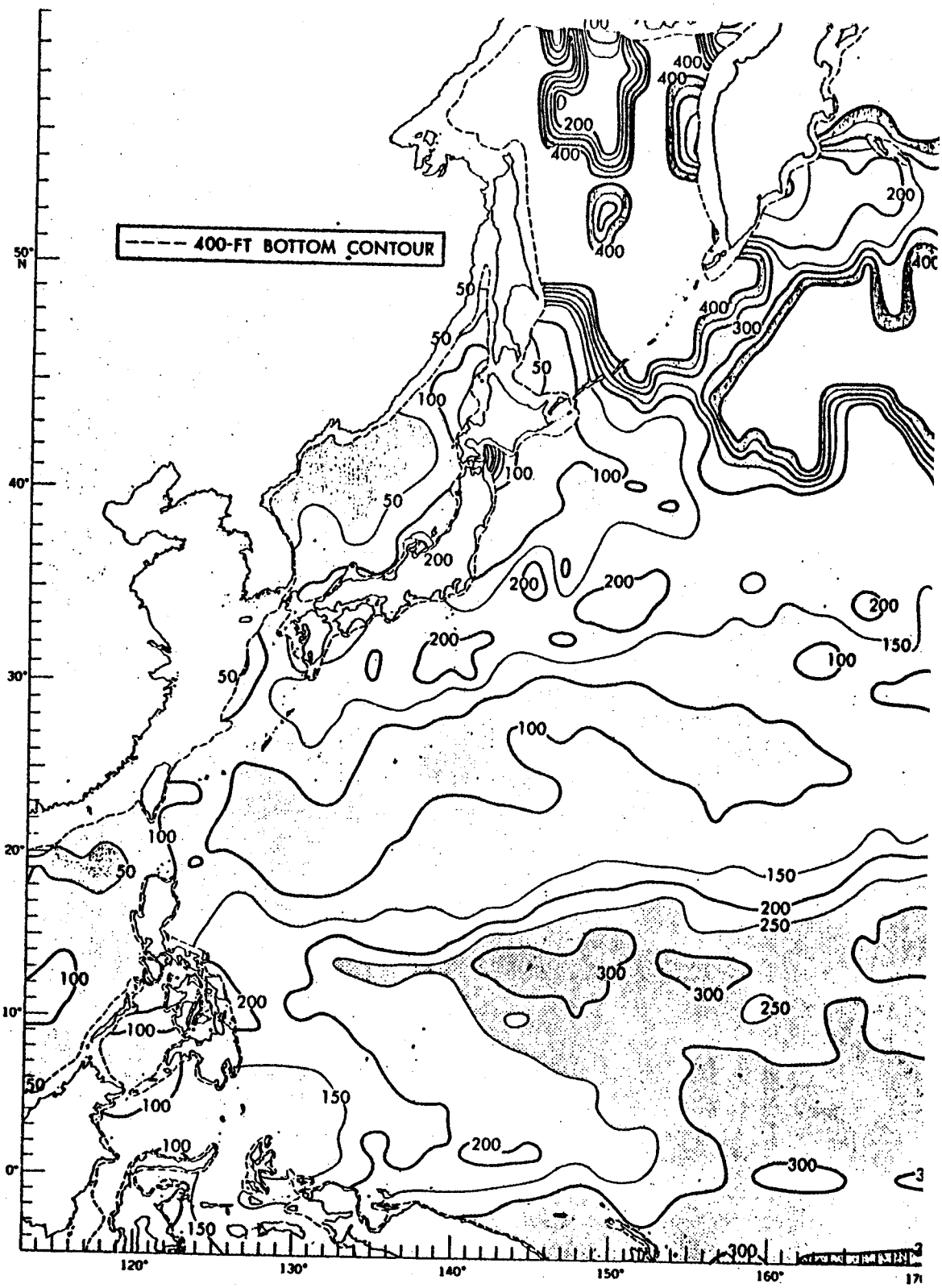



Figure 88.--Mean depth (in feet) to the top of the thermocline, May (from Robinson 1976).

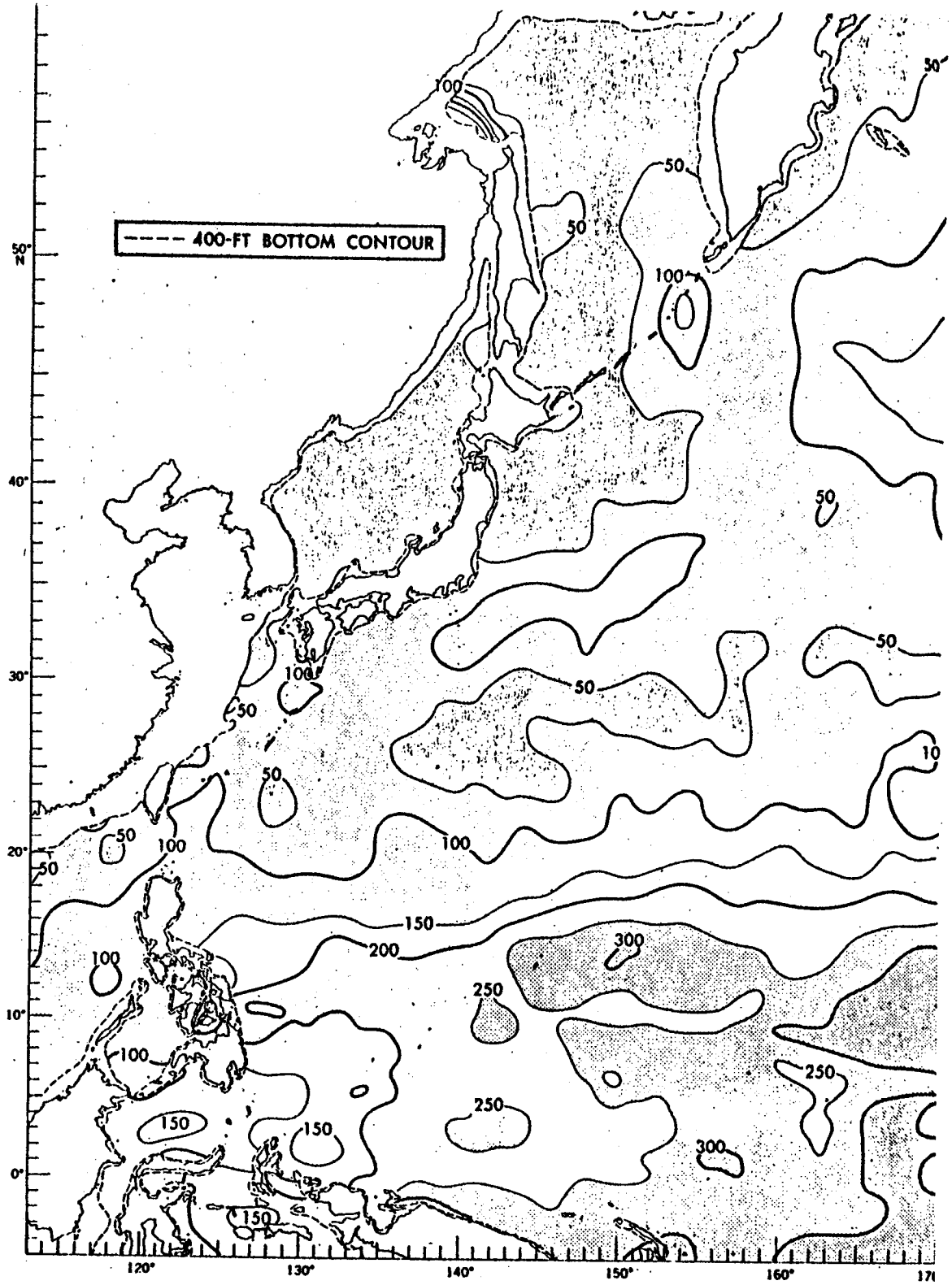



Figure 89.--Mean depth (in feet) to the top of the thermocline, June (from Robinson 1976).

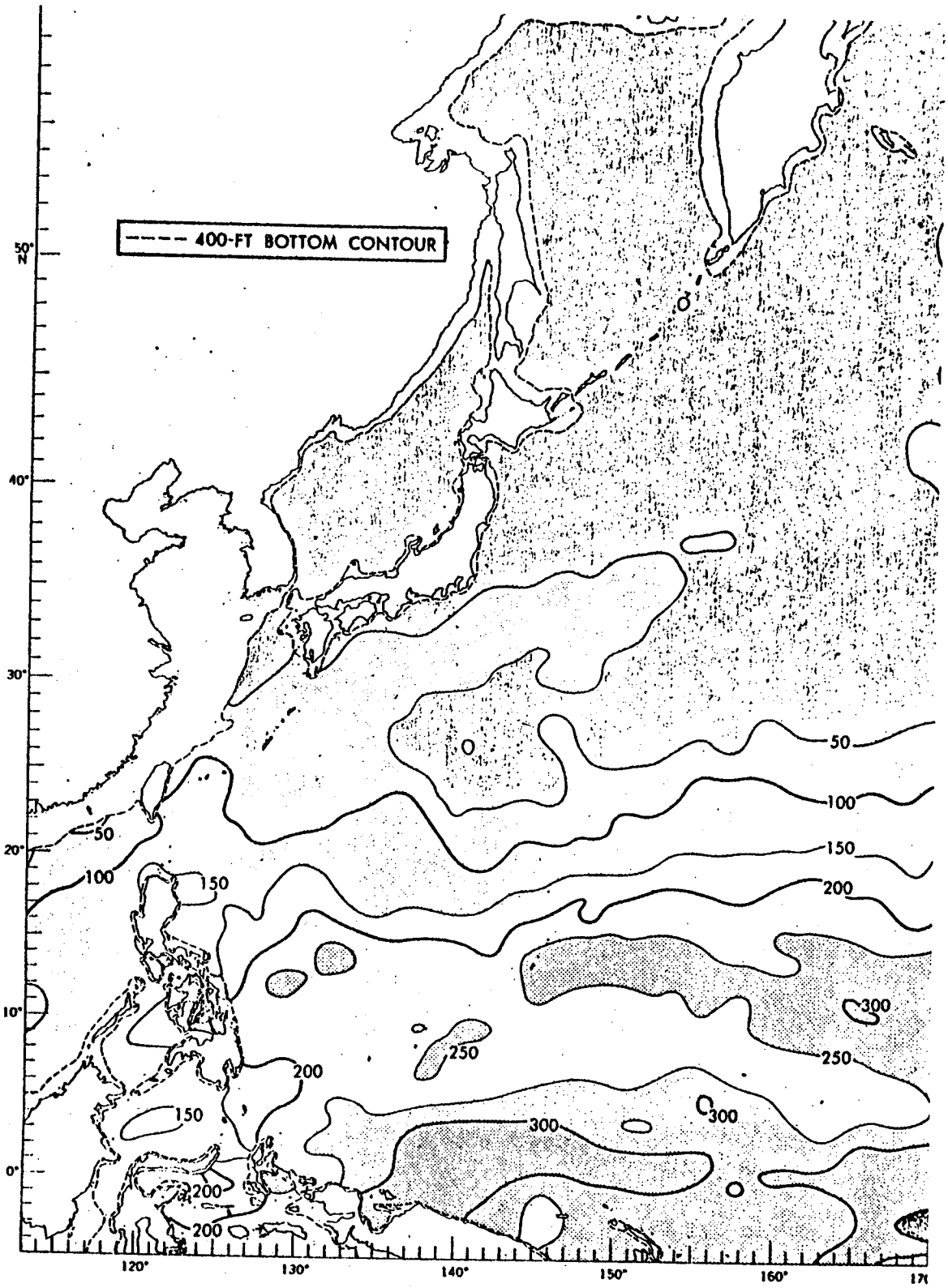



Figure 90.--Mean depth (in feet) to the top of the thermocline, July (from Robinson 1976).

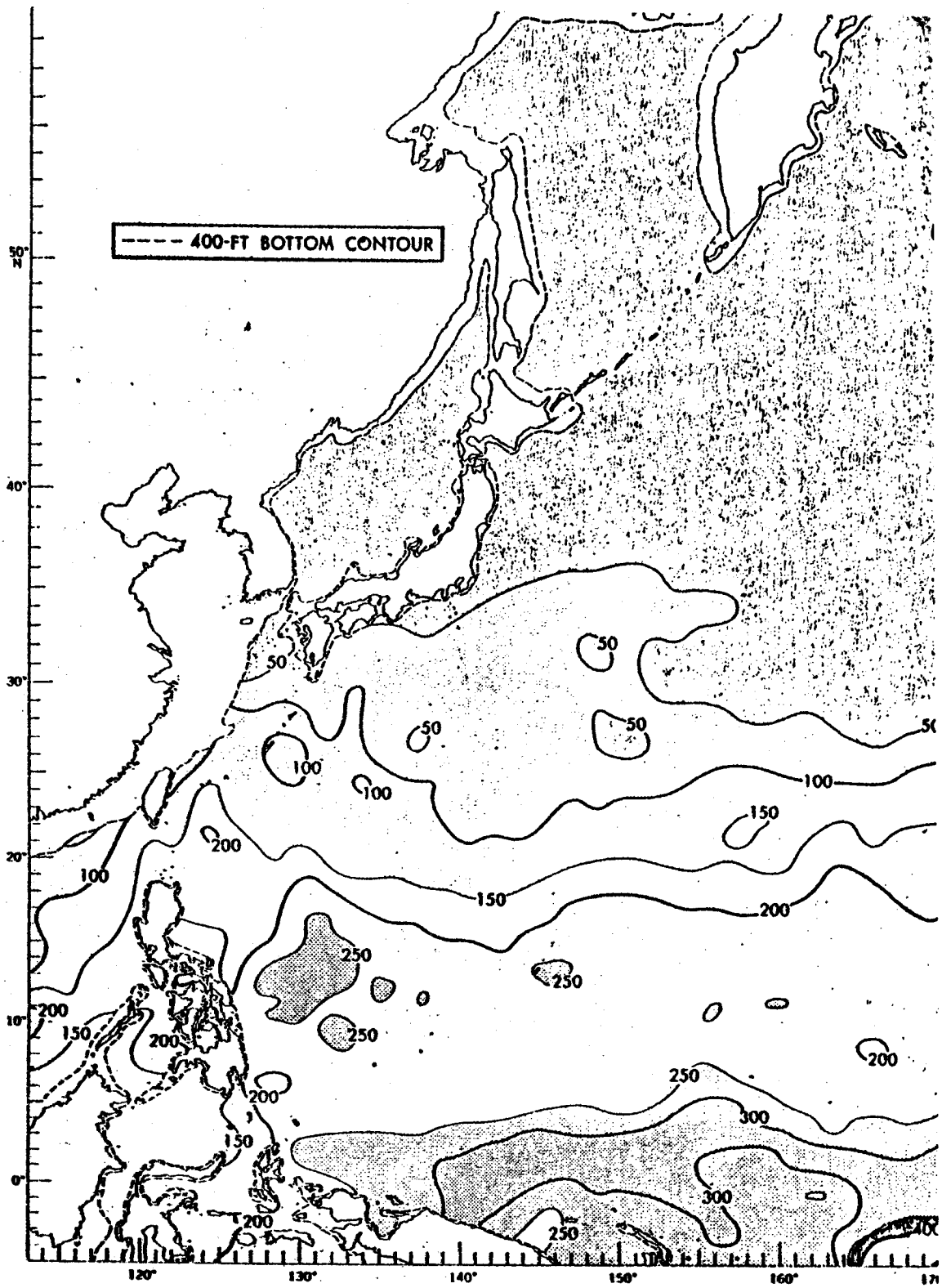



Figure 91.—Mean temperature (in feet) to the top of the thermocline, August (from Robinson 1976).

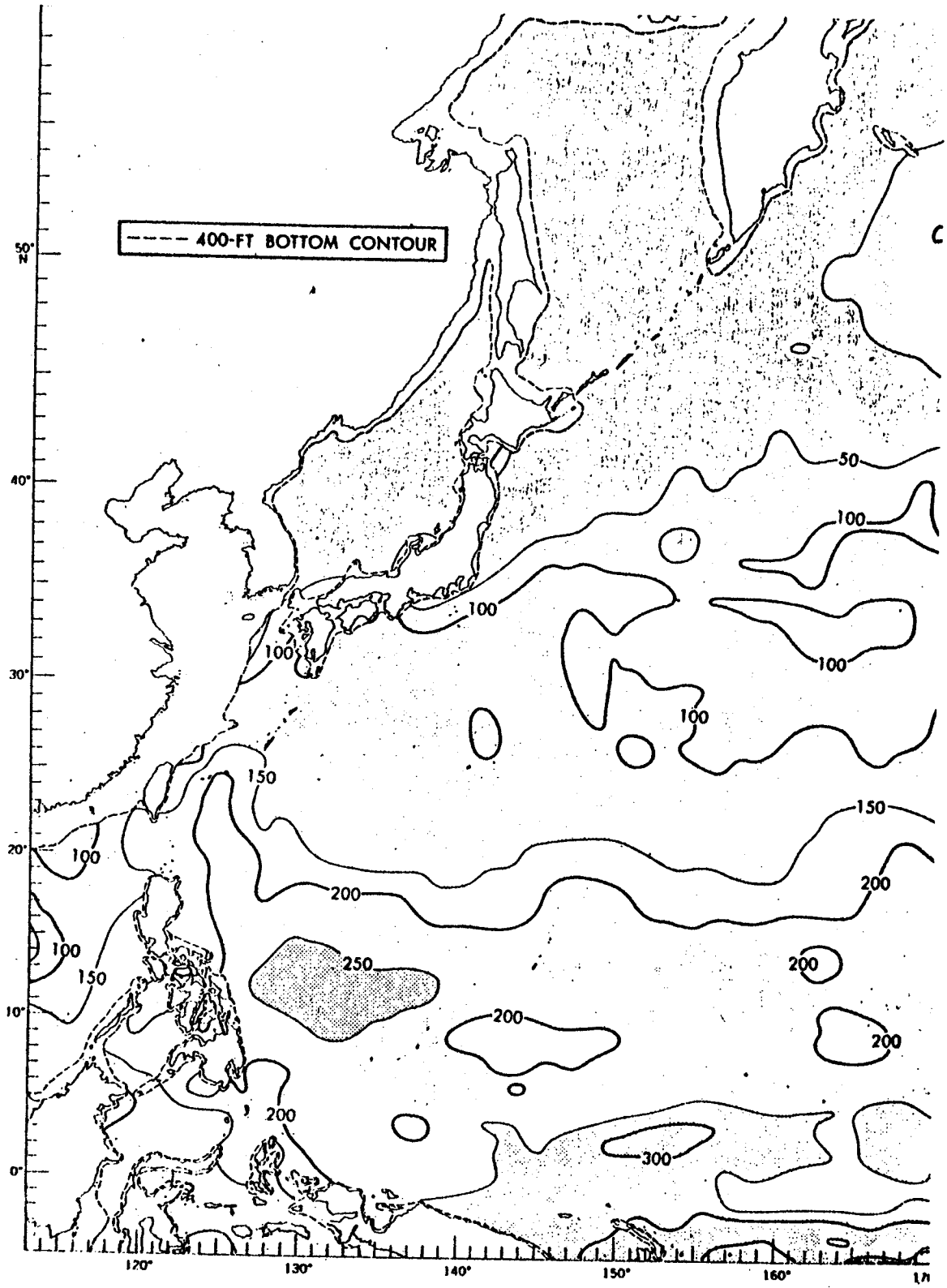



Figure 92.— Mean temperature (in feet) to the top of the thermocline, September (from Robinson 1976).

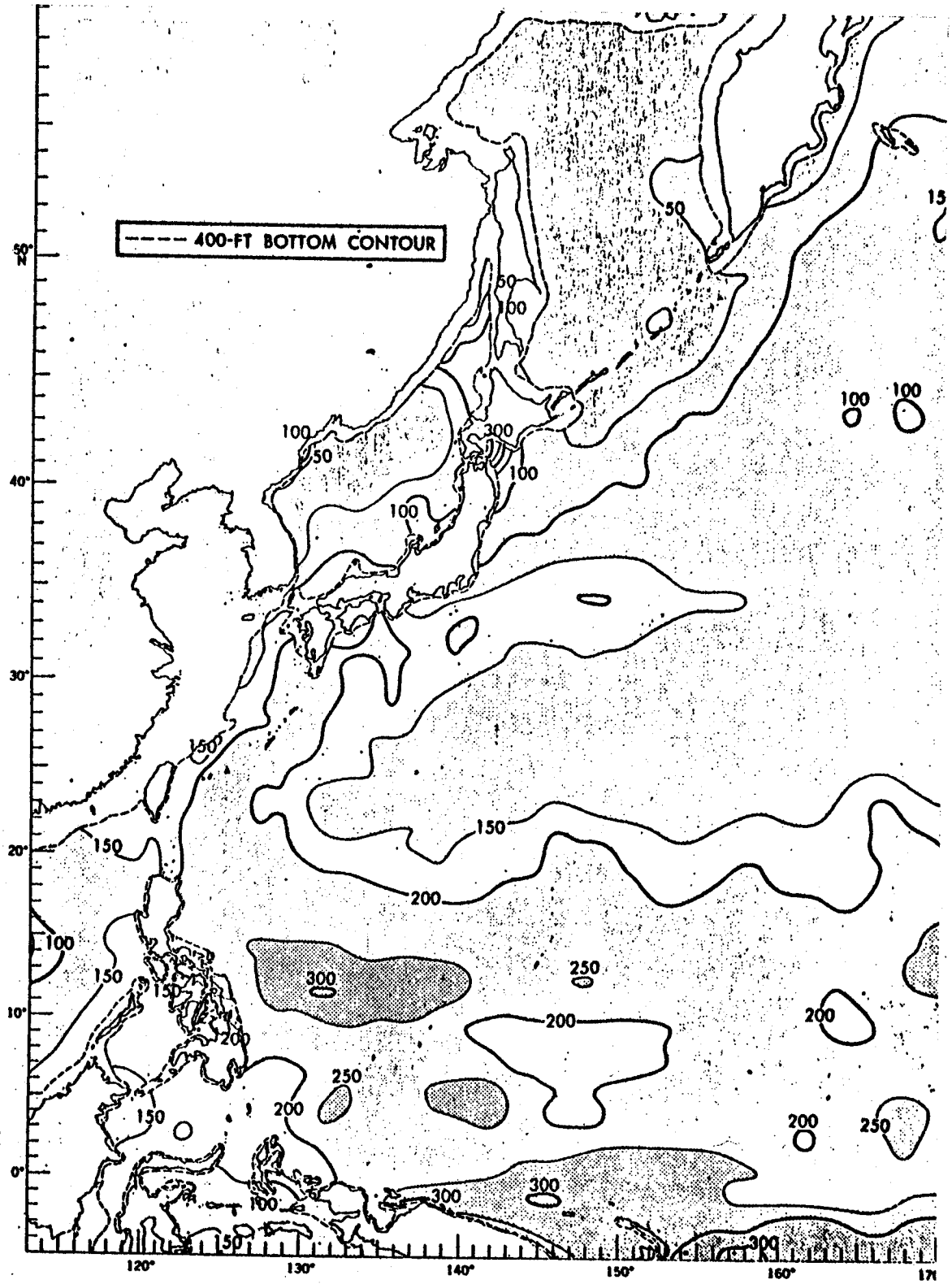



Figure 93.--Mean temperature (in feet) to the top of the thermocline, October (from Robinson 1976).

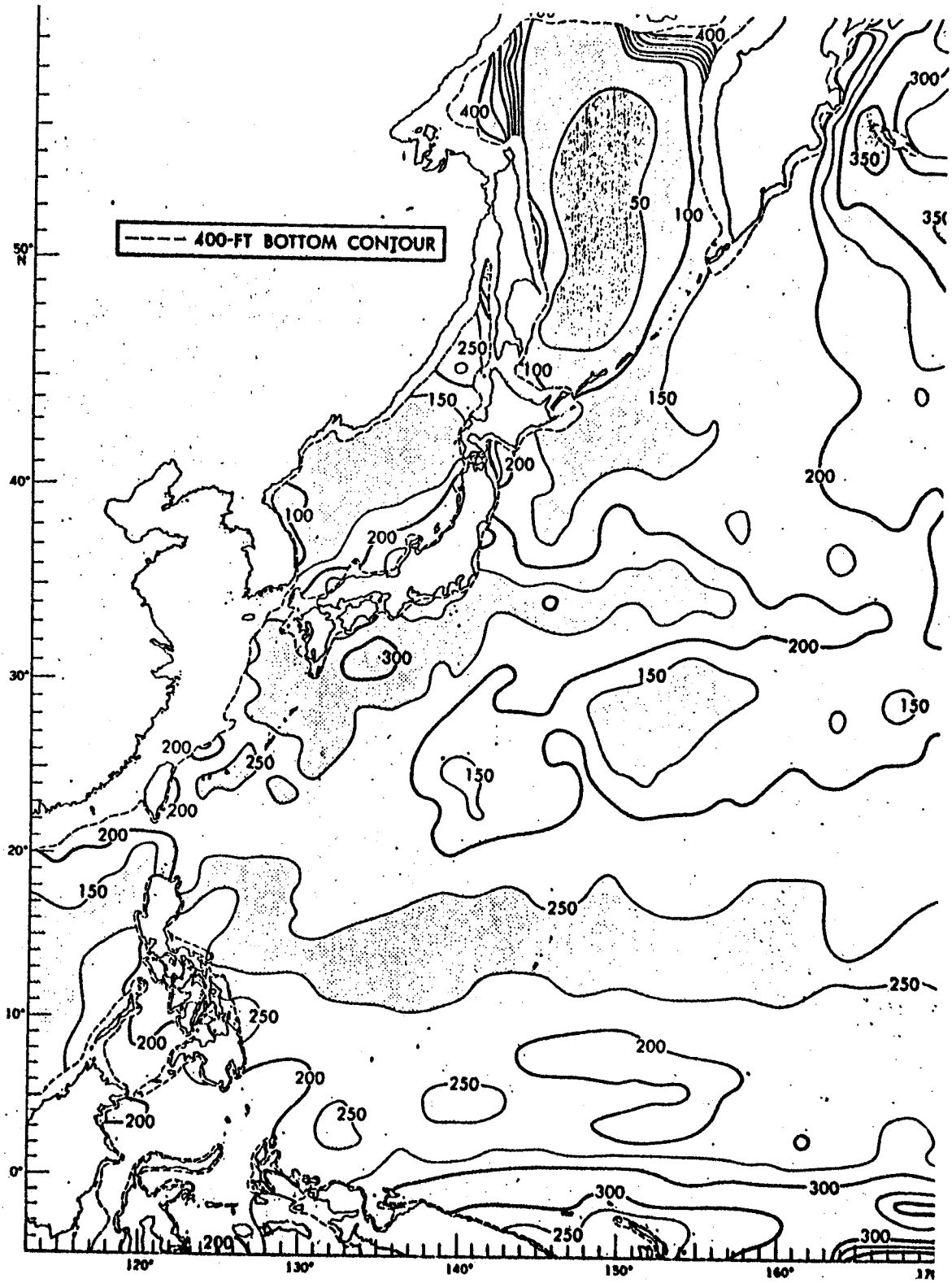



Figure 94.--Mean temperature (in feet) to the top of the thermocline, November (from Robinson 1976).

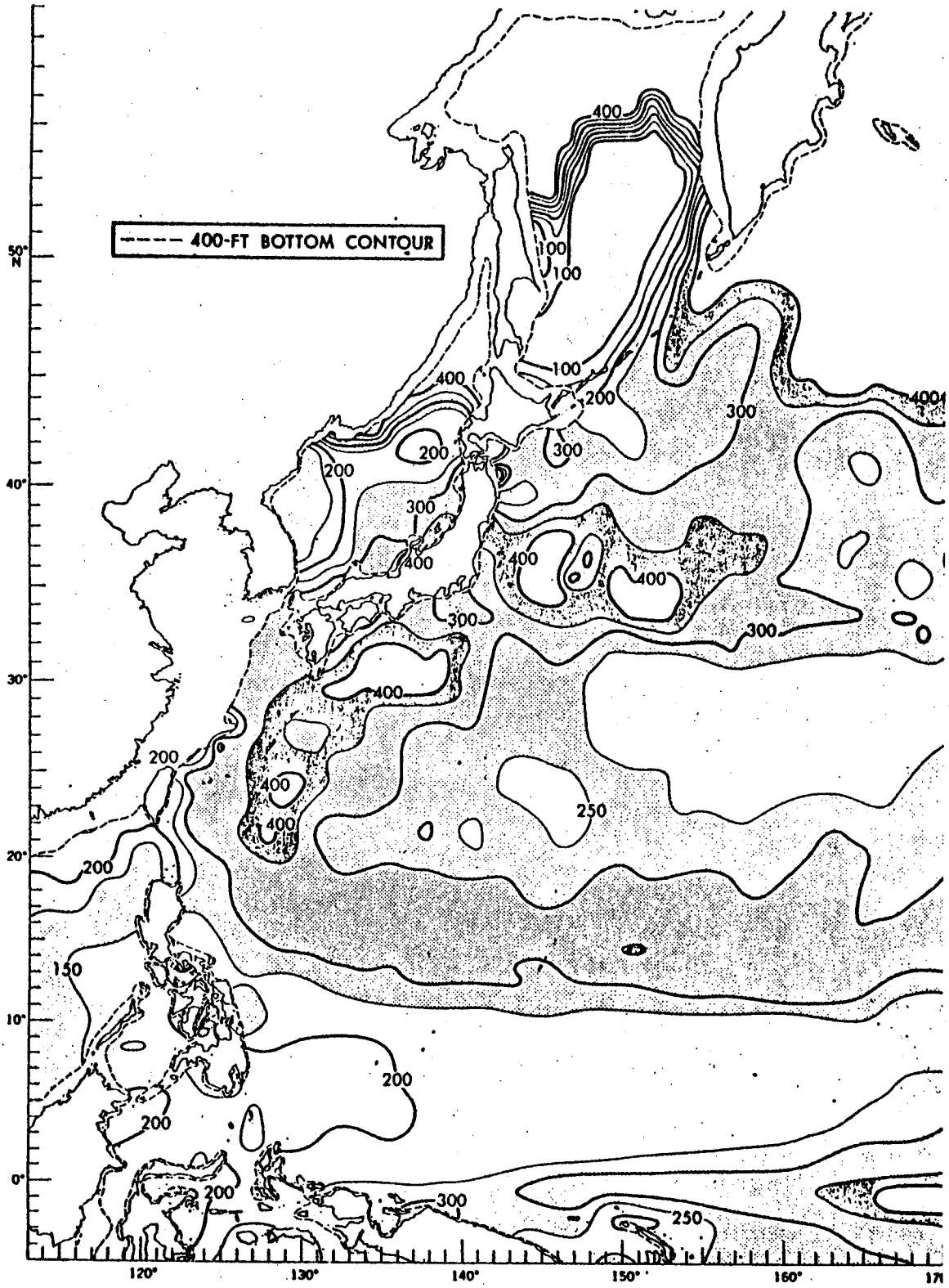



Figure 95.--Mean temperature (in feet) to the top of the thermocline, December (from Robinson 1976).

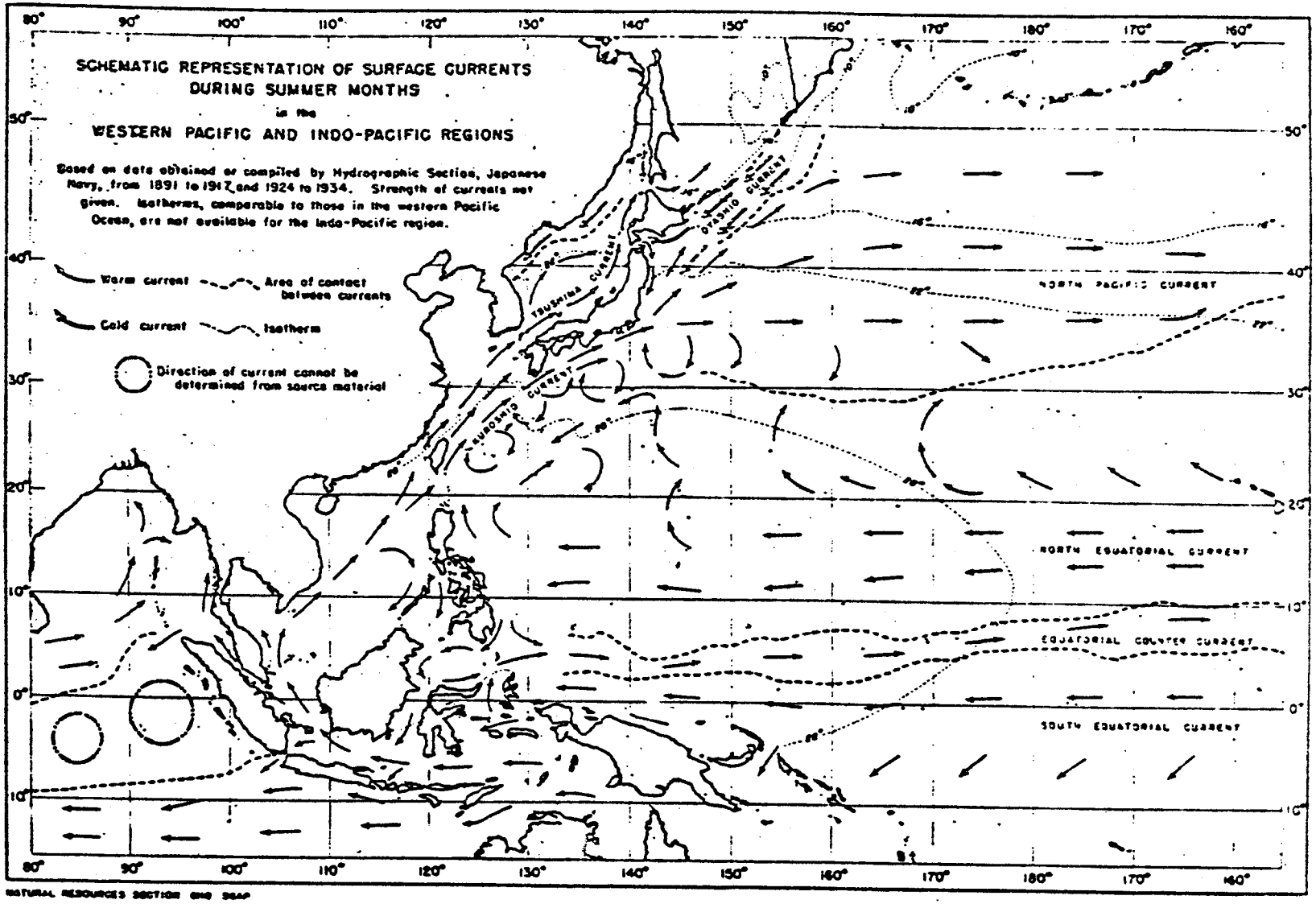



Figure 96.-- Surface currents during summer months (from Shapiro 1948).

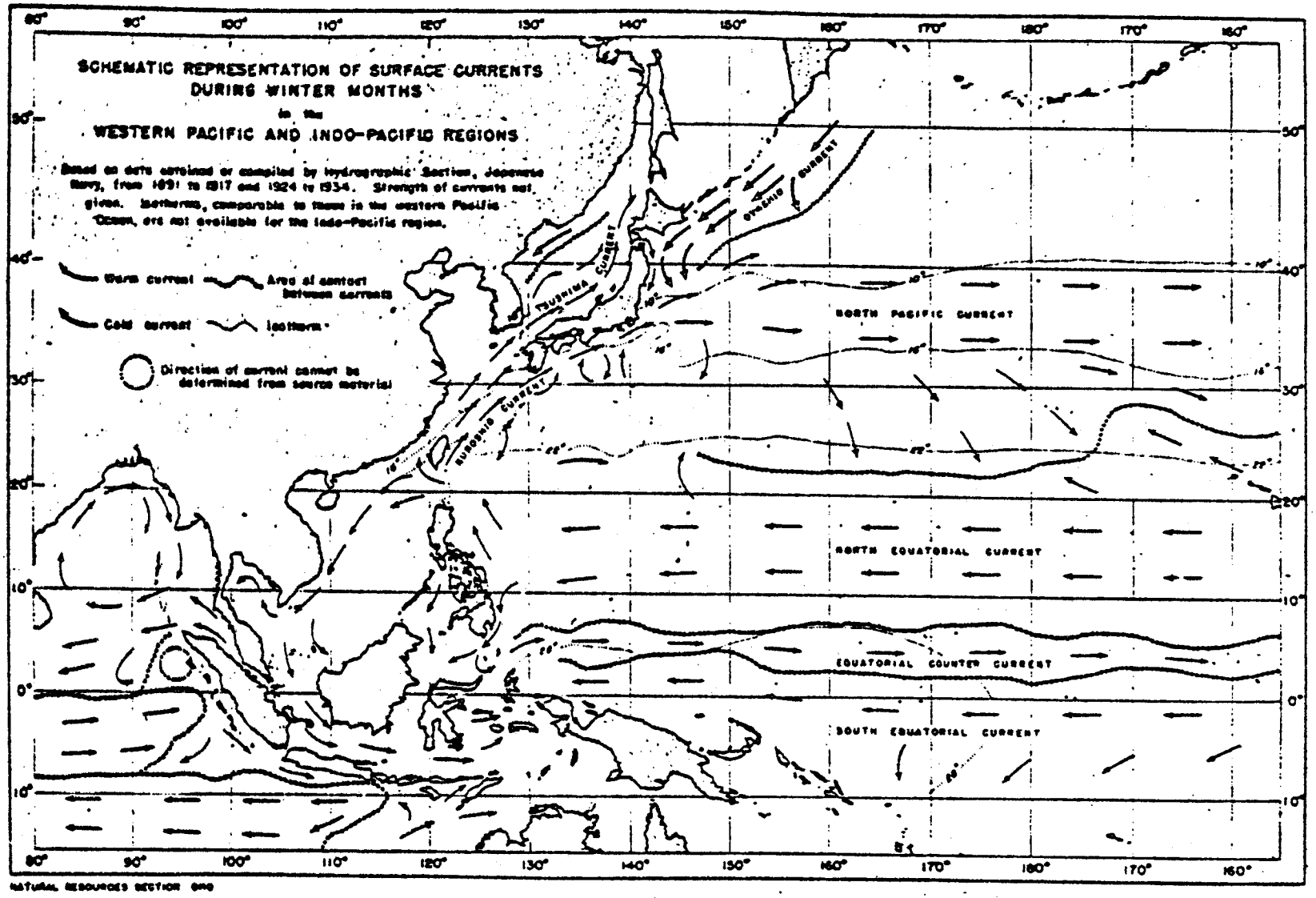



Figure 97.--Surface currents during winter months (from Shapiro 1948).

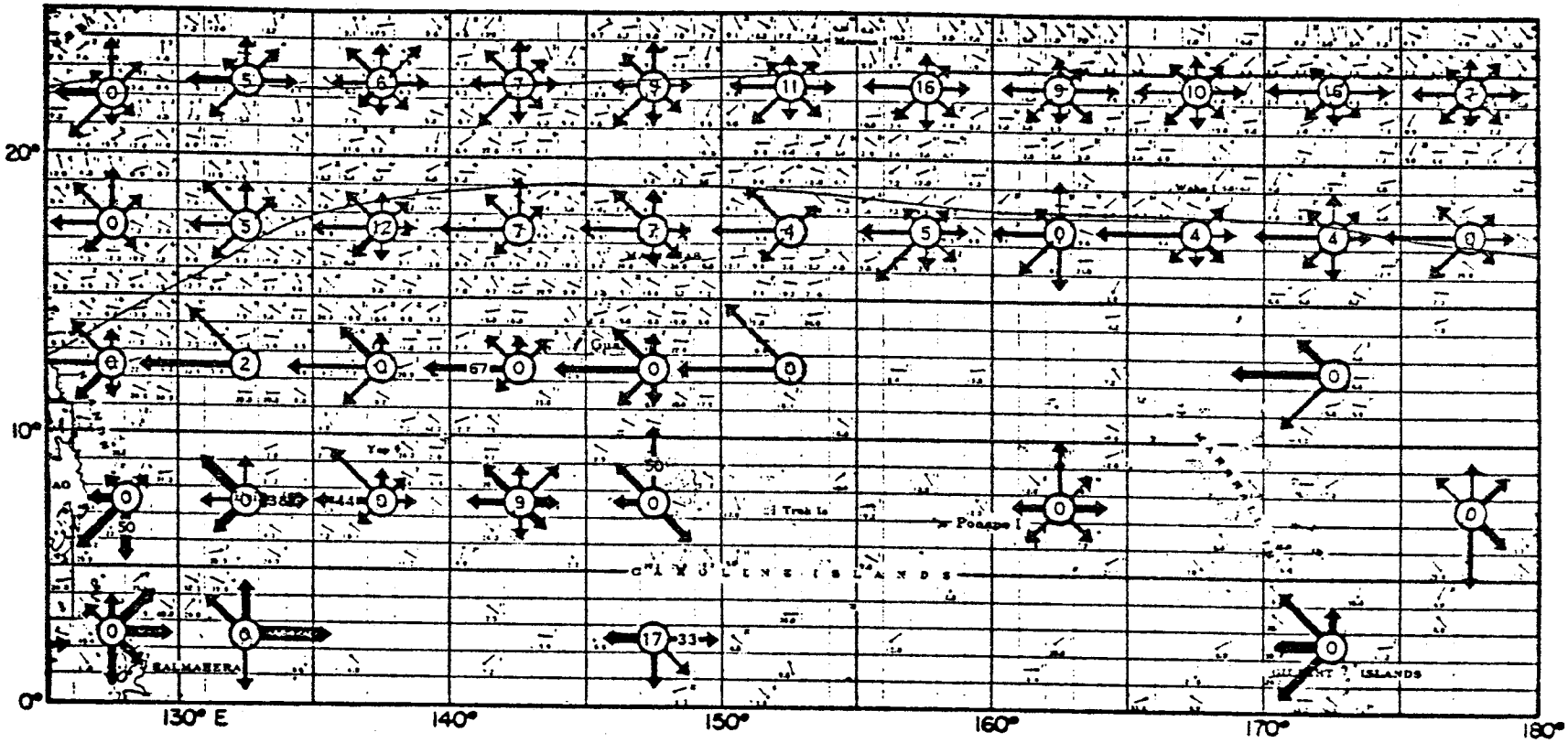



Figure 98.--Surface currents in the northwestern Pacific Ocean, January (from U.S. Navy Hydrographic Office 1944).

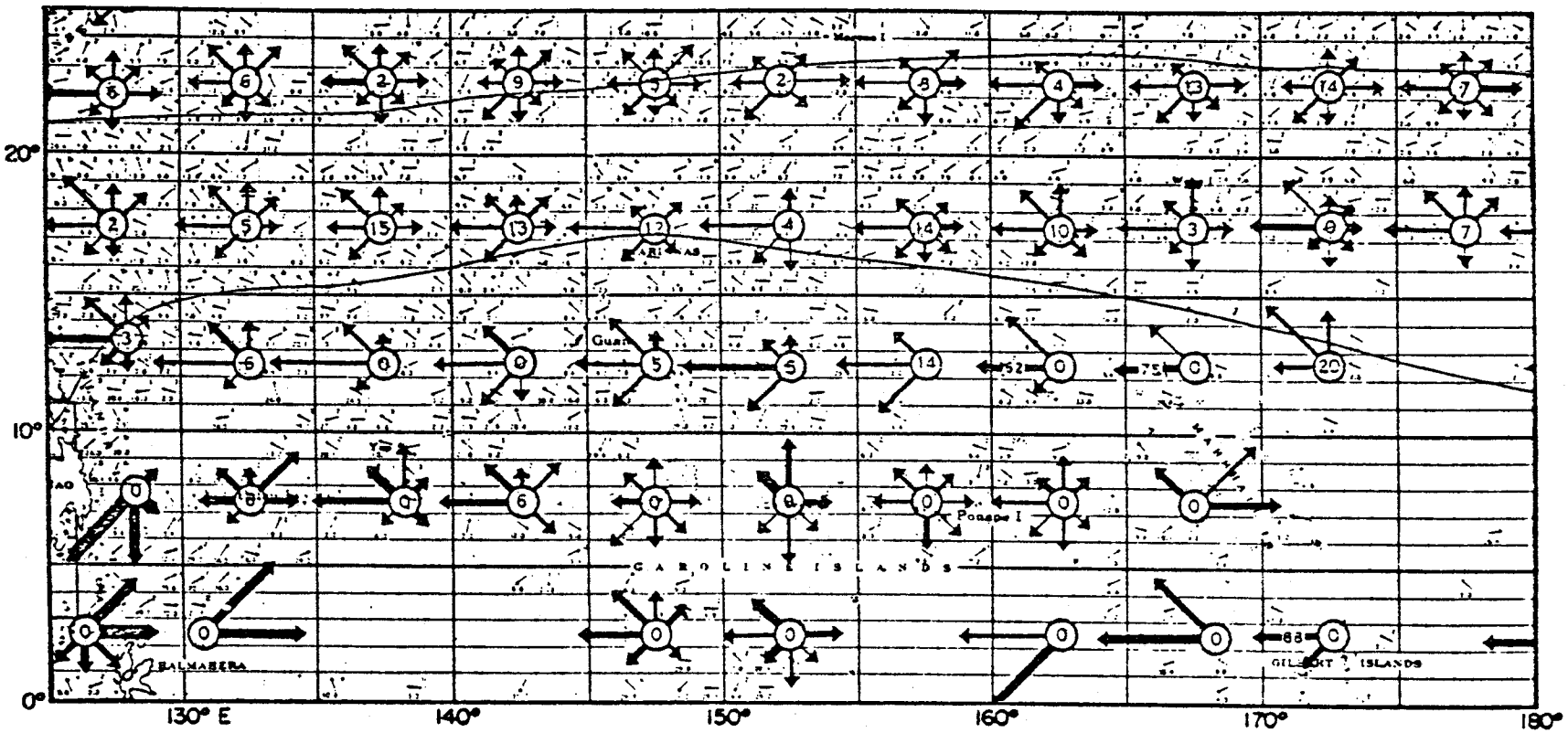



Figure 99.--Surface currents in the northwestern Pacific Ocean, February (from U.S. Navy Hydrographic Office 1944).

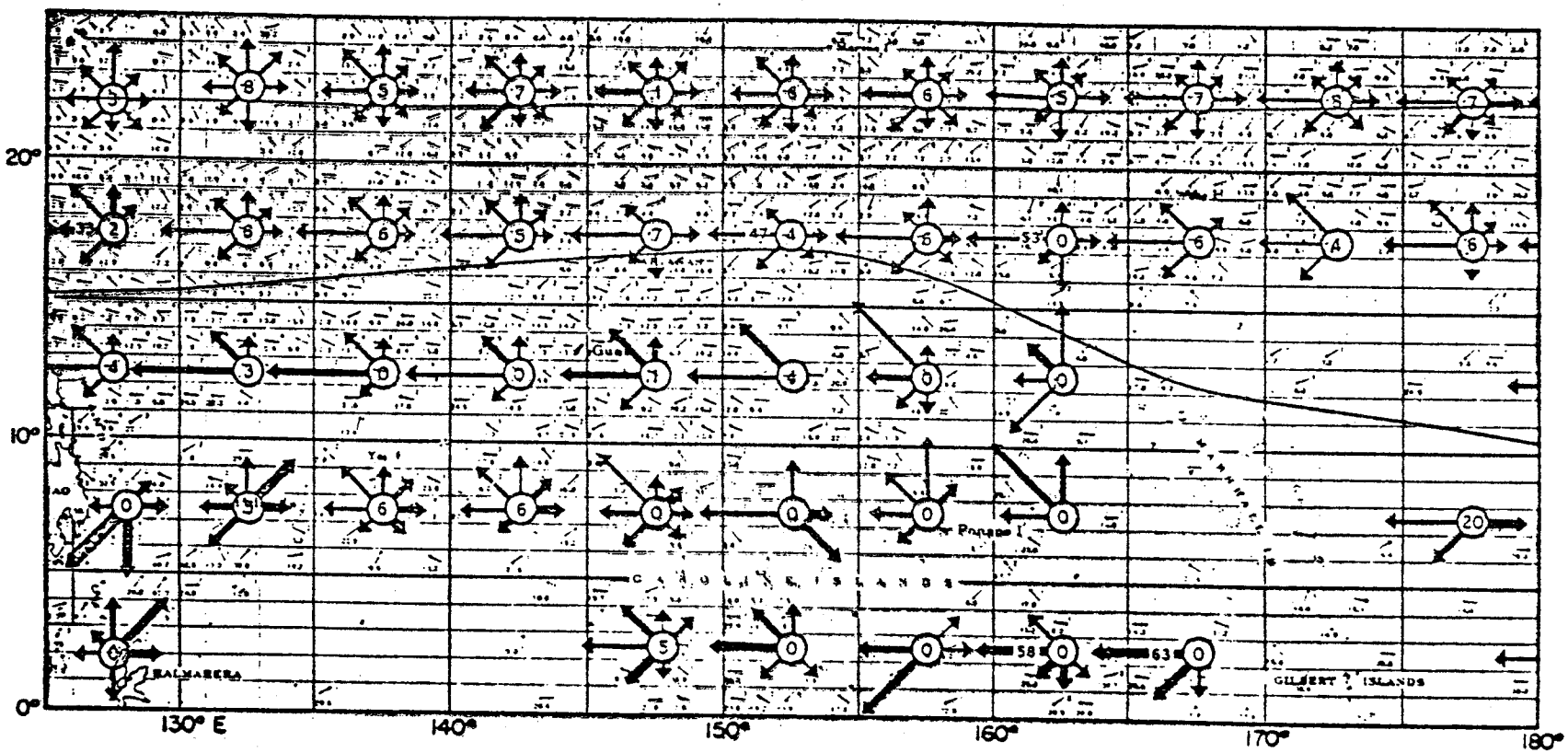



Figure 100.--Surface currents in the northwestern Pacific Ocean, March (from U.S. Navy Hydrographic Office 1944).

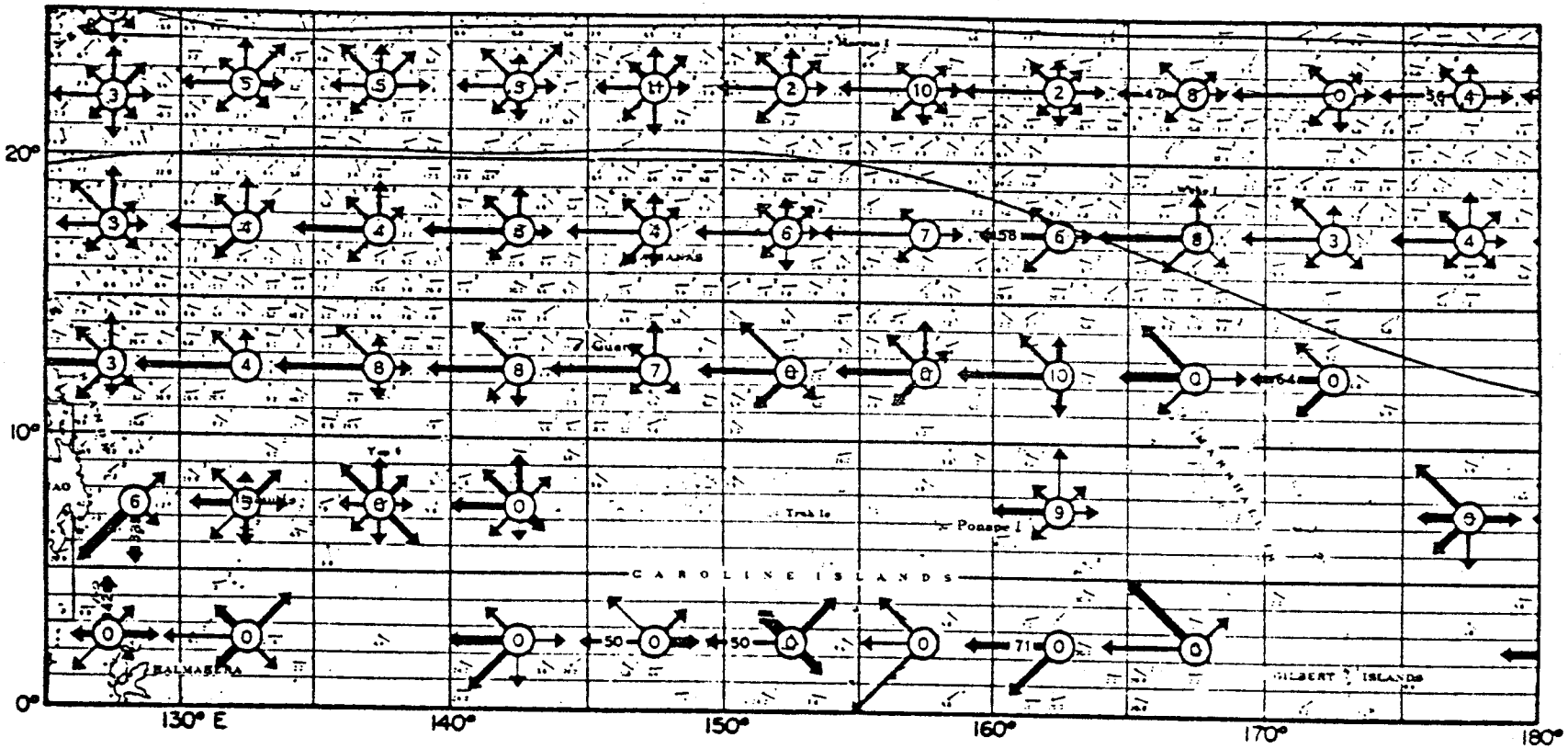



Figure 101.--Surface currents in the northwestern Pacific Ocean, April (from U.S. Navy Hydrographic Office 1944).

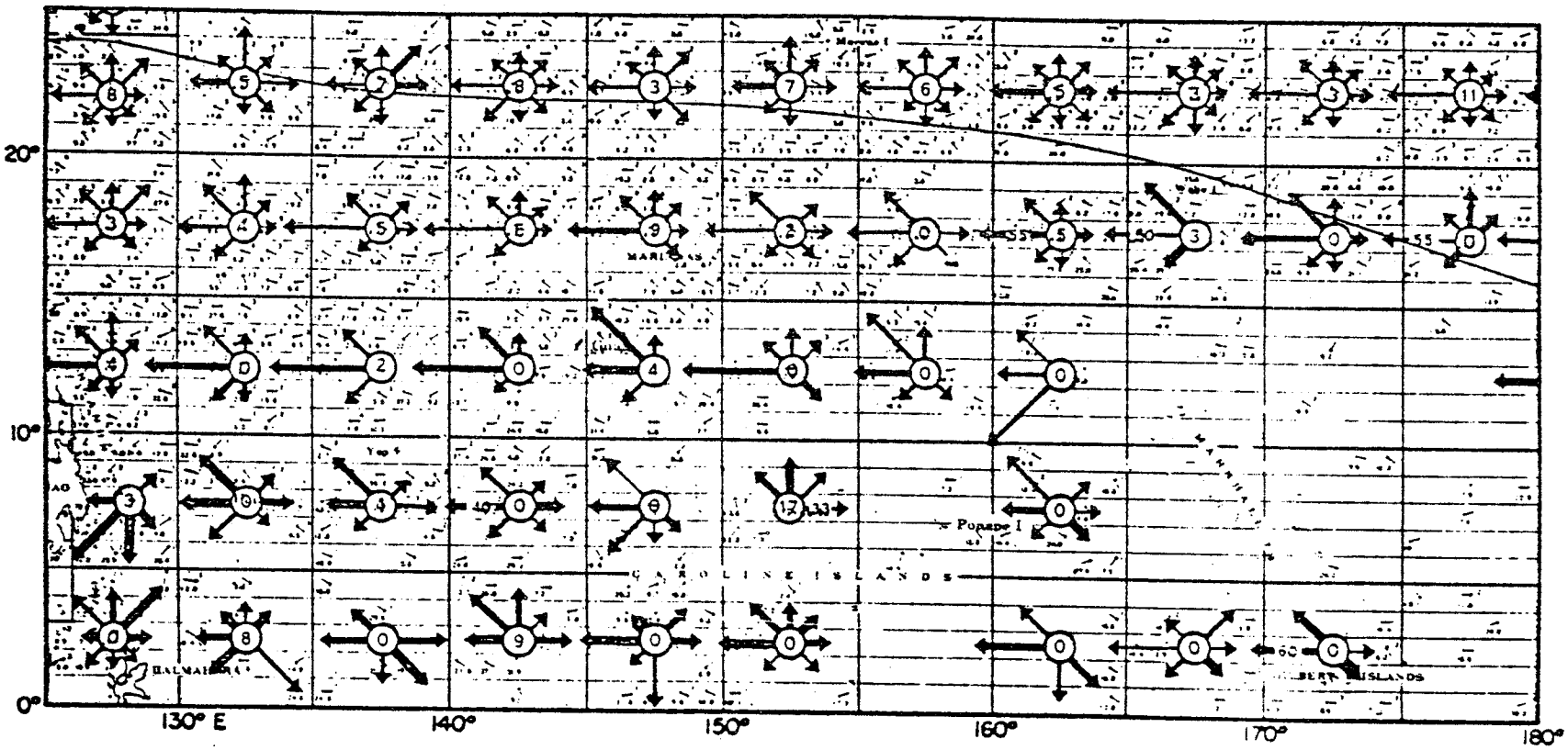



Figure 102.--Surface currents in the northwestern Pacific Ocean, May (from U.S. Navy Hydrographic Office 1944).

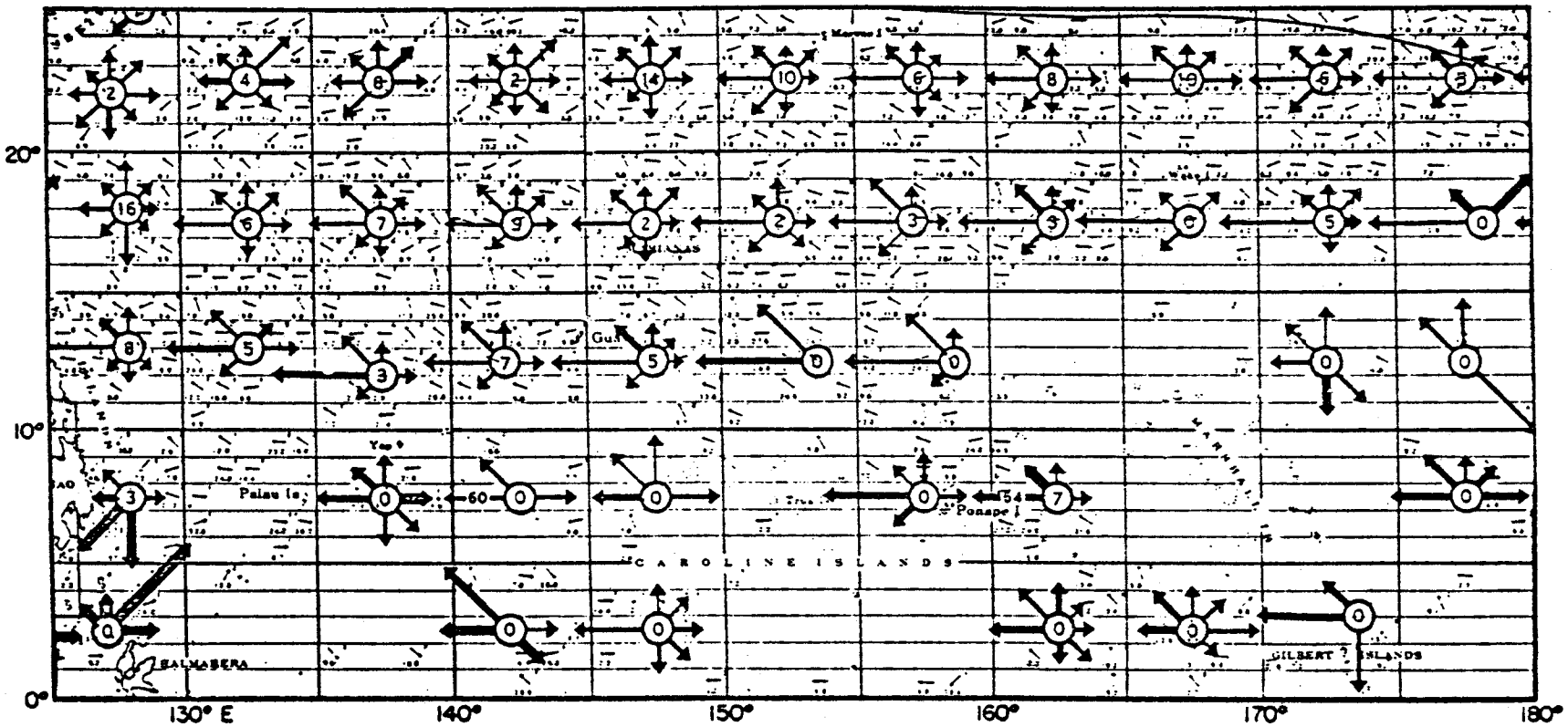



Figure 103.--Surface currents in the northwestern Pacific Ocean, June (from U.S. Navy Hydrographic Office 1944).

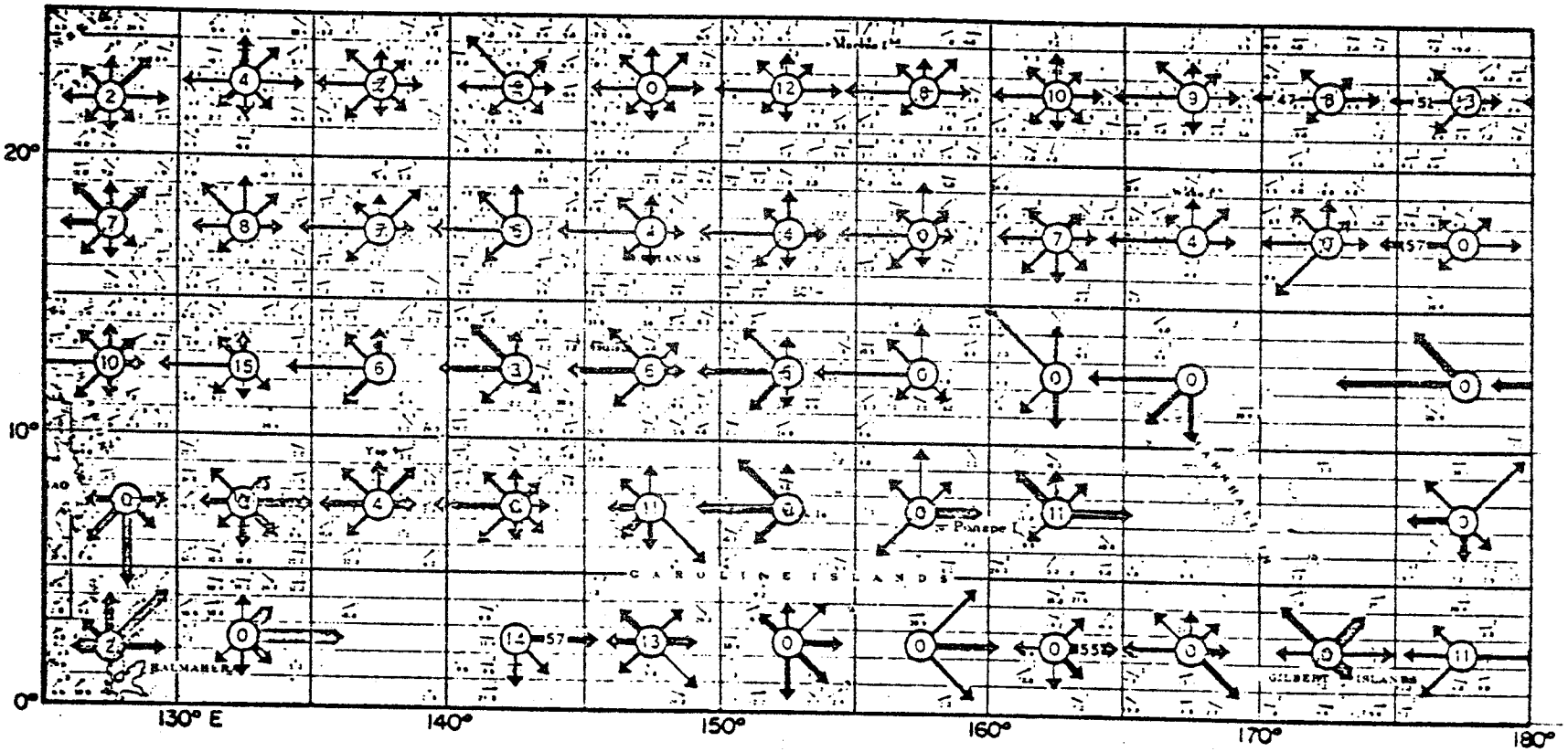



Figure 104.--Surface currents in the northwestern Pacific Ocean, July (from U.S. Navy Hydrographic Office 1944).

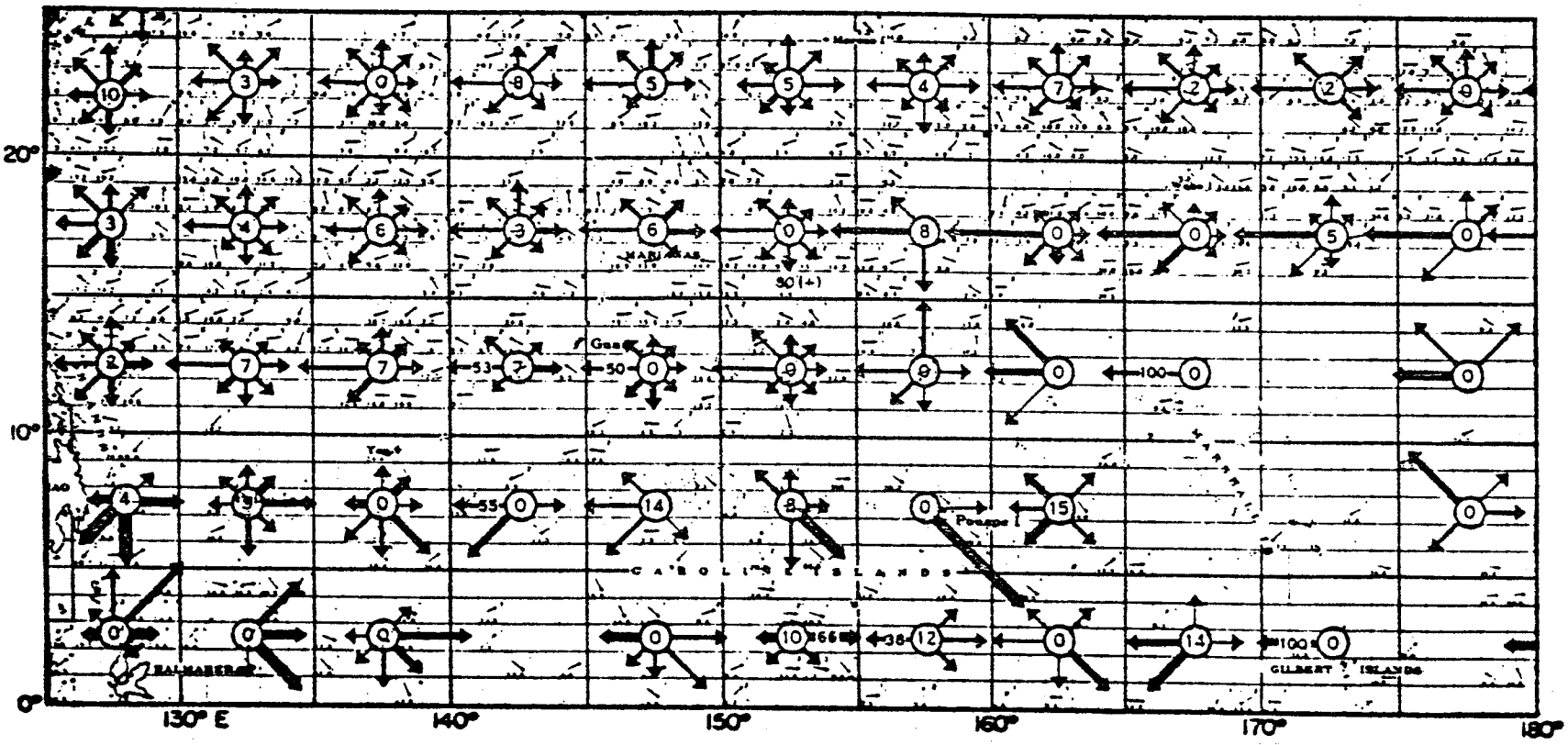



Figure 105.--Surface currents in the northwestern Pacific Ocean, August (from U.S. Navy Hydrographic Office 1944).

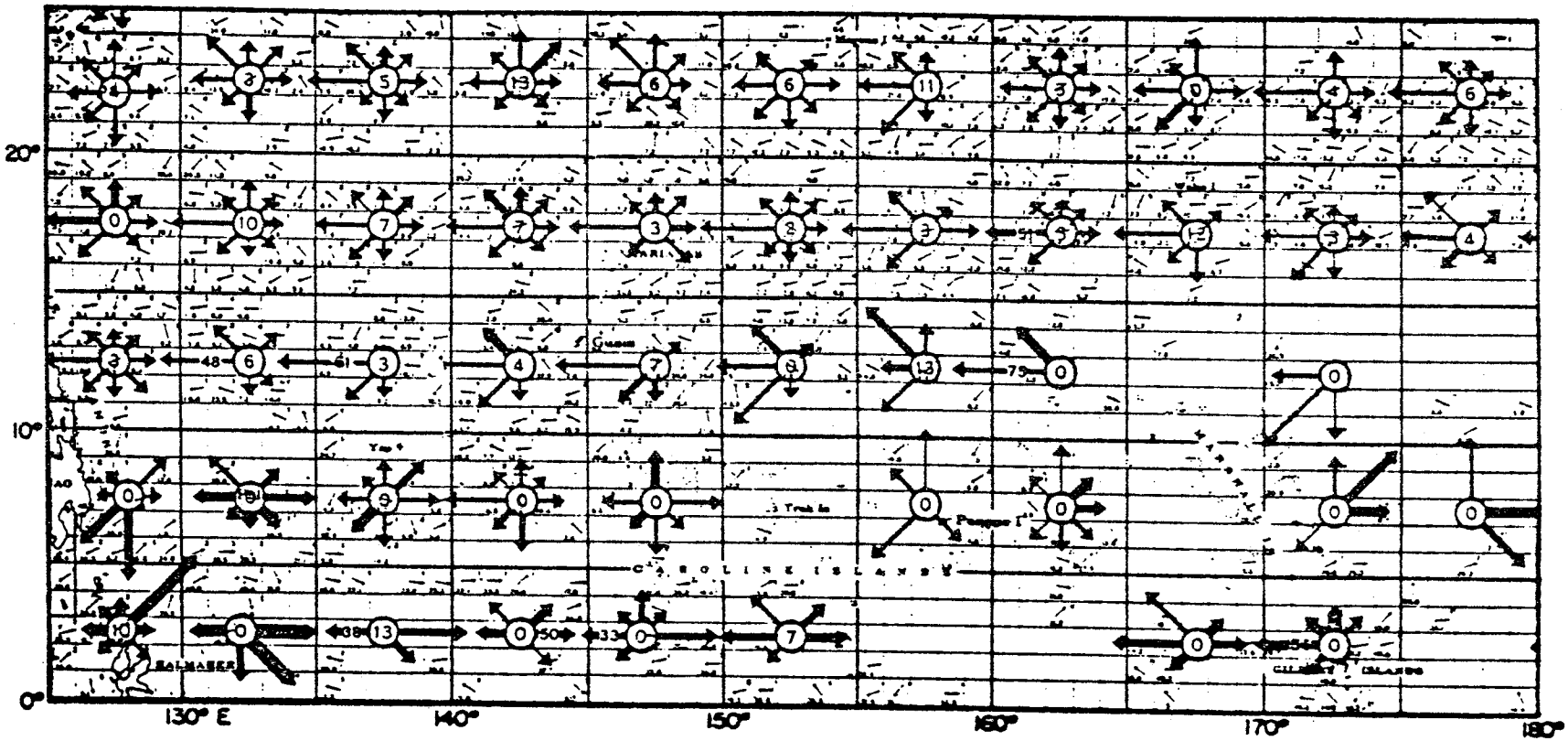



Figure 106.--Surface currents in the northwestern Pacific Ocean, September (from U.S. Navy Hydrographic Office 1944).

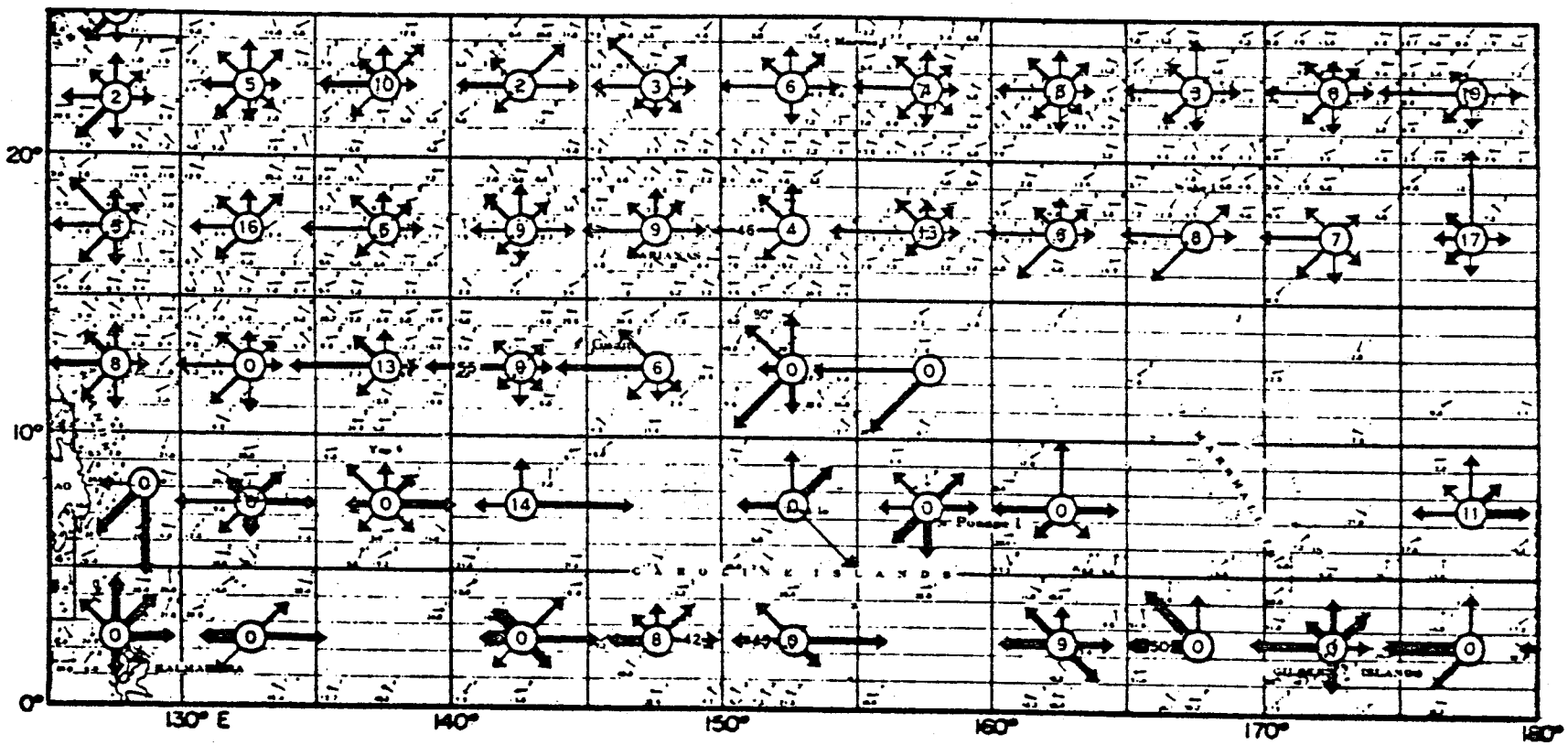



Figure 107.--Surface currents in the northwestern Pacific Ocean, October (U.S. Navy Hydrographic Office 1944).

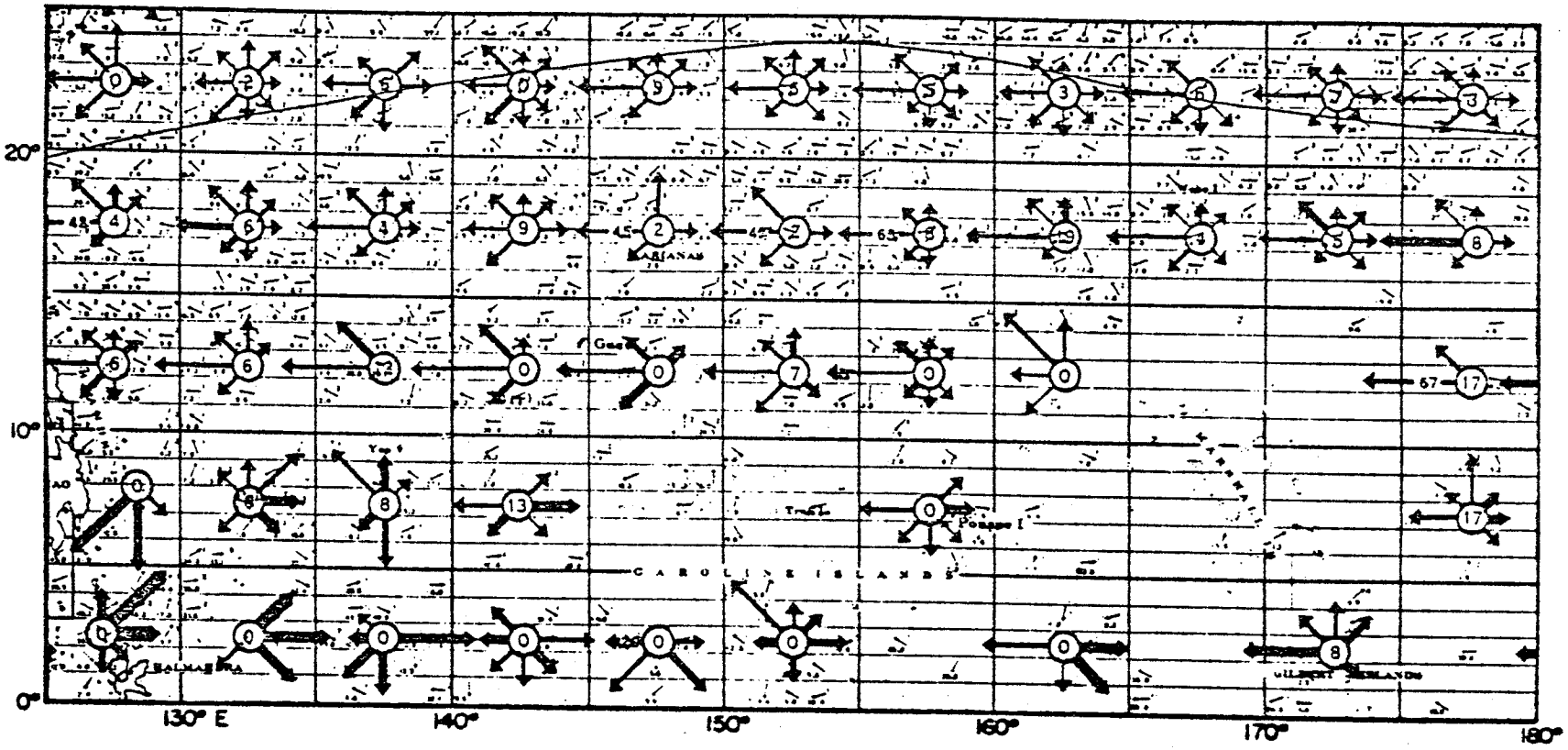



Figure 108.--Surface currents in the northwestern Pacific Ocean, November (from U.S. Navy Hydrographic Office 1944).

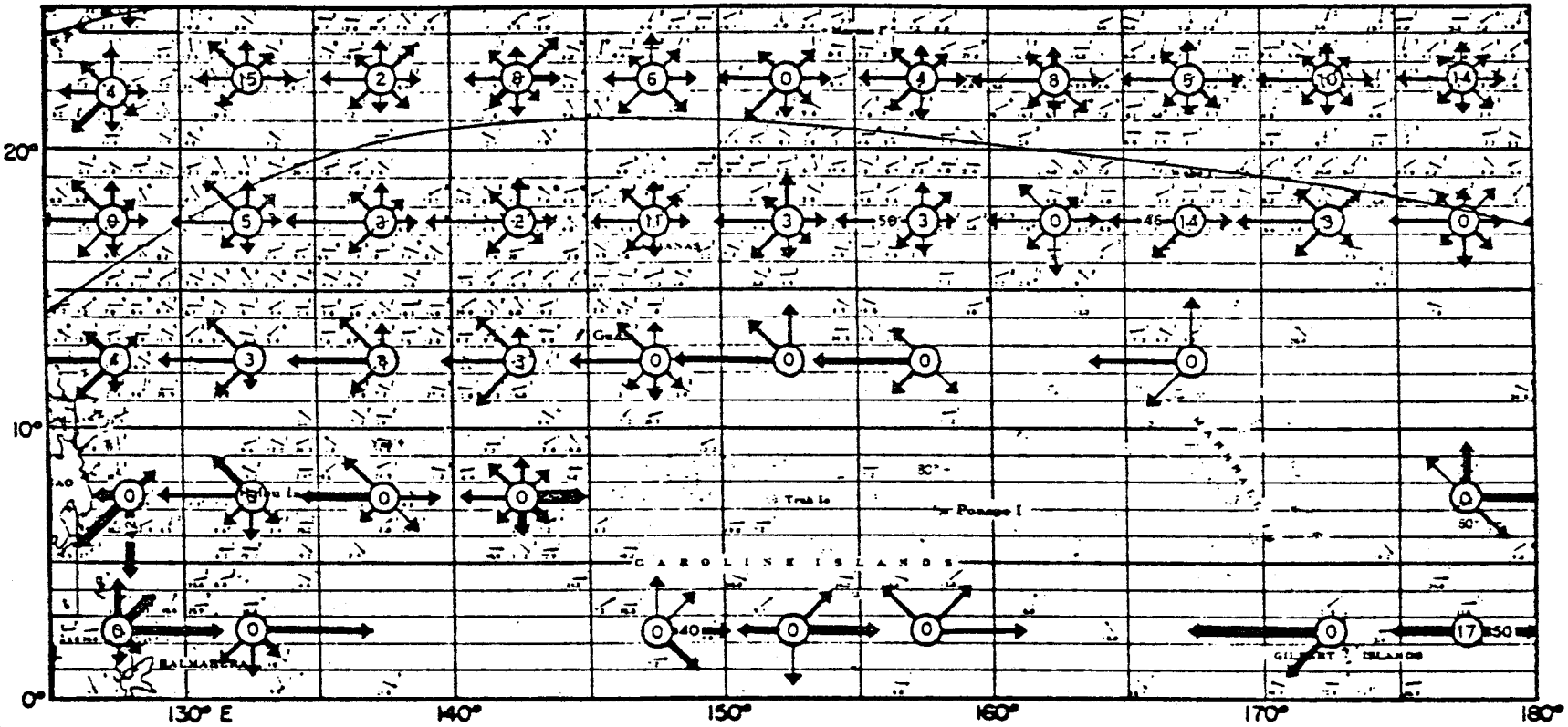



Figure 109.--Surface currents in the northwestern Pacific Ocean, December (from U.S. Navy Hydrographic Office 1944).

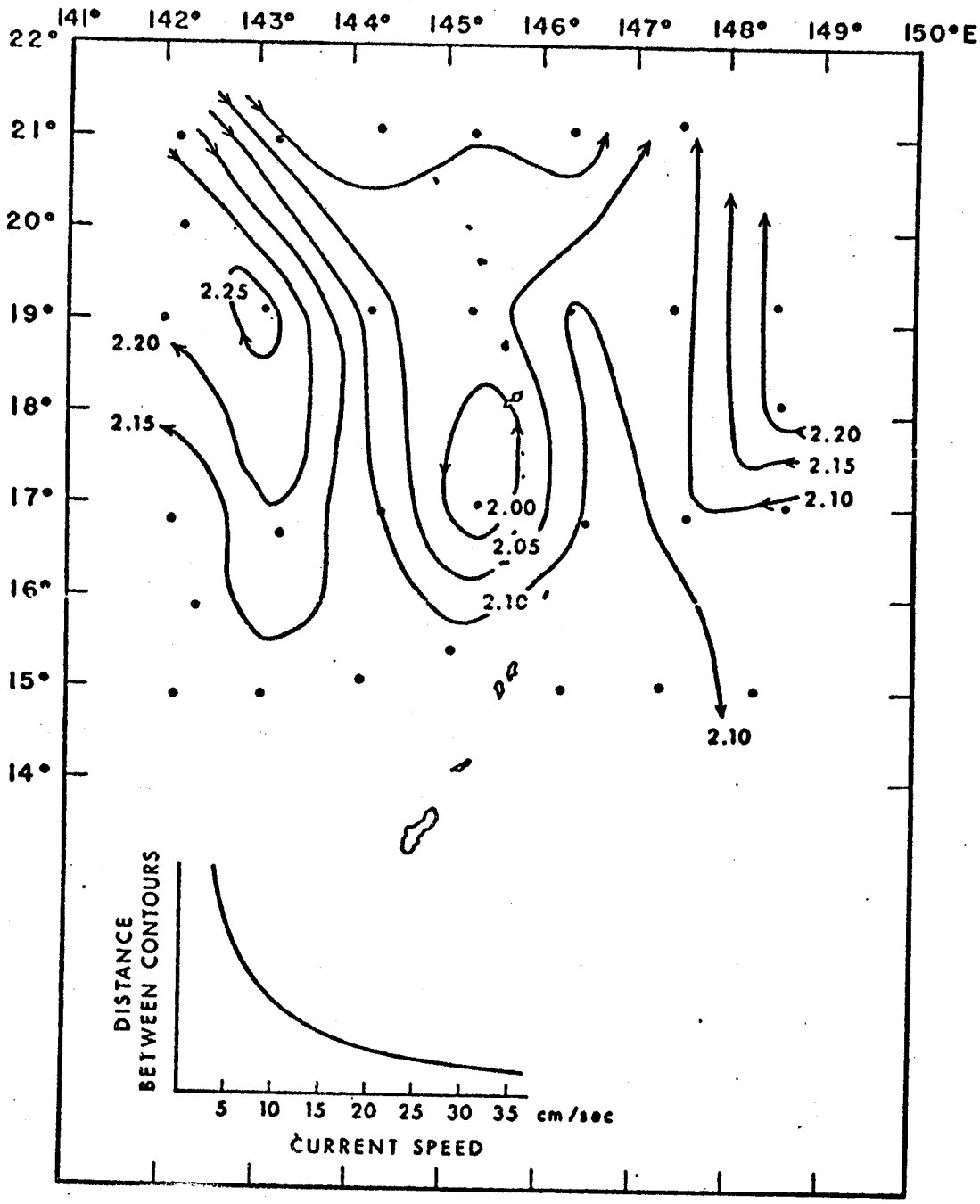



Figure 110.--Dynamic topography in dynamic meters of the sea surface relative to the 1000-db surface (21 April-2 May 1971) (from deWitt 1972).

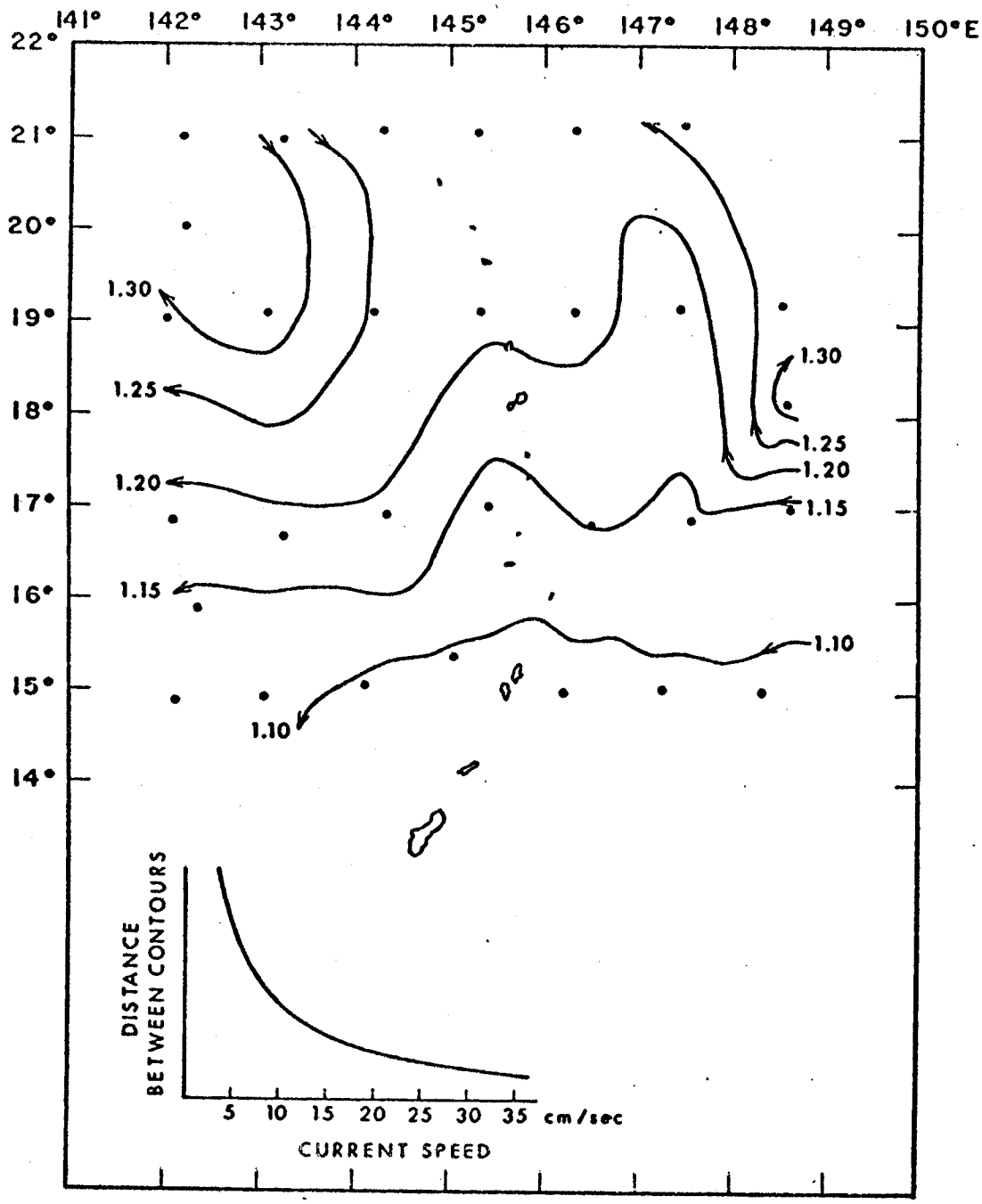



Figure 111.--Dynamic topography in dynamic meters of the 200-db surface relative to the 1000-db surface (from deWitt 1972).

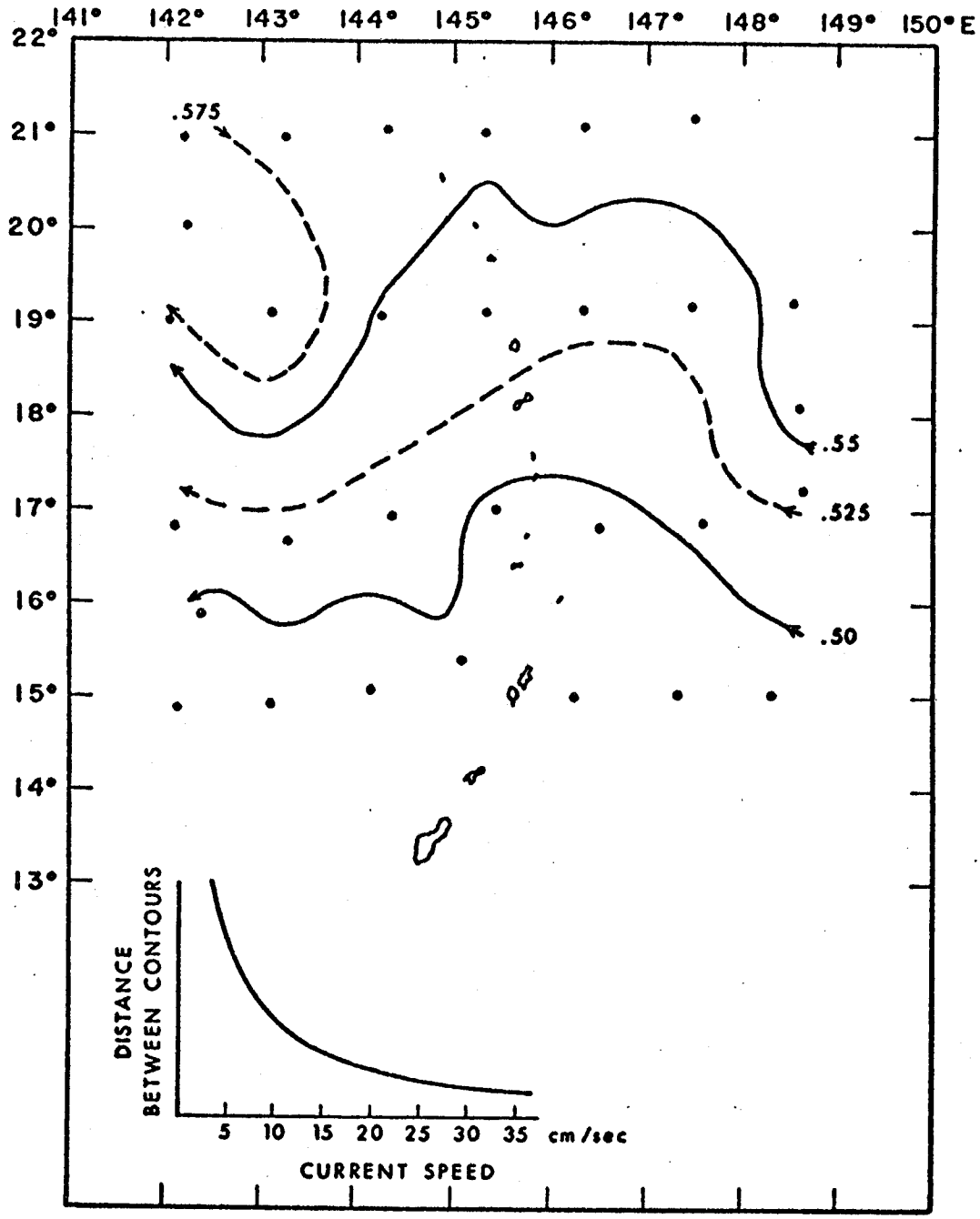



Figure 112.--Dynamic topography in dynamic meters of the 500-db surface relative to the 1000-db surface (from deWitt 1972).

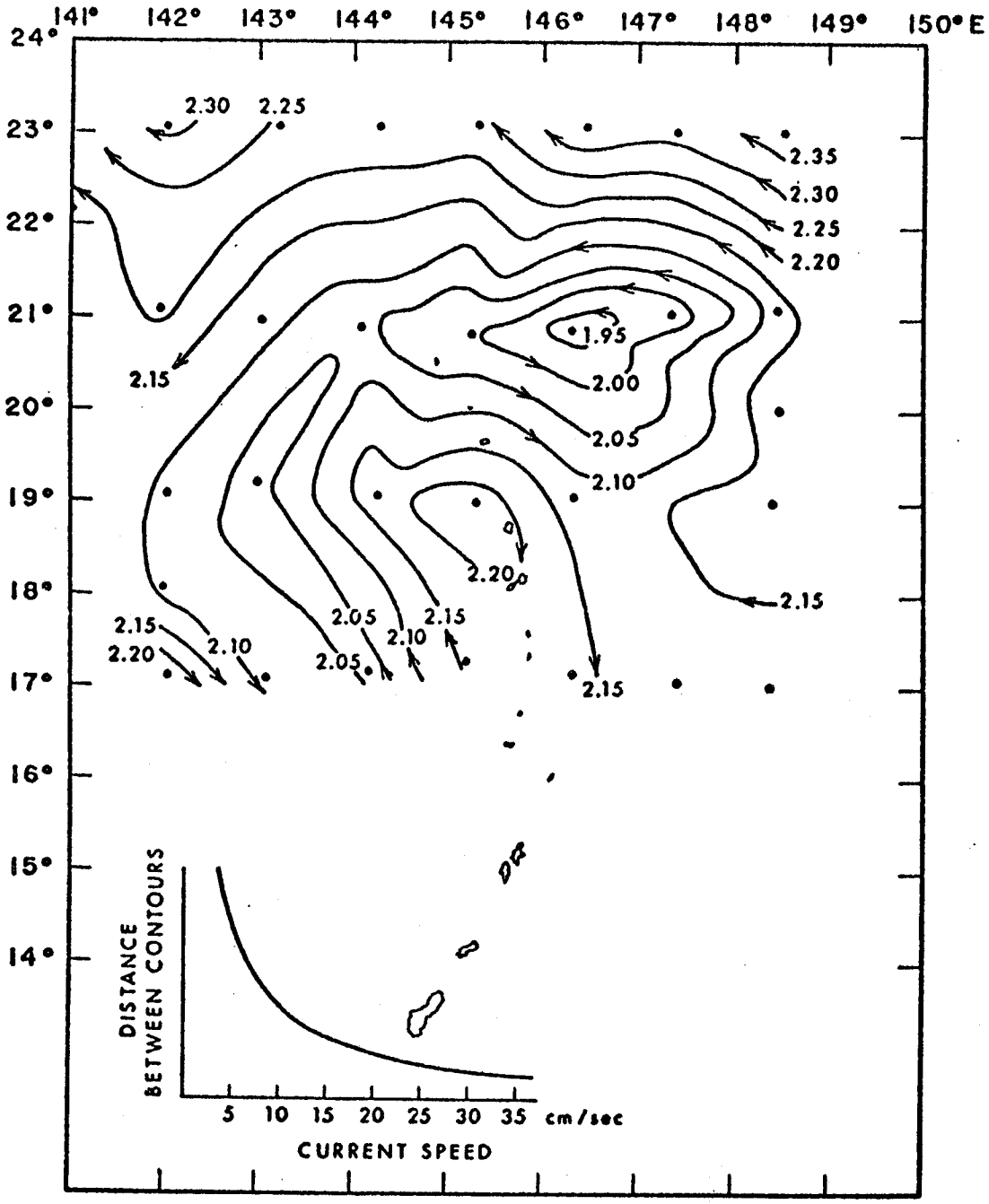



Figure 113.--Dynamic topography in dynamic meters of the sea surface relative to the 1000-db surface (2-12 November 1971) (from deWitt 1972).

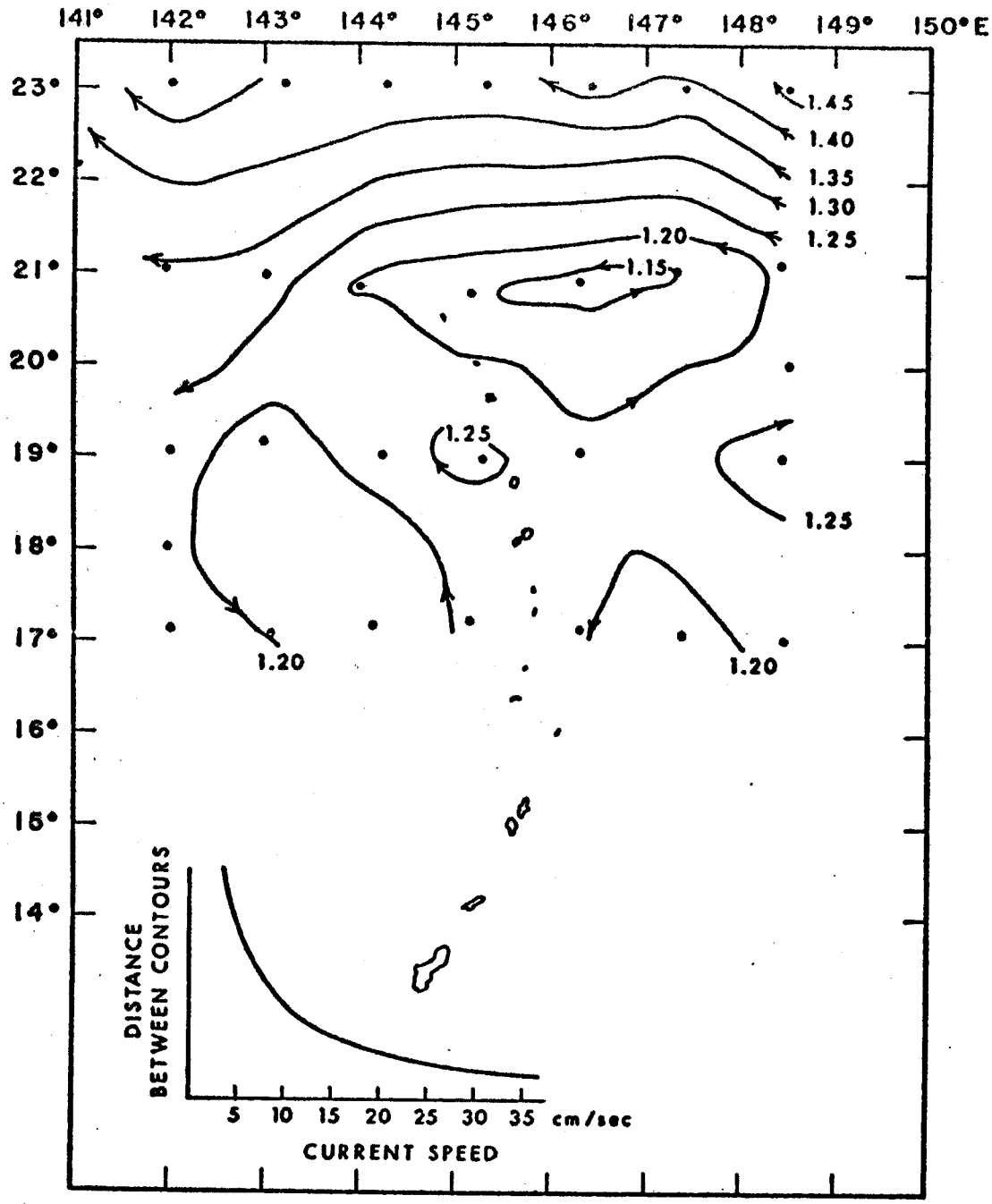



Figure 114.--Dynamic topography in dynamic meters of the 200-db surface relative to the 1000-db surface (from deWitt 1972).

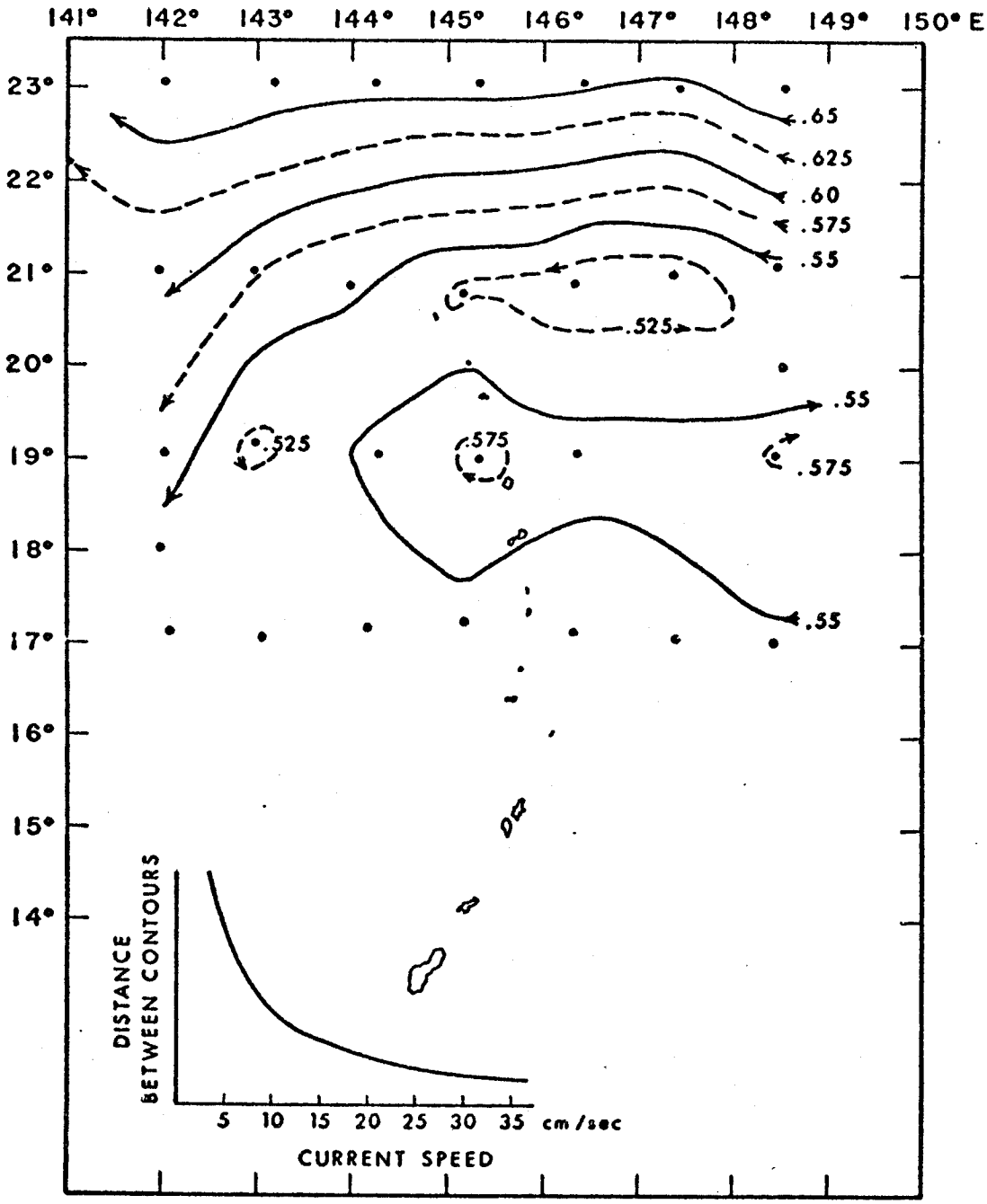
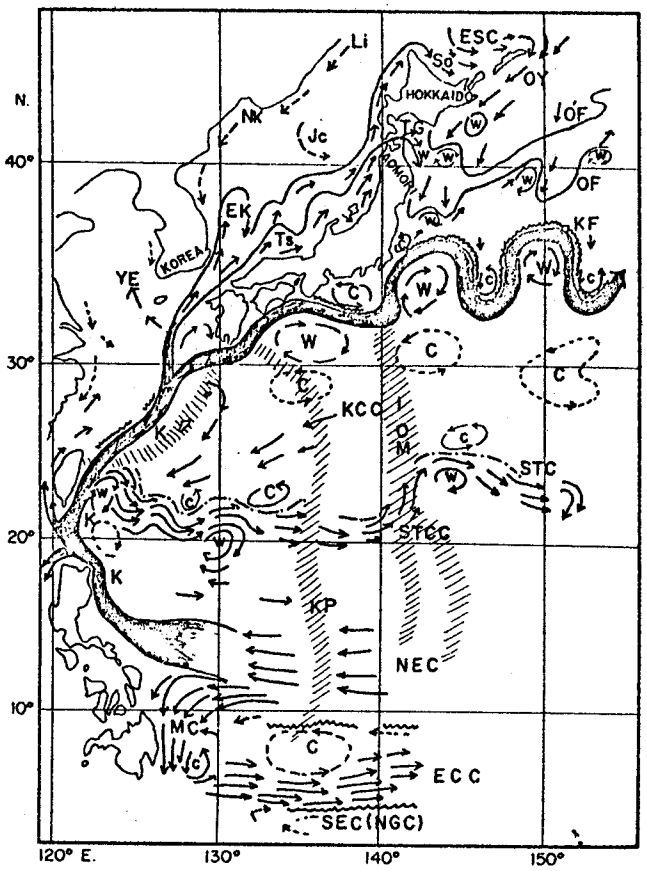



Figure 115.--Dynamic topography in dynamic meters of the 500-db surface relative to the 1000-db surface (from deWitt 1972).




Explanation of symbols in map:

| | |
|---|---|
| K | Kuroshio |
| OY | Oyashio |
| ESC | East Saghalin Current |
| Ts | Tsushima Current |
| EK | East Korean Current |
| NK | North Korean Current |
| Li | Liman Current |
| Jc | Sea of Japan Central Cold Current |
| So | Soya Warm Current |
| TG | Tsugaru Warm Current |
| YE | Yellow Sea Warm Current |
| KCC | Kuroshio Countercurrent |
| STCC | Subtropical Countercurrent |
| NEC | North Equatorial Current |
| ECC | Equatorial Countercurrent |
| MC | Mindanao Current |
| SEC | South Equatorial Current |
| NGC | New Guinea Current |
| O'F | Kuril front |
| OF | Oyashio front |
| KF | Kuroshio front |
| STC | Subtropical Convergence |
| IOM | Izu-Ogasawara-Mariana Ridge |
| KP | Kyushu-Palau Ridge |
| W | Warm eddy |
| C | Cold eddy |

Figure 116.--Compiled schematic map of the Kuroshio and neighboring currents, oceanic fronts, and eddies based on CSK data (summer 1965, winter 1966) with reference to the geosyncline ridges; STCC=Subtropical Countercurrent (fron Uda 1970).

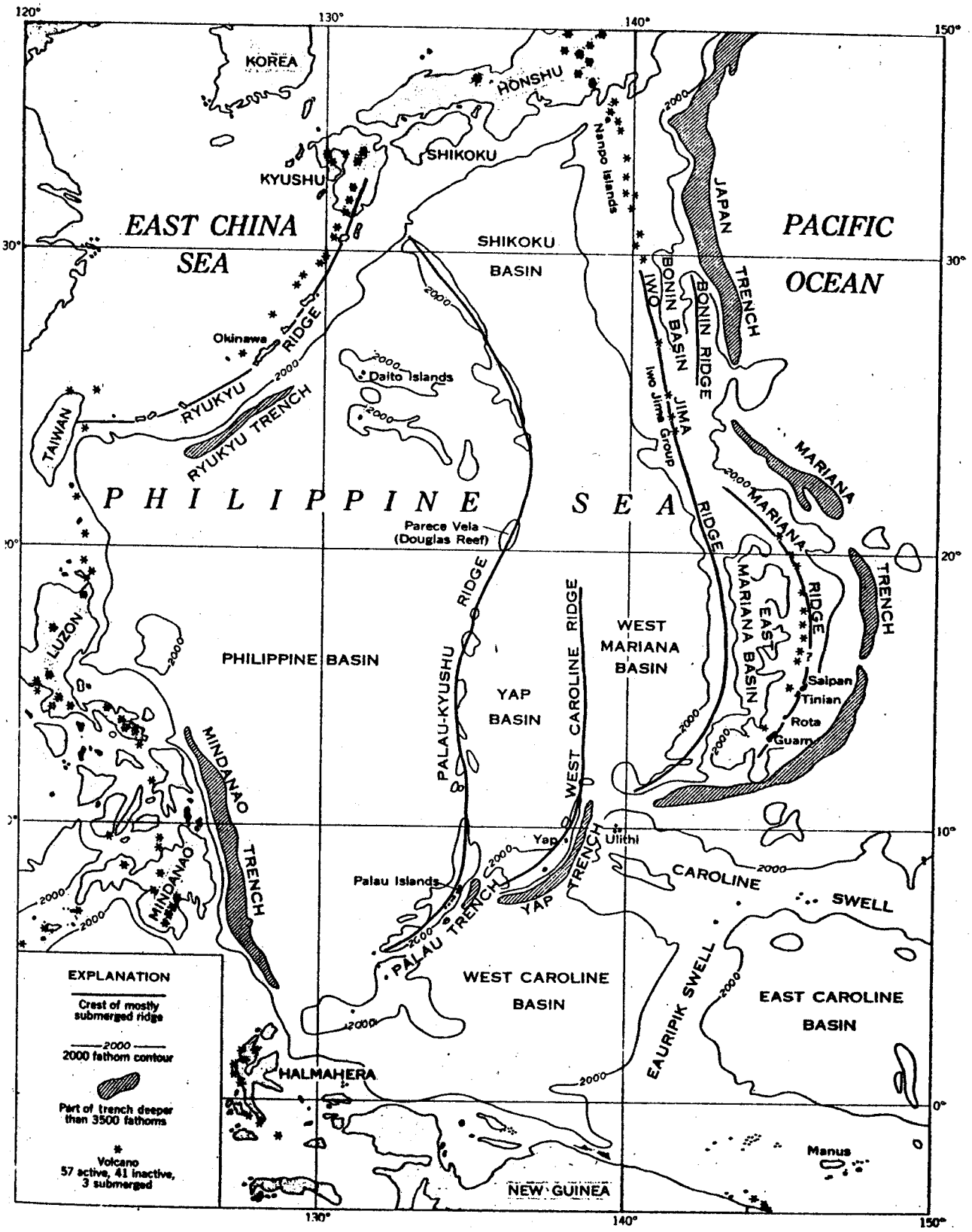



Figure 117.--Regional relationships in the western North Pacific Ocean (from Cloud et al. 1956).

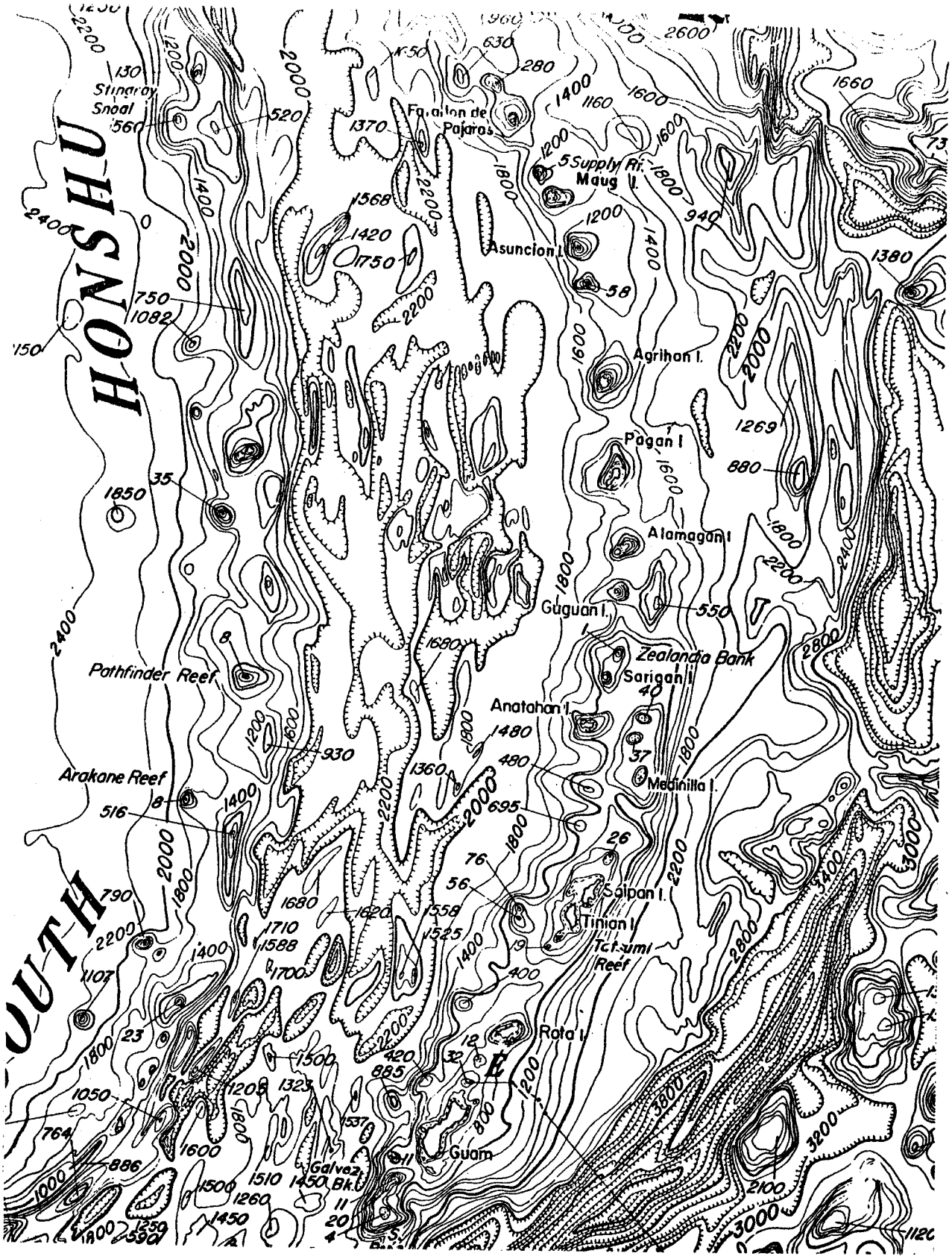



Figure 118.--Bottom topography along Mariana Archipelago (from Chase et al. 1968).

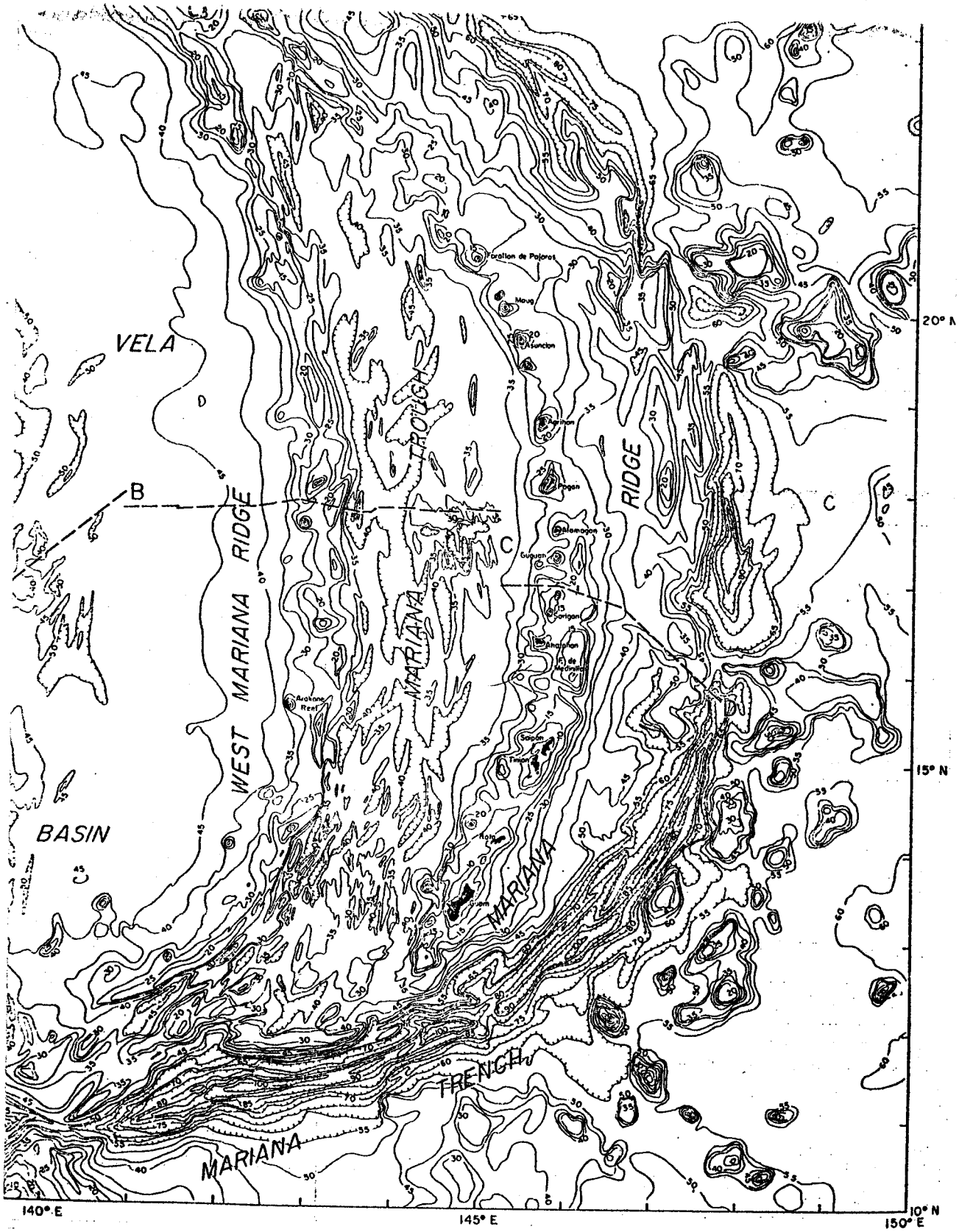



Figure 119.--Bathymetry of the southeastern Philippine Sea (from Karig 1971).

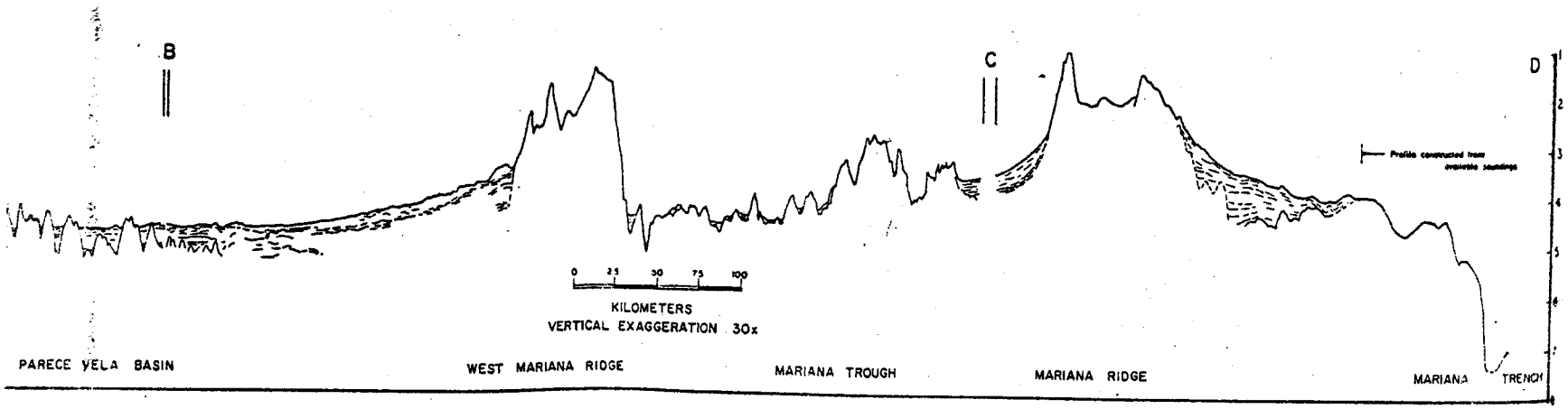



Figure 120.—Composite seismic profile across southeastern Philippine Sea (from Karig 1971).

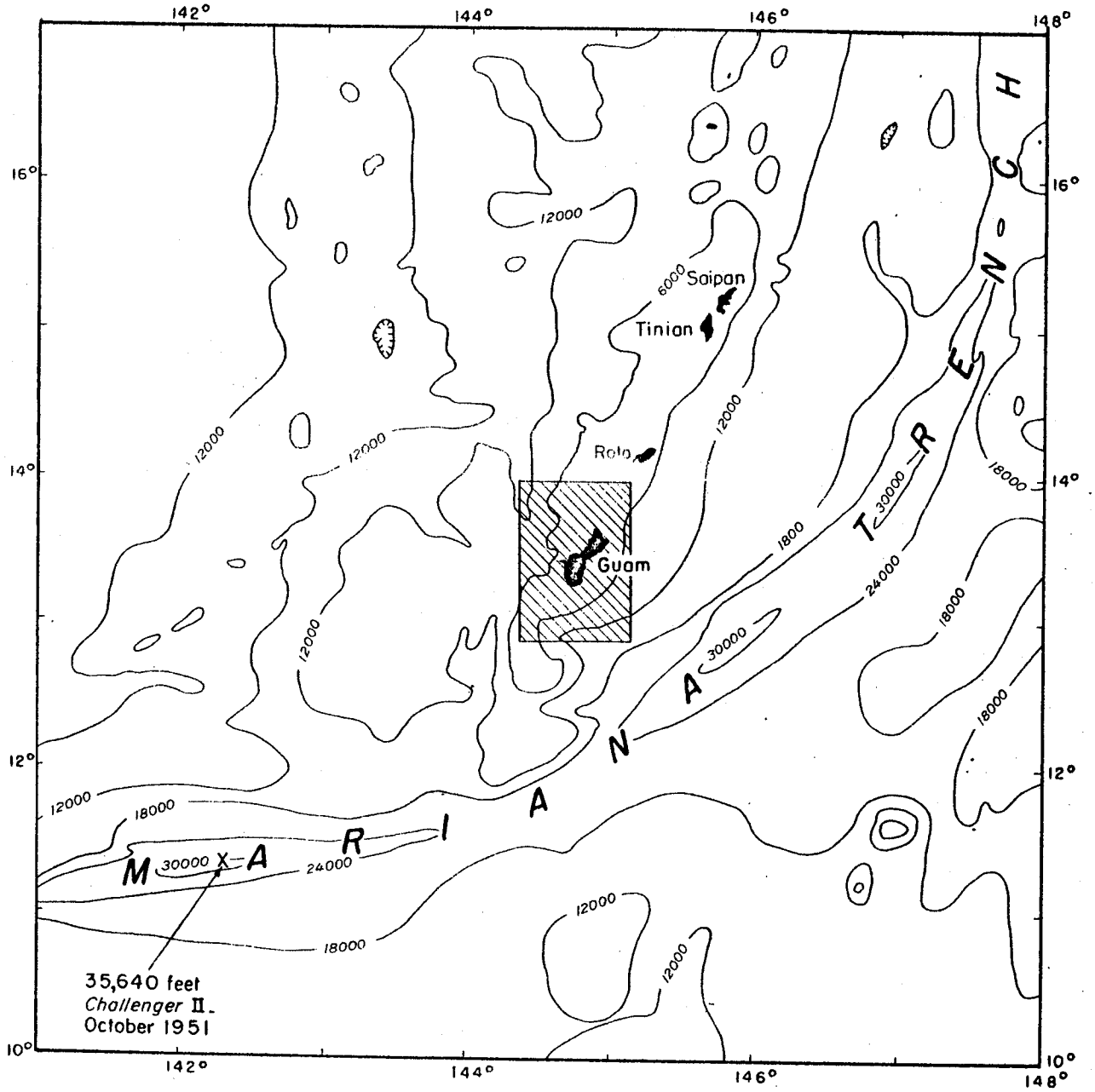



Figure 121.--General bathymetric chart of archipelago area; contour interval is 6000 feet (1000 fathoms) (from Emery 1962).

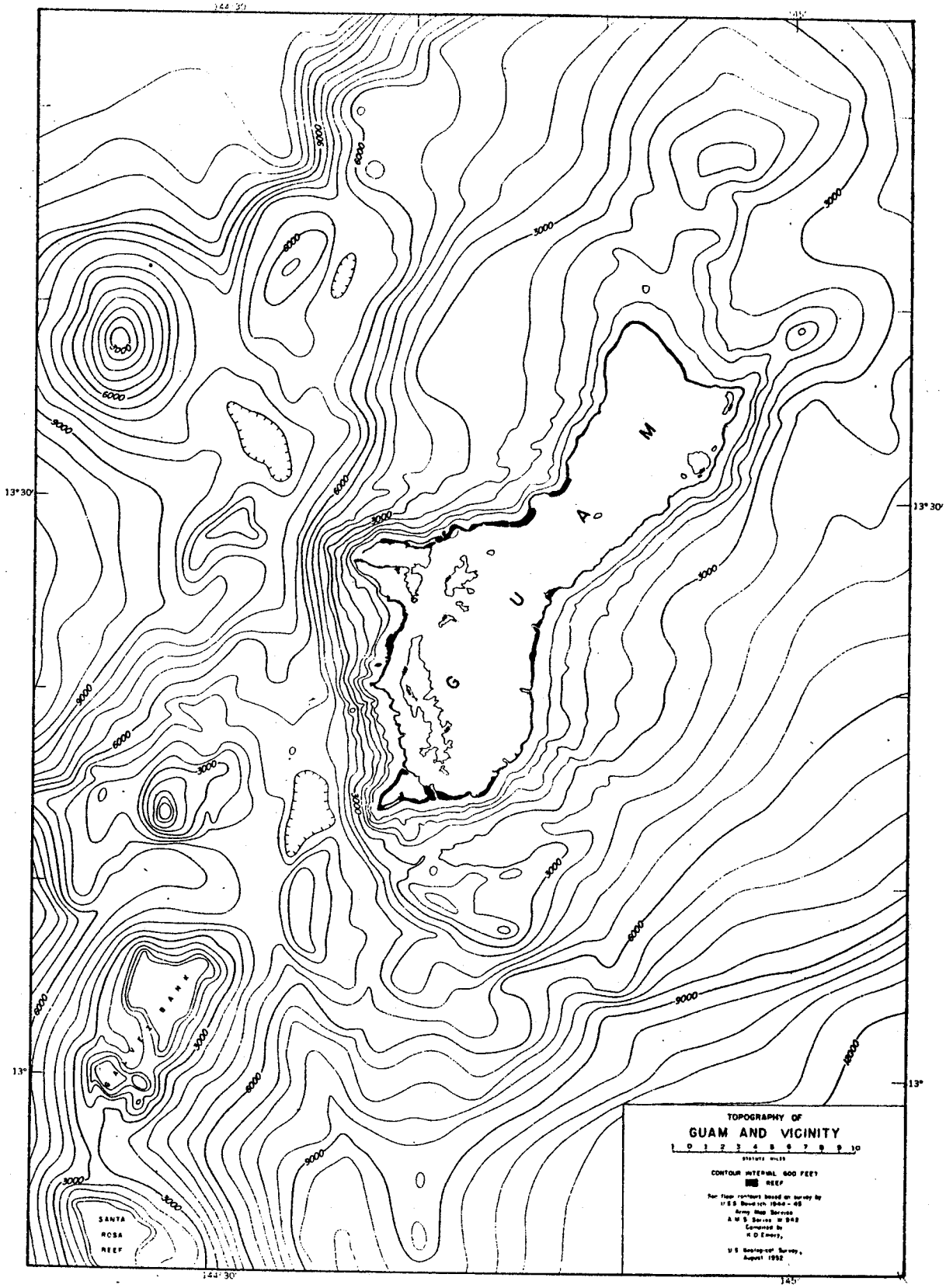



Figure 122.--Bathymetric chart of Guam and vicinity; contour interval is 600 feet (100 fathoms) on both land and sea floor; reef areas shown by solid black pattern (from Emery 1962).

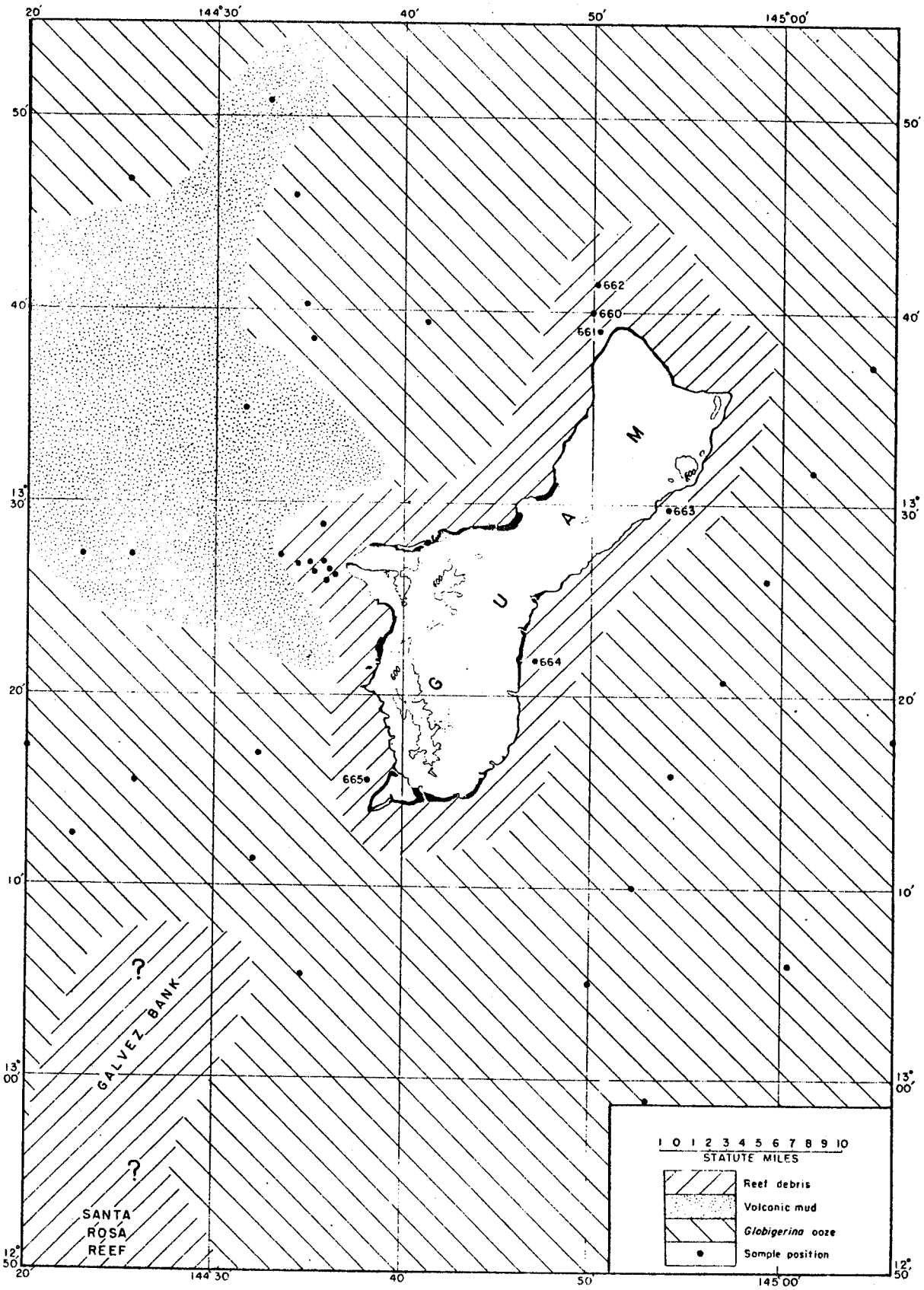



Figure 123.--Distribution of deep-sea sediments near Guam (from Emery 1962).

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