Reprinted from the "Proceedings of the Indian Academy of Sciences," Vol. XLVI, 1957

OCEANOGRAPHIC STUDIES IN THE BAY OF BENGAL

BY

E. C. LAFOND

5

Reprinted from "The Proceedings of the Indian Academy of Sciences",
Vol. XLVI, No. 1, Sec. B, 1957

OCEANOGRAPHIC STUDIES IN THE BAY OF BENGAL

BY E. C. LAFOND*

Received January 4, 1957
(Communicated by Sir C. V. Raman)

TABLE OF CONTENTS

INTRODUCTION

Indian Ocean.—The Indian Ocean remains one of the unexplored frontiers of our earth. It encompasses nearly 3,000 miles of coast-line and stretches hundreds of miles to the south, east, and west. It has an area 23 times as great as that of India itself and is the only major ocean named after a country. It is only fitting, therefore, that the study of this vast

* The author was Visiting Professor of Oceanography at Andhra University during 1952–53 and 1955–56. His services were made available through the U.S. Educational Exchange Program (Fulbright). He is currently Head of the Physical Oceanography Section of the U.S. Navy Electronics Laboratory, San Diego, California.

body of water has been taken up as a major subject here in India. The Andhra University, a pioneer in many fields, has introduced the scientific study of the north-eastern part of the Indian Ocean—the Bay of Bengal—into its curriculum, and some of the progress in this field is here reported

Bay of Bengal.—The Bay of Bengal has many fascinating and unique features. The offshore area lying between 8 and 22 degrees north is clear blue tropical water. The nearshore waters, on the other hand, undergo seasonal cycles of color, varying from deep blue to the greenish hue of plankton and the brown of coastal drainage.

The wide changes in the physical and chemical properities of the water and its circulation are the result of unique meteorological conditions associated with the monsoons. These not only completely change the current direction with the season, but monsoons also produce the largest rainfall and dilution in the world.

From a geological standpoint, the Bay of Bengal is famous for its unprecedented drainage and the associated deposition of sediments. The submarine canyon, " Swatch of No Ground," and the littoral sand drift along the east coast beaches are world renowned. Oceanography of the Bay of Bengal is more complex and intriguing than that of any other similar body of water and many fascinating problems await only investigation.

OCEANOGRAPHIC PROGRAMS

Previous expeditions.—In the past, several expeditions have studied oceanographic features of parts of the Indian Ocean—namely, the research vessels Challenger, Planet, Dana, Valdivia, Mahabiss, Discovery, Snellius, Gauss, Novarra, Siboga, etc. None have been sustaining studies, that is, repeated or systematically planned for the entire ocean. The main oceanographic work in the Bay of Bengal was done from the Investigator, operated by the British and running from Ceylon to the Andaman Islands, but sometimes veering to Madras or Calcutta. These are nearly all surface observations and were reported in the *Memoirs of the Asiatic Society of Bengal* by Col. Sewell a quarter of a century ago. Within the last ten years two round-the-world deep sea expeditions, the Danish Galathea and the Swedish Albatross, have traversed the Bay of Bengal. The Albatross passed through only the southern part, but the Galathea took soundings up to Calcutta. No deep oceanographic stations have been occupied in the Bay and it still remains to be thoroughly investigated.

Present studies.—The Central Government is currently sponsoring some oceanographic work. The new INS Investigator has been employed for oceanographic measurements, along with hydrographic surveys. The Survey of India has a long record of tides, and publishes a forecast for Indian Ports. The Meteorological Department has been collecting meteorological and current data from merchant vessels plying the Indian Ocean. Also, the Department of Fisheries Research has initiated measurements of temperatures, surface currents, and chemical properties of the water in several near-shore areas, together with studies of the biological populations, especially commercial fish. Another recent agency is the Indian Navy Physical Laboratory which has initiated several oceanographic studies along the west coast. However, the group most concerned with the development of oceanographic research in the Bay of Bengal is the Andhra University at Waltair.

Andhra University.—Most of the credit for the oceanographic program at Andhra University must be given to the Vice-Chancellor, Professor V. S. Krishna, who first realized the desirability for oceanographic instruction in India and took the necessary steps to provide facilities and to obtain assistance in getting the program started. And he has made sure that once initiated, the work would continue and expand.

The academic teaching of oceanography had been carried on in the Geology, Zoology, and Geophysics Departments for a number of years. Offshore oceanographic research, however, dates from 1952, for at that time vessels for oceanographic work were made available through the Minister of Defense. So far, the University has conducted 47 cruises in the Bay of Bengal, each lasting from one day to one week. Over 700 oceanographic stations have been occupied, ranging from Madras on the south to the Swatch of No Ground on the north. Most of the work, however, is centered off the Visakhapatnam coast, as this area is especially well suited for the study of the Bay (Fig. 1).

Oceanographic cruises were carried out from Navy minesweepers by from 6 to 20 students and teachers. A cruise consists of proceeding to prearranged locations (stations), stopping the ship and lowering oceanographic instruments to measure the properties of, and to sample, the seawater. Silk plankton nets are used to filter out the small plankton organisms and dredges scoop up the benthonic forms. Sea floor sediments are sampled and the shallower depths are sounded. Some of the collected samples must be processed on shipboard in order to avoid changes in properties on storing, but the majority of data and samples are returned to the University laboratories for complete analyses. These operations are depicted in Figs. 2 and 3.

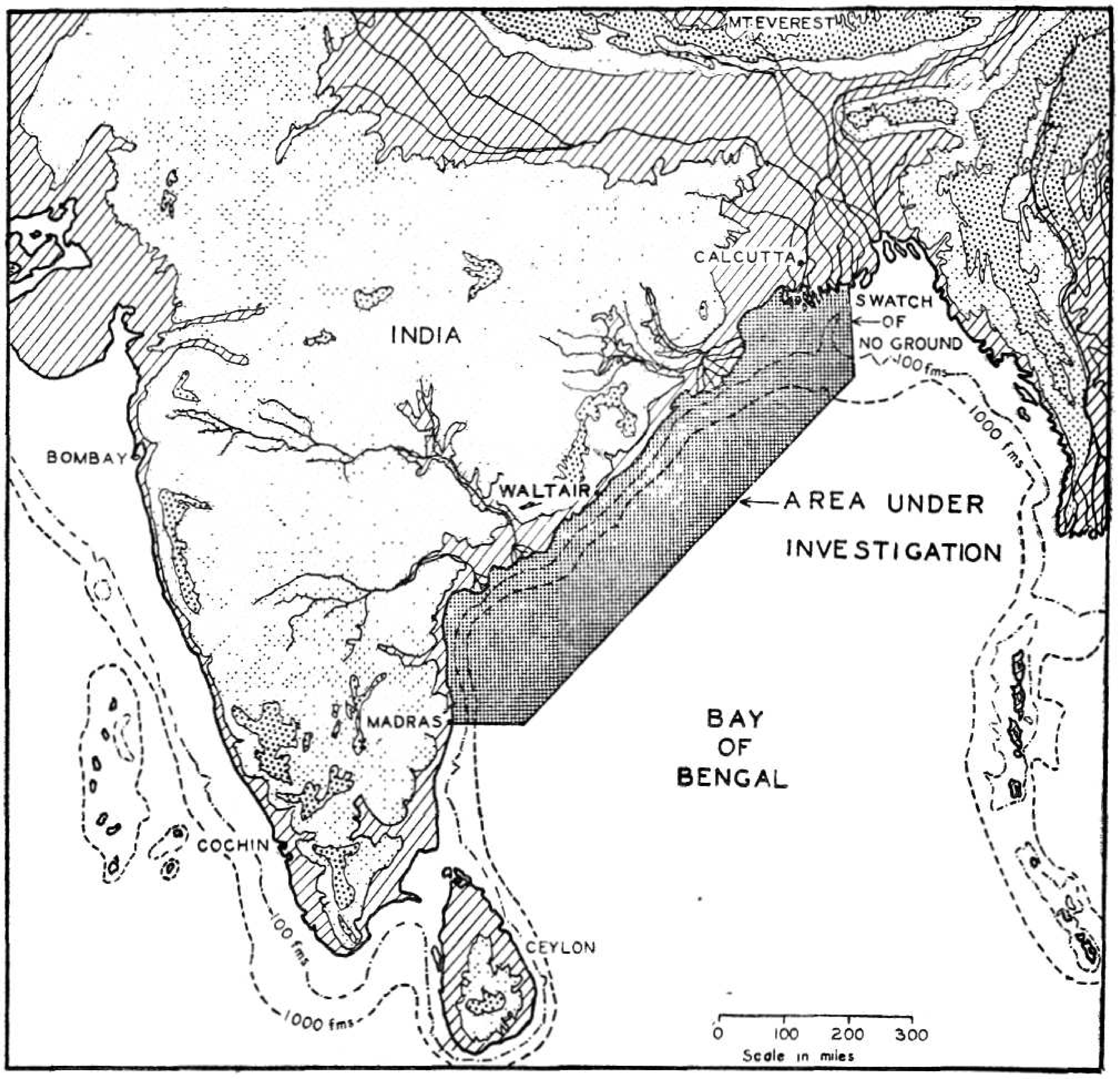

Fig. 1. Area of the Bay of Bengal currently under investigation by oceanographers of the Andhra University.

Most of the results of oceanographic studies are used for thesis material, though some are published in scientific journals and in the *Andhra University Memoirs in Oceanography*. A summary of the more important studies which have materially added to the knowledge of the area are here briefly discussed by subject—marine geology, marine zoology and physical oceanography.

Studies in Marine Geology

The marine geological studies, under the direction of Professor C. Mahadevan, deal with variations in depth of the Bay of Bengal, especially the continental shelf, and the nature of sediments of the shelf, river deltas, and beaches. More recently the concentration and distribution of heavy mineral sands have been intensely studied, due to their scientific and economic importance.

Topography of Bay of Bengal

Deep sea bathymetry.—The sea floor topography of the central part of the Bay of Bengal is extremely simple, Fig. 4. The head of the Bay off the Ganges Delta is flat and shallow, cut only by the Ganges Submarine Canyon, or Swatch of No Ground. Below 100 fathoms the slope steepens, then decreases again very gradually, resulting in a smooth southward sloping plain with a gradient of about one fathom per mile. This uniform slope indicates that the sea floor here has been tectonically stable for a long period of time and any initial tectonic features present in this broad plain have been masked by sedimentation.

The amount of sediment discharged into the head of the Bay by the Ganges, Brahmaputra, Mahanadi and other rivers is difficult to say. One estimate is that the seaward edge of the continental shelf is steadily moving southward at the rate of one mile in 40 years.[1] Another speculation is that if the discharge during the flood season[2] contains one per cent of sediment this would amount to 4×10^9 cubic meters of sediment, or enough to cover the entire Bay of Bengal to a depth of 2 mm. every year. These, of course, are very rough estimates, because the exact figures for both runoff and sediment bedload content are uncertain. But it does give an insight into the vast sedimentation problem which exists in the Bay and its influence on the topography.

Minor irregularities.—Profiles of the southern Bay of Bengal were taken by continuous echo sounders on the Swedish deep sea ship, Albatross. In an east-west section they show that the sea floor is extremely smooth except for occasional trough-shaped depressions.[3] Five of these profiles are reproduced in Fig. 5. Their positions (A–E) lie to the east of Ceylon and are shown in Fig. 4.

The striking feature is the bilateral symmetry of the depressions. The sides are leveed like the banks of a river. It has been suggested that they are the results of turbidity currents, probably extending the length of the Bay, or 1000 nautical miles, from the Swatch of No Ground or other uncharted canyons in the head of the Bay.[3]

This process may conceivably come about by, (1) the enormous sedimentation of the rivers at the head of the Bay, and (2) a density circulation

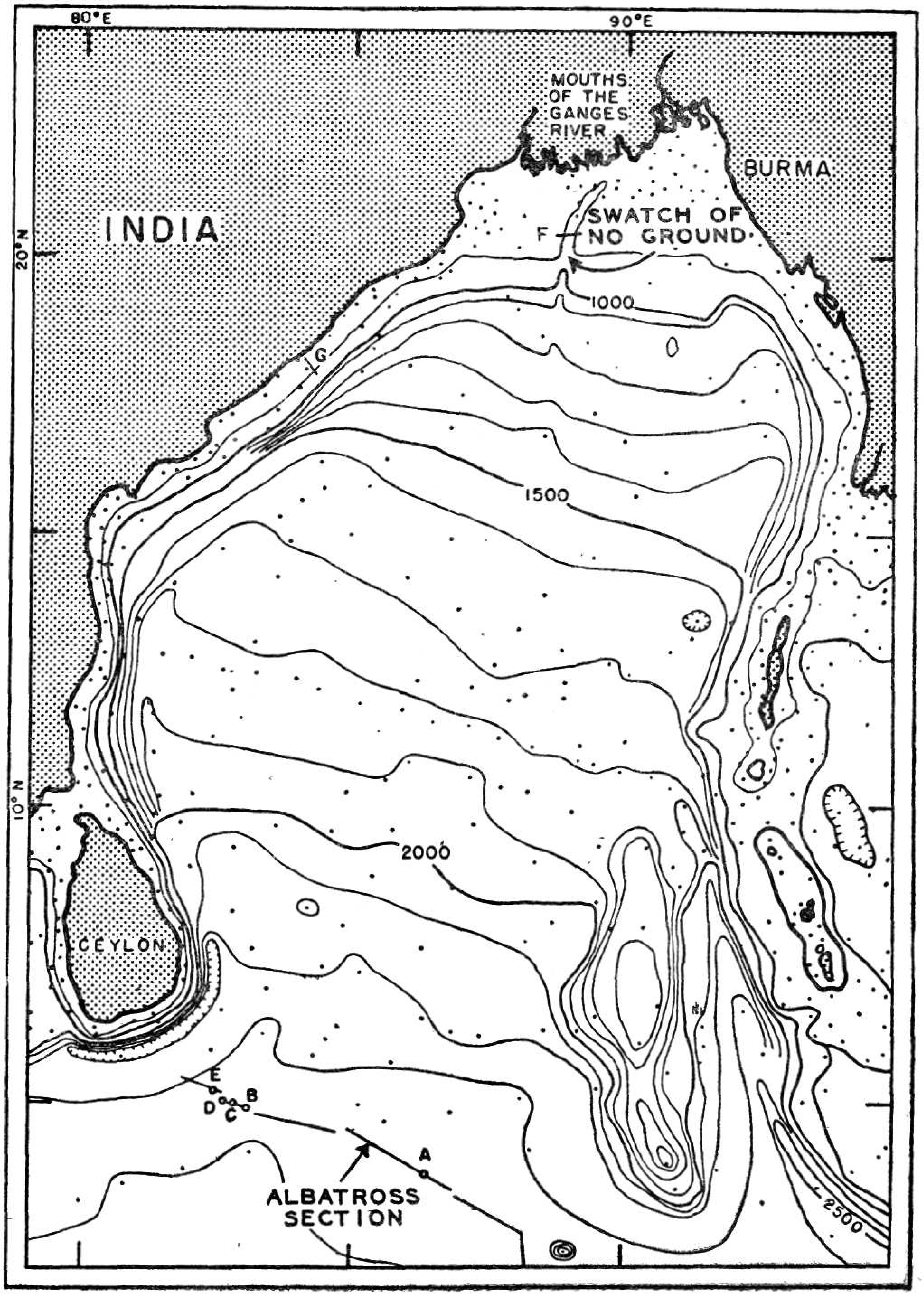

Fig. 4. Bathymetric chart of the Bay of Bengal.[3] The gradual decrease in depth to the south is shown by the nearly equal spacing of the 100-fathom interval contours. The location of detailed bottom topography (A–F) is shown in Fig. 5 and G in Fig. 6.

set up by "relaxing currents" at the termination of the upwelling period (The latter will be discussed later.)

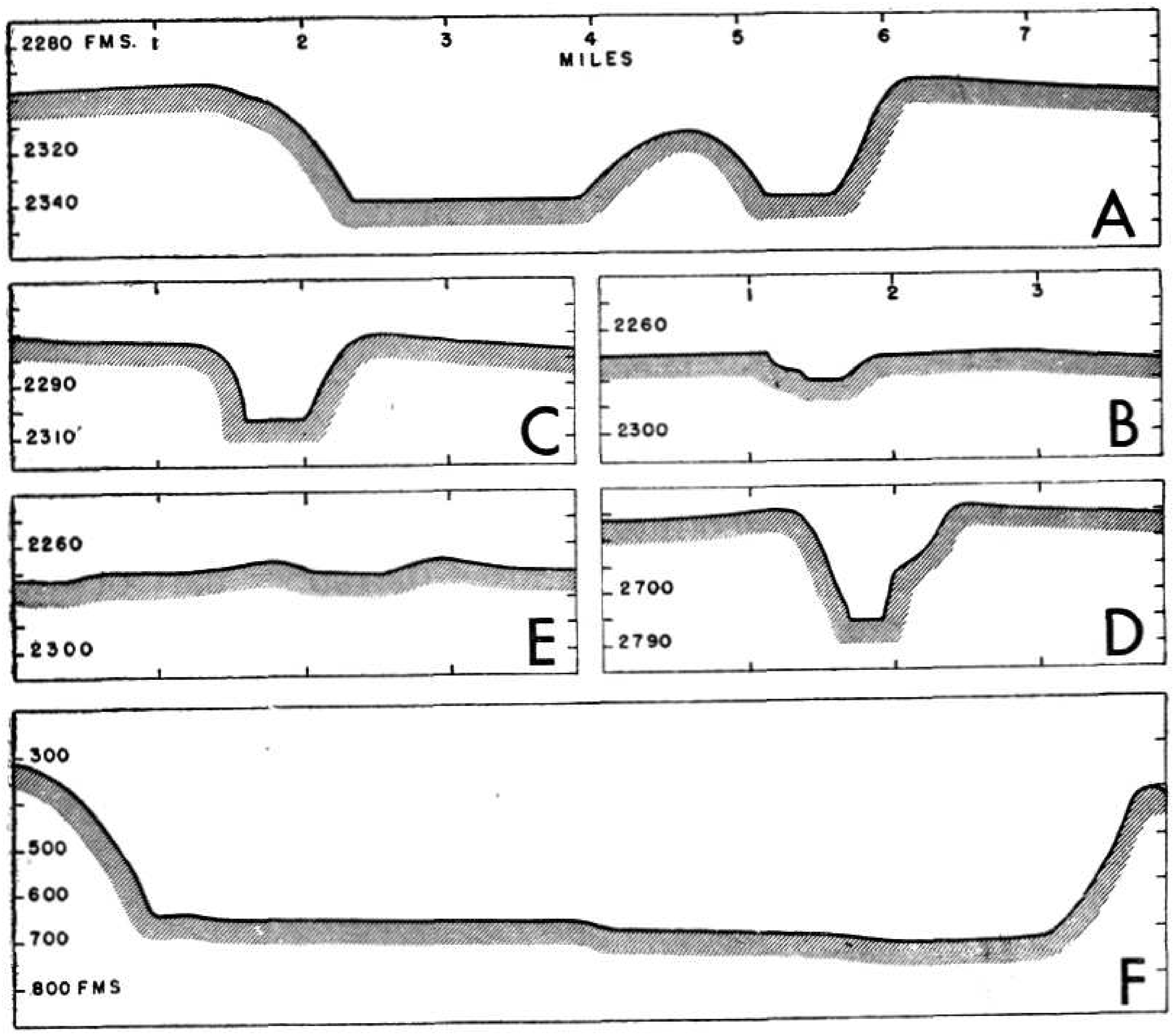

FIG. 5. Bathymetric profiles of trough-like features in the Bay of Bengal. A—E in southern part of Bay (vertical = 18 × Horizontal scale) and F across the Swatch of No Ground[4] (vertical = 3 × Horizontal scale).

Thus, the sea floor of the entire Bay appears to be a very gentle slope cut by a network of channel-like depressions running north to south.

Swatch of no ground.—A world famous feature of the Bay of Bengal is the submarine canyon with the impressive name, Swatch of No Ground. This canyon cuts the continental shelf in a general north-east—south-west direction at the northern end of the Bay.[4]

Five profiles across the canyon were made by the Danish Deep-Sea Expedition's vessel H.M.S. Galathea. One of them is represented in Fig. 5, and its approximate position is given as F in Fig. 4.

This crossing, F, shows the canyon to be about 8 nautical miles wide and about 700 fathoms deep. In this region the canyon is cut down into the surrounding plain at 3 to 400 fathoms. The slopes are steep, 1 : 1·5, but he bottom is nearly level. The width remains rather constant over a long stretch. Eighteen miles farther south the bottom of the canyon is only 100 fathoms below the surrounding plain. Here it turns slightly to the south. Thirty-six miles south, the canyon was lost to the west, but some small undulations were found running down slope at about 960 fathoms. These are similar to the levees observed in the southern end of the Bay and might also have been caused by turbidity currents.

Continental shelf.—The continental shelf in the head of the Bay of Bengal is as much as 100 miles wide but narrows to the south. Detailed profiles have been made off the Andhra Coast[5] and a representation of these sections is shown in Fig. 6. The features of the continental shelf in this region are, (1) a width of about 25 miles, (2) an average slope of 0° 15′, and (3) a depth at the outer edge of around 100 fathoms. The unique feature is that the shelf can be divided into five zones, each having characteristic slopes and sediments. A sixth zone comprises the upper part of the continental slope. Each zone runs nearly parallel with the shore.

The average widths and slopes of the zones comprising the continental shelf off the Waltair Coast are given in Table I. The widths of the zones are somewhat variable and become a little greater towards the north, in the Bhimilipatam area.

TABLE I

Characteristics of the Waltair Continental Shelf

Zone	Width (mi.)	Slope (degrees)	Depth (fms.)
Shore A–B	2	0° 26′	0–15
B–C	11	0° 04′	15–35
C–D	6	0° 11′	35–58
D–E	2	0° 35′	58–70
E–F	2	1° 09′	70–112
Beyond F (Continental slope)	?	4° 38′	112

All zones are relatively smooth, with the exception of zone C–D, lying between 35 and 58 fathoms. Here, irregularities in the bottom are as much as two to three fathoms. These are called broken bottoms. From the character of the slope and the breaks in the different zones it appears that the deposition or erosion of the sea floor is in turn caused by currents and water masses, which are oriented parallel to the coast. Previous sea level changes must also have played a part in this irregular formation. This is discussed in the Shelf Sediments section.

Sea Floor Sediments

Deep water sediments.—The sediments of the deep Bay of Bengal basin are characterized by their content of Globigerina ooze. This area comprises only the central and deeper parts of the deeper Bay and extends north to about 17° N.[6] Terrigenous deposits comprise the northern and shallower portions.

Samples taken on the continental slope are plastic and soft in consistency and are colored dark grey with a blue tinge. They appear to consist of clay minerals, glauconite, fine mineral grains, and an abundance of micro-organisms such as foraminifera, radiolaria, etc.[7, 8]

Shelf sediments.—The shelf sediments closely correspond to the slopes of the shelf, Figure 6. They, too, can be divided into zones.[7] And though there is some overlapping, the zones are distinct enough for definite delineations. The near-shore sediment, up to about two miles or 15 fathoms, was found to be composed of sand and was named the sand zone. The sand in this zone appears to be graded and sorted, with the fineness of the grains increasing with distance from shore. The outer limit (15 fathoms) may be taken as the limit of inshore currents and effective wave action.

The second zone, extending from about 2 to 13 miles off shore, and ranging from 15 to 30 fathoms, is known as the clay zone. Here the sediments consist of clay minerals and fine grains of sand. The fine sand continues to decrease in size and amount with distance from the coast, together with a corresponding increase in the clay fraction. Shell fragments are rare.

The next sedimentary zone is called the shell zone. It lies between about 13 and 21 miles off shore and is characterized by fragments of shell and concentrations of sand. The depth extends from about 30 to 70 fathoms, with the maximum shell content occurring between 58 to 70 fathoms. In the shell zone the sands are coarser than those found in the proceeding clay zone, or beyond 70 fathoms. This interesting zone disproves the old concept of progressive diminution of grain size with distance from the coast.[9]

The shell zone may be further broken up into a central zone between 35 and 58 fathoms, termed a rock zone. Although no rock has been dredged

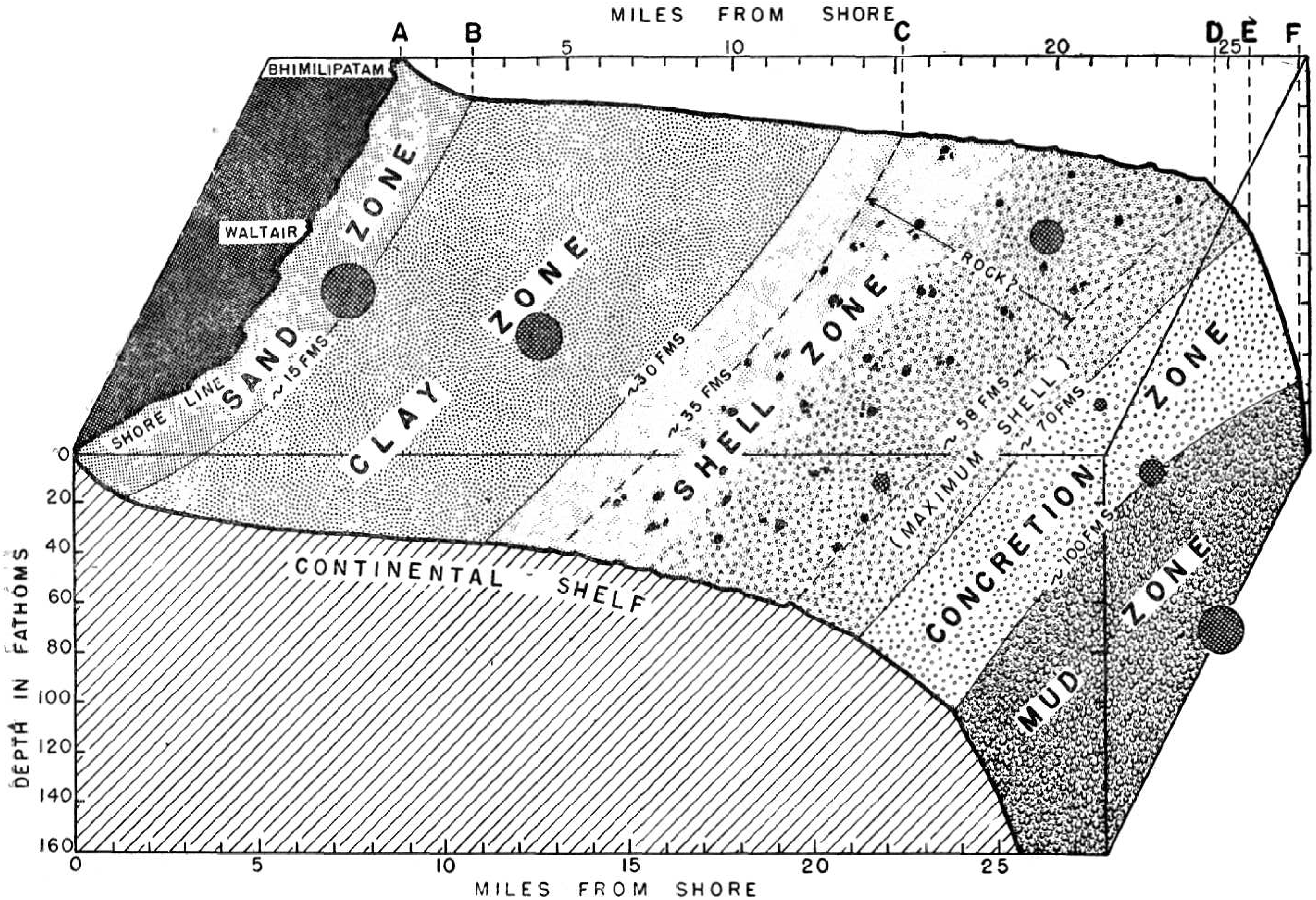

FIG. 6. Schematic diagram of the continental shelf off Waltair showing bottom profiles and zones of sediments. The dark shaded circles represent the locations where sediments were collected for radioactivity and the size is proportional to the amount.

or sampled, strong evidence points to its presence. In addition to the sharp vertical irregularities in the echo sounding record, the dredge when operating at 35 fathoms repeatedly "hung up" on hard solid objects. A sample broken off consisted of biological forms (bryozoan, sponge, hydroid and pecten, Fig. 12 J) which normally are attached to large stable rocks. Such evidence strongly implies that rock exists in this zone. It appears likely that this may have been a former beach during Pleistocene's lowered sea level, thus accounting for the coarser sediments, shells and possible rock formations.[10]

The next deeper sediment zone overlaps the shell zone and extends from 40 fathoms to the continental slope. The outer part extending out beyond the shell zone lies between 70 and 100 fathoms, roughly 21 to 23 miles off the Waltair coast. This strip is termed the concretion or oolite zone. Although the sediment in this zone is composed of clay, fine sand and shell fragments, the unique feature is that much of the material is cemented together in oval-shaped concretions or oolites. They vary in size from microscopic dimensions up to about 1 mm. in diameter. They are easily dissolved by acid, since part of the composition is calcium carbonate, iron, and other acid-soluble material. The formation of these oolites is another one of the mysteries of the Bay of Bengal.[11]

Delta sediments.—Sampling of sediments was also carried out off the Ganges, Mahanadi, Godavari, Krishna and Pennar Deltas. Though not identical, they can be discussed together. These sediments are finer than the coastal sediments, and consist mostly of silts and clays. They are generally darker (Krishna and Godavari) than the coastal samples. Another contrasting feature is the surprisingly low shell content off the deltas. A deltaic environment is apparently not conducive to the production of molluscan type organisms. The deltaic sediments, then, are the product of deposition and settling out of the finer sediments, probably facilitated by the electrolytic action of salt-water on the finer particles at the outer parts of the delta.

Radioactivity of sediments.—Samples of sediments collected along the east coast in the Bay of Bengal were also examined for their β-activity, from which the equivalent radium content was deduced.[12] On the continental shelf in the Waltair area the relative radium content of the sediments can be grouped in zonal patterns similar to those of the bottom slopes and sediments. For example, in Fig. 6 the dark circles indicate that there is a zone of relatively high intensity ($11\text{–}14 \times 10^{-6}$ gm. of *U.* per gm. of sediment) extending from shore out about 12 miles and to a depth of 30 fathoms. This high value was presumably caused by the presence of monozite and zircon in sediments, which are common minerals on the beach.

The second zone is composed of sediments with low values of radioactivity ($3–7 \times 10^{-6}$ gm. of *U.* per gm. of sediment) and was found between 12 and 23 miles off shore in a depth of between 30 and 100 fathoms. The low intensity of radioactivity on this former beach area has not been satisfactorily explained.

The third radioactive zone on the continental slope again contained a relatively high concentration ($13–15 \times 10^{-6}$ gm. per gm. of sediment). This high level is in accordance with other places in the world and attributed to the greater thickness of sedimentation containing thermal energy.

Beach Erosion

Beautiful sandy beaches extend all along the east coast. They derive their sand not so much from the Ganges River at the head of the Bay as from the numerous smaller rivers to the south and, to a lesser extent, from the erosion of the shore line (Fig. 1).

Sand sorting.—When the sediments are first deposited at the confluences of rivers, they consist of varying grain sizes and densities. Here at the confluences the sediments are initially sorted according to size—the coarser sands remain on the beach and the finer particles are carried off and deposited farther off shore. The beach sediments are further partially sorted according to density, whereby the heavier minerals (monozite, garnet, ilmenite, magnetite, etc.) settle out near the confluences and the lighter minerals (quartz, felspars, micas, etc.) are carried progressively further along the beach to the north and west by the predominant littoral drift (Fig. 12 A, B). From cores and magnetometer studies it was found that heavy mineral concentrates or black sands are developed near the river mouths from which they are derived.[13, 14]

Other black sand concentrates develop on open beaches where erosion takes place. This may be by a storm, during which the foreshore is eroded, or it may be caused by a long period of high waves, such as in the summer. In the process a greater concentration of heavy mineral sand remains due to the higher resistance of these to the water forces.

The greatest factors in concentrating black sands are continued erosion, or beach regression. Such conditions occur when an unnatural structure is placed in the water, such as the Madras Harbour or the Visakhapatnam breakwater. Sand from the south is trapped by the obstruction, but the sand to the north erodes, until equilibrium is reached.[15]

Another example of heavy mineral concentration is the case of Godavari Point. In its development over the past century, it has trapped the sand which formerly supplied Uppada Beach, causing the beach there to erode over a furlong, and resulting in considerable property damage.[16] This extensive beach regression, however, results in a large mineral deposition of commercial value.

Annual cycles of beach erosion.—The sand level changes on Waltair Beach were measured by a method which, though accurate, is simple and inexpensive. An eight-foot bamboo staff was marked off in feet and inches. This was used both for horizontal and vertical measurements across the beach. The latter were made by a line of sight intersections on the vertical staff between a permanent reference rock and the horizon of the sea, Fig. 7. It was found that the width of the beach does not remain fixed. Under the influence of waves, currents and, to some extent, wind and rain, the sand is moved towards land and out to sea.[17] Such movements are reflected in the sand level on the beach. Some of the movements appear to fluctuate in cycles related to the season and tides.

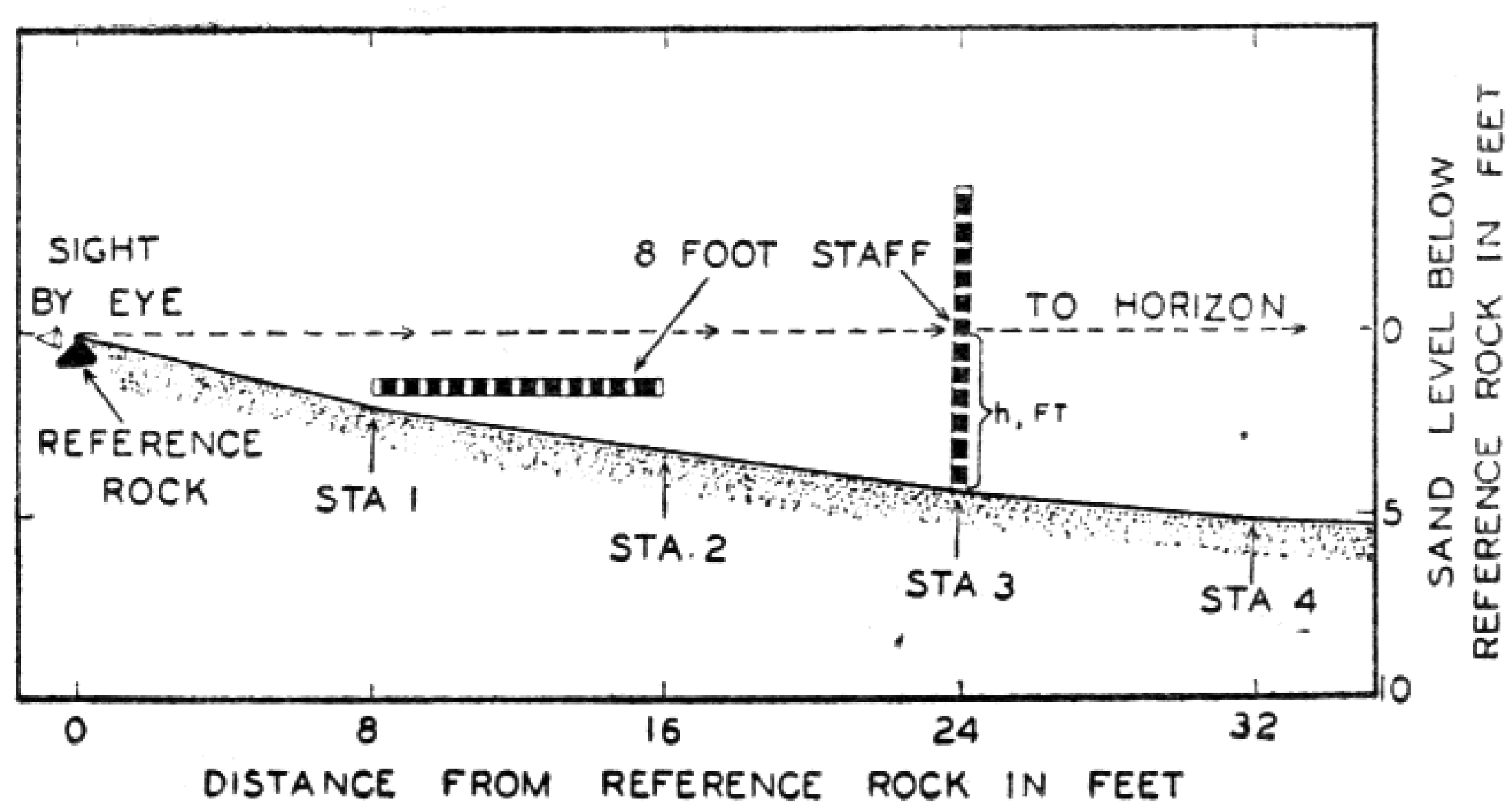

FIG. 7. Method of measuring sand level and beach profile with staff.

The seasonal sand level changes on Waltair Beach are represented in Fig. 8 together with the seasonal cycles of wind, waves, current and sand deposition for the central east coast. It can be seen that during the period of maximum waves the foreshore is eroded and the sand is deposited offshore. On the other hand, during the quiet weather period the sand "creeps" shoreward again, building up the beach. Thus, there is an annual cycle of sand levels, with the high values in March and April and low levels in October and November. The change on the Waltair Beach amounts to as much as 10 feet.[18]

Bimonthly sand level cycles.—The profile of the beach frequently varied from spring to neap tides, describing a bimonthly cycle in sand level.[19] The

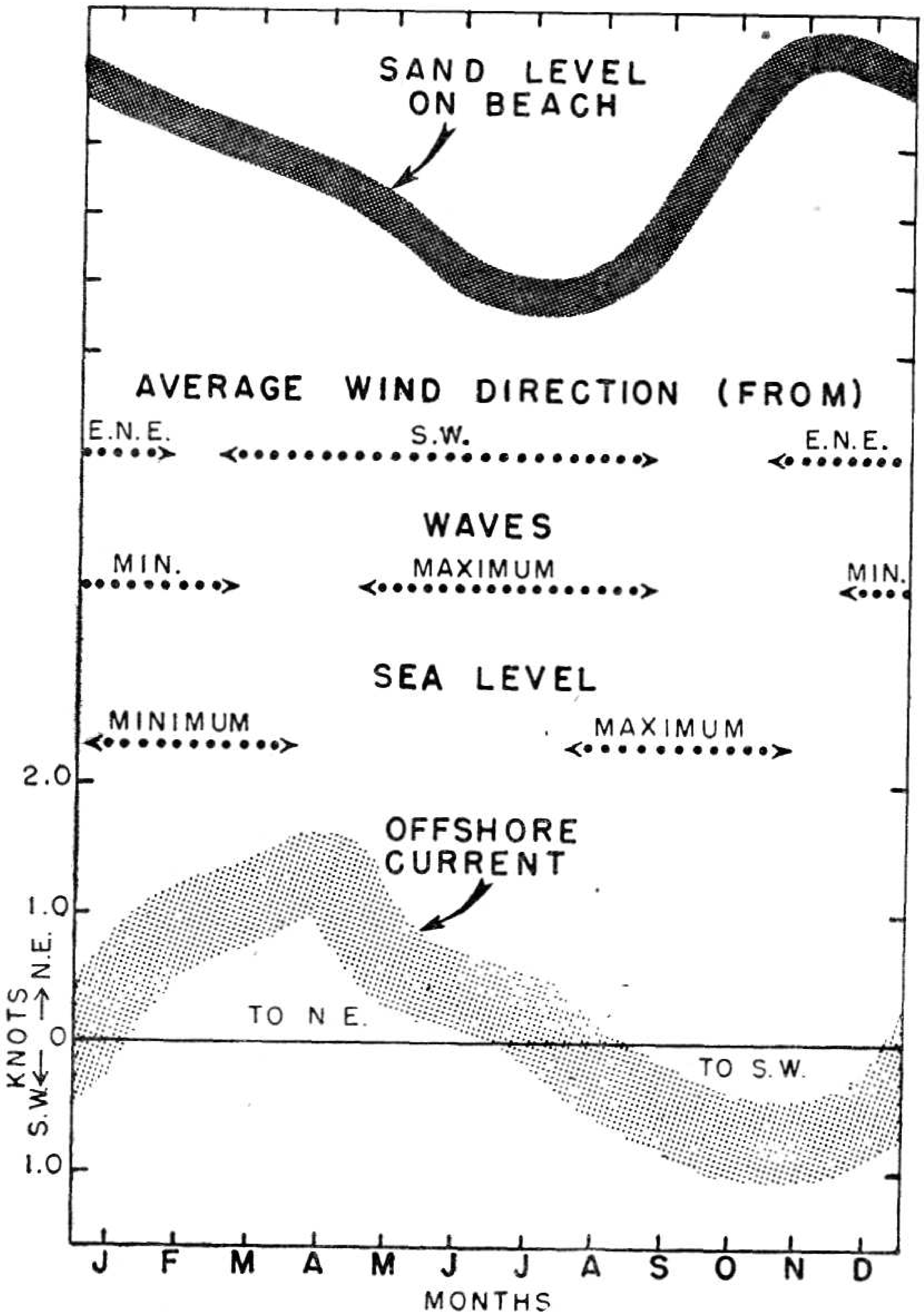

Fig. 8. Seasonal variation of sand level, sand deposition and the environmental factors affecting beach erosion.

change in observed sand levels, which took place during a series of spring and neap tides, is depicted in Figs. 9 A, B, C, and 9 A′, B′, C′. Here, too, the observed tide height and the per cent of time the beach is washed by the tide (and waves) are shown in the same vertical scale as the mean sea level.

The sand level appears to oscillate about a nodal point approximately one foot below mean tide level (C, C′). The main differences in the environmental conditions, aside from the height of water during the spring and neap tides, are (1) relative time that any vertical level of the beach is washed by the waves, and (2) the character of the waves caused by the difierence

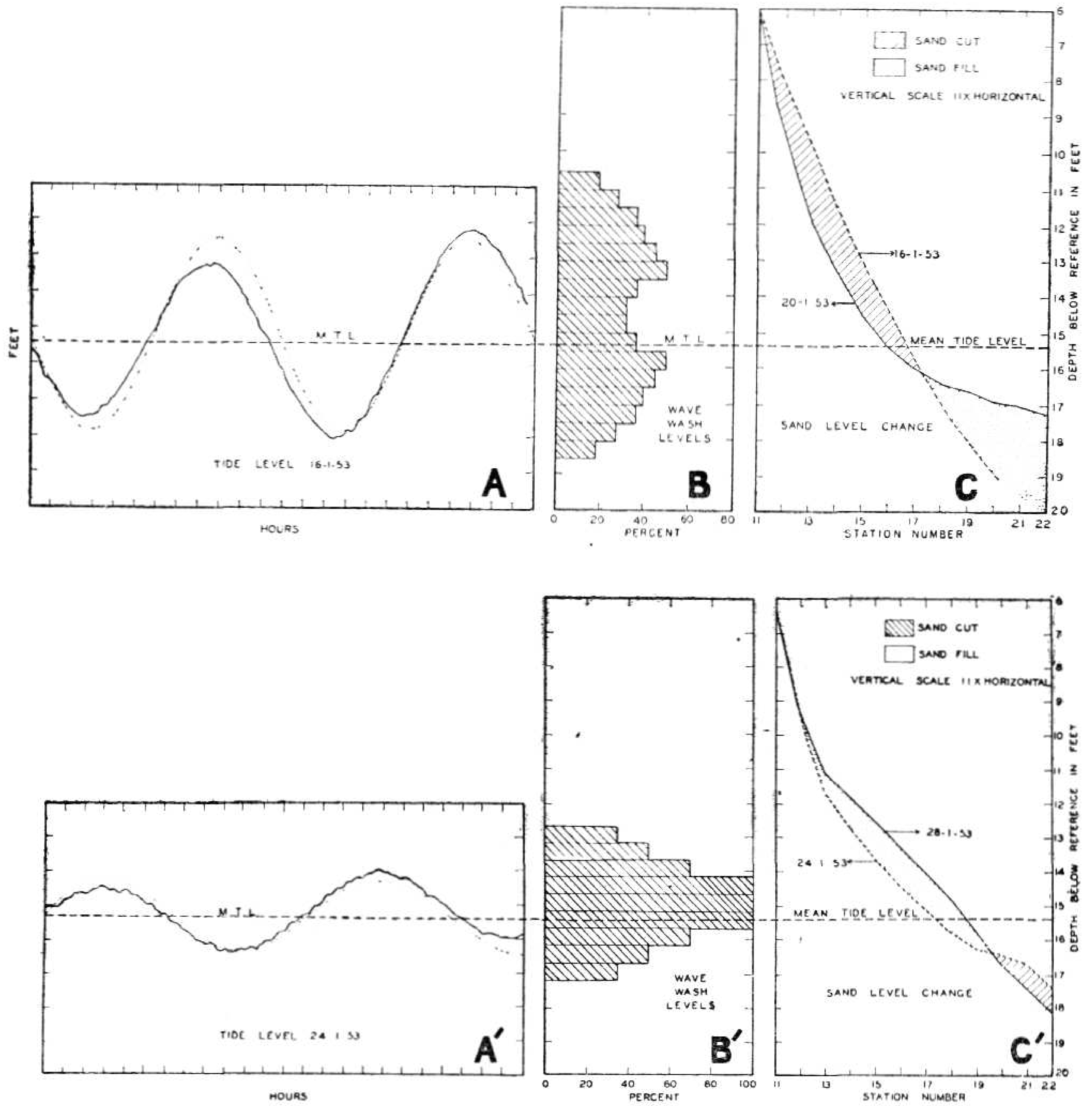

FIG. 9. Comparison of observed neap tide (A) and spring tide (A′) heights in Visakhapatnam Harbour, calculated per cent of time each beach level is washed by waves during neap tides (B) and spring tides (B′), and the change in sand level during neap tides (C) and spring tides (C).

in water depth. By calculating the washed zones it was found that spring tides produce two zones of long duration wash (B), while neap tides produce only one (B′). This is thought to be a major factor in sand movement on the beach. In addition, the wave energy at low tides is believed to be dissipated over the long shallow offshore area, whereas at high tide the energy is expended on the local zone high on the foreshore.

Slope of the beach.—Studies of the slope of the beach were made with reference to the nature of the swash and backwash. The speed of the wave as it rushes up the beach, stops, and recedes was determined with a simple manometer, as shown in Fig. 10. The maximum speed of the water, both up and down the beach, was obtained by holding this instrument in the water and reading the manometer scale. Several beaches of different slopes were examined, from which it was ascertained that a direct relationship exists between the difference in speed of swash and backwash, and the slope of the beach.[20] In other words, in order to maintain a steep beach a faster shoreward motion is required in the swash than the offshore motion in the backwash.

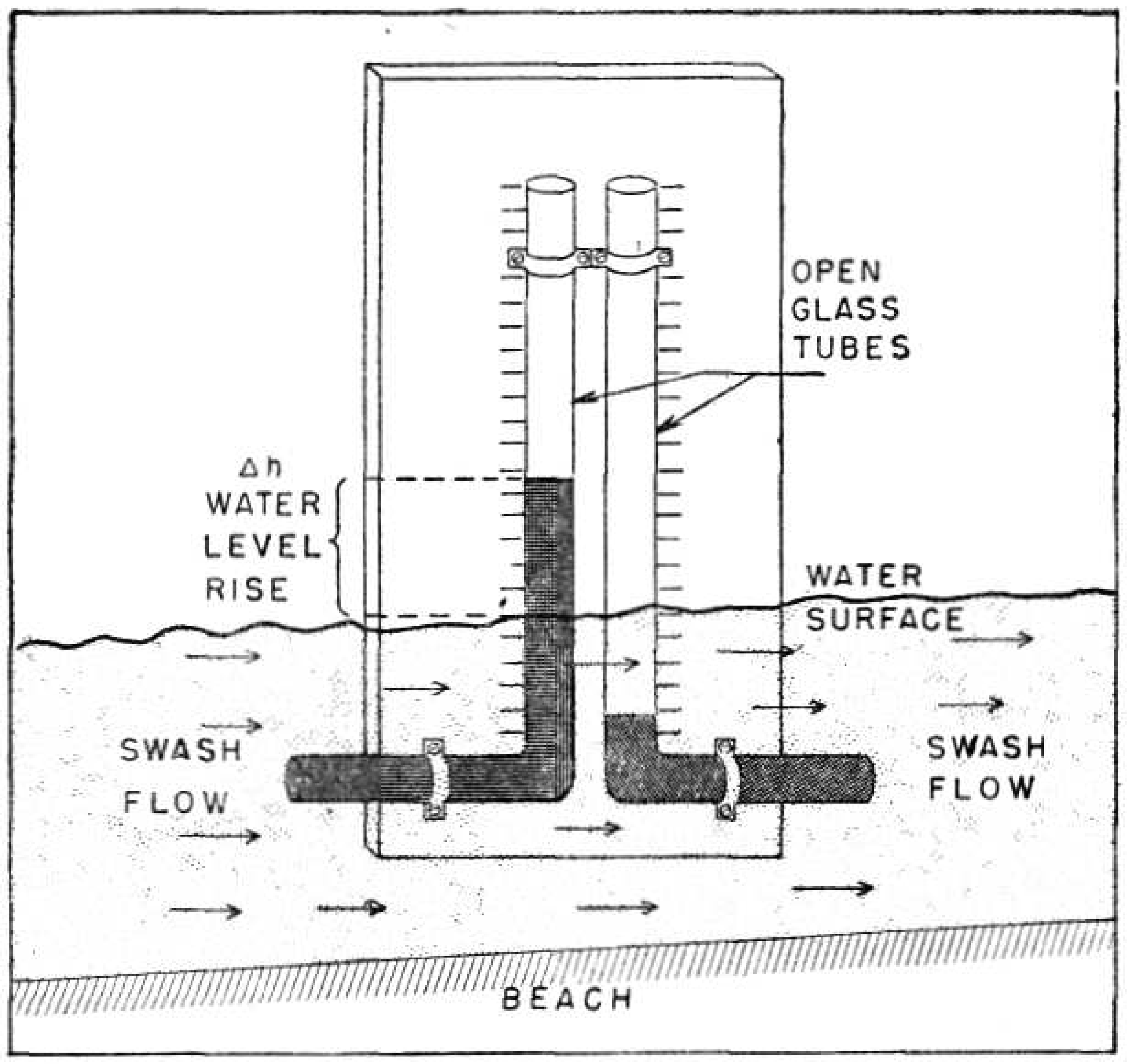

Fig. 10. Manometer to determine speed of swash and backwash.

Littoral drift of sand.—The sand on the beach acts as a fluid, slowly flowing along the beach, as well as on and off shore. The main direction of this littoral drift is to the north-east and the head of the Bay. Some reversals of drift are evident, but the environmental conditions which cause the drift (waves, currents, etc.) are more influential in a north-easterly direction. For example, it can be seen in Fig. 8 that the current flows north-easterly for 7 of the 12 months. Its speed in that direction is also greater than when it is south-westerly. Another important factor is that the waves are higher during the north flowing current. This facilitates suspension of the sand, so that it is easily transported by the along shore currents. Still another factor is that the major waves are from the south. This is due in part to the longer fetch in the south Indian Ocean, over which the wind may blow and develop large waves.

The littoral drift of sand in a northerly direction is manifested in several ways. One is the sand bar partially across small river mouths. The bar invariably extends from the south bank, indicative of sand flow from that direction.

The development of the broad sandy beach south of the Madras Harbour breakwater is evidence of the large quantity of sand accumulated from the south. The Visakhapatnam breakwater ingeniously traps sand from the south before it fills the channel. However, the building up of Godavari Point is the best example of a northerly drift and deposition of sand.[16]

A century ago, Godavari Point was indistinguishable from other sand bars at the mouth of the Godavari River, Fig. 11. Due to floods or deforestation in the Godavari delta, more of the river flow began to discharge in the open sea rather than into Kakinada Bay. It brought with it increased sedimentation which began flowing up the coast, and depositing at Godavari Point. Over the past century the Point has steadily grown from south to north until it reached its present size. Other deposition has taken place in the southern part of the Harbour, as well as north of Kakinada jetty. Uppada Beach, on the other hand, has been eroded and its supply of new sand has been cut off by the development of Godavari Point. The deposition rate at Madras, Visakhapatnam, and Godavari Point is approximately one million tons per year—about 400,000 cubic yards. From the foregoing, it can be seen that the marine geological problems are varied and unlimited—a real challenge to students in this field.

Studies in Marine Zoology

The marine zoological program, directed by Professor P. N. Ganapati, Head of the Zoology Department, comprises studies of the marine fauna and flora of the east coast. These include plankton, as well as benthonic forms, and their relation to fish. Research problems dealing with nutrients and other chemical properties of the water, turbidity and surface appearance are also pursued.

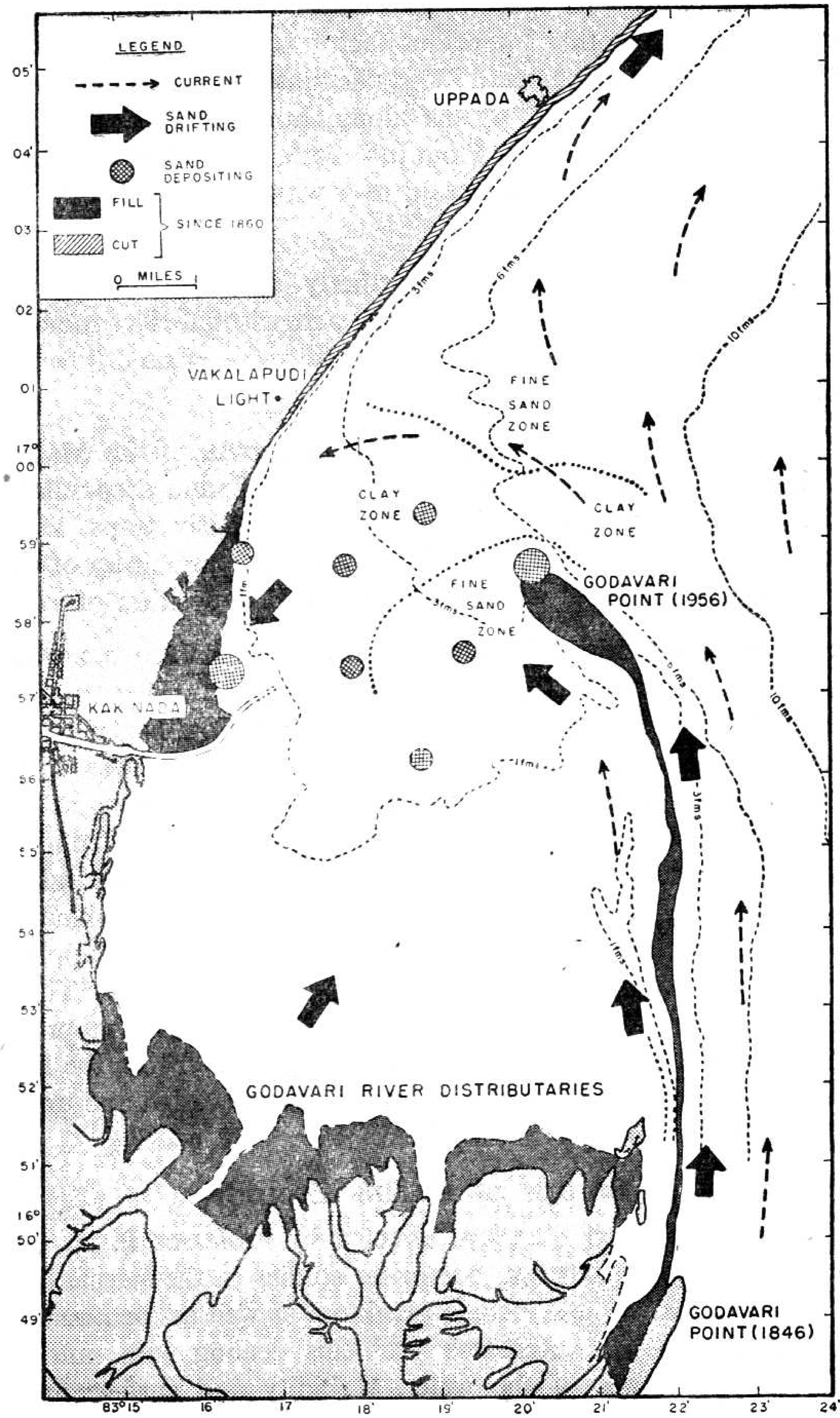

Fig. 11. Composite chart of the northern distributaries of the Godavari River, Kakinada, and Uppada Beaches (from Admiralty Chart No. 81, published in 1846 and 1860, and U.S. Hydrographic Chart No. 1711, published in 1951). Shown are the cut and fill over a century, currents, sand drift and sand depositing.

Sea Surface Features and Water Transparency

Sea surface.—Two phenomena of the sea surface, namely slicks and foam, were found to be related to the organic or biological characteristics of the water.[21] The surface water under slicks (glossy patches or streaks on a ruffled sea) was collected and examined in the laboratory. It was found to contain a high concentration of organic matter—mainly decomposing phytoplankton and zooplankton. This film produces a lower surface tension, reducing the formation of small wavelets and giving the water its glassy appearance, Fig. 12 C. The streaks are a concentration of this film caused by convergent circulation. In other words, there is a tendency towards a downward motion under the slicks, verified by a lower thermocline.

Foam, or white caps, on the open sea are caused by strong winds breaking the wave crests, entrapping air and developing foam at the surface. Sometimes this foam will persist for only a few seconds, sometimes for 20 seconds or longer after the wave breaks. The duration of its persistence correlates with the planktonic content of the water. That is, in the spring during high plankton blooms the foam will persist longer than it does in the winter. In some near-shore eddies and streaks on the sea, foam persists for hours or days, Fig. 12 G. Samples of this foam revealed a very high concentration of organic material.

Sea-water foam was also investigated by means of an electric shaker, in which different samples of sea-water were mechanically shaken and the characteristics of the resulting foam layers were examined, Fig. 12 D, E. It was found that the half life of the foam layers varied inversely with the temperature and directly with the salinity. Harbor water, water in slicks, and water of high organic content produced a thicker layer of foam that persisted longer than did normal open sea-water, Fig. 12 F.

Water transparency.—The transparency of the sea was initially made by visual observation of a secchi disc as it was lowered into the sea,[22] Fig. 3 A. Later a hydrophotometer (Fig. 3 H, J) was utilized in which light, transmitted through one meter of water to a photocell, was electrically recorded on deck. The degree of light absorbed or scattered in the water is dependent upon the nature of the material suspended or dissolved. These suspensoids may be organic, such as plankton, or inorganic, such as fine particles of sand or clay.

In the upper twenty meters of water off the east coast there are two turbidity cycles during the year.[23] In winter the water is beautifully clear and blue, but at the onset of upwelling (to be discussed later) a subsurface layer of turbid water develops. This is believed to be caused by the rise of nutrient laden water into the euphotic zone, facilitating the production of phytoplankton (Fig. 13 A). Later, with increased upwelling,

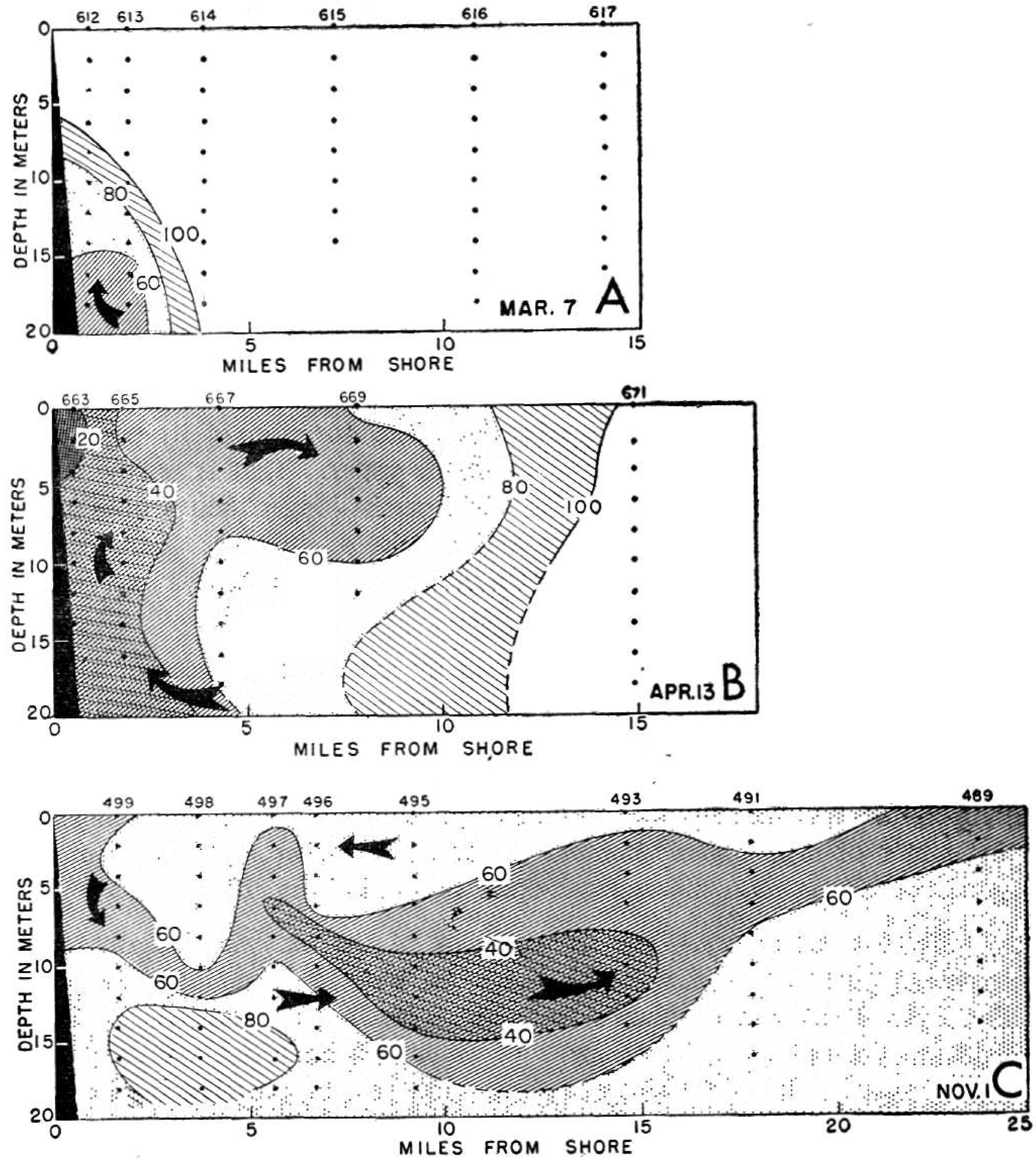

FIG. 13. Turbidity patterns and probable vertical circulation of the water in a section extending seaward from the Waltair Coast. (A) Beginning of upwelling in March. (B) Upwelling developed in April. (C) Near-shore sinking in November. (Units and shading are relative—contours represent the approximate per cent of light transmitted through one meter of water as compared to air.)

the high phytoplankton concentration or turbid zone reaches the surface. The characteristic feature of the fully developed spring upwelling is a highly turbid band of water near shore which spreads seaward at the surface and decreases with distance from shore (Fig. 13 B). In the fall, coinciding with the rainy season and runoff, another turbid pattern develops. Turbid runoff water, which is composed mainly of fine inorganic particles discharged by rivers, develops a dense layer at the surface and a very muddy layer along the botton. The latter is influenced by the downward circulation at that season. By using turbidity as a conservative property of the water it is possible to trace the circulation from these patterns. The deduced circulations are shown in Fig. 13 C.

Plant Nutrients and Other Chemicals

Surface salinity.—The general distribution of the salinity of the surface water of the entire Bay of Bengal is known.[24] The central and southern parts of the Bay are relatively uniform throughout the year, ranging from 33 to 34‰. The coastal regions and head of the Bay, on the other hand, are

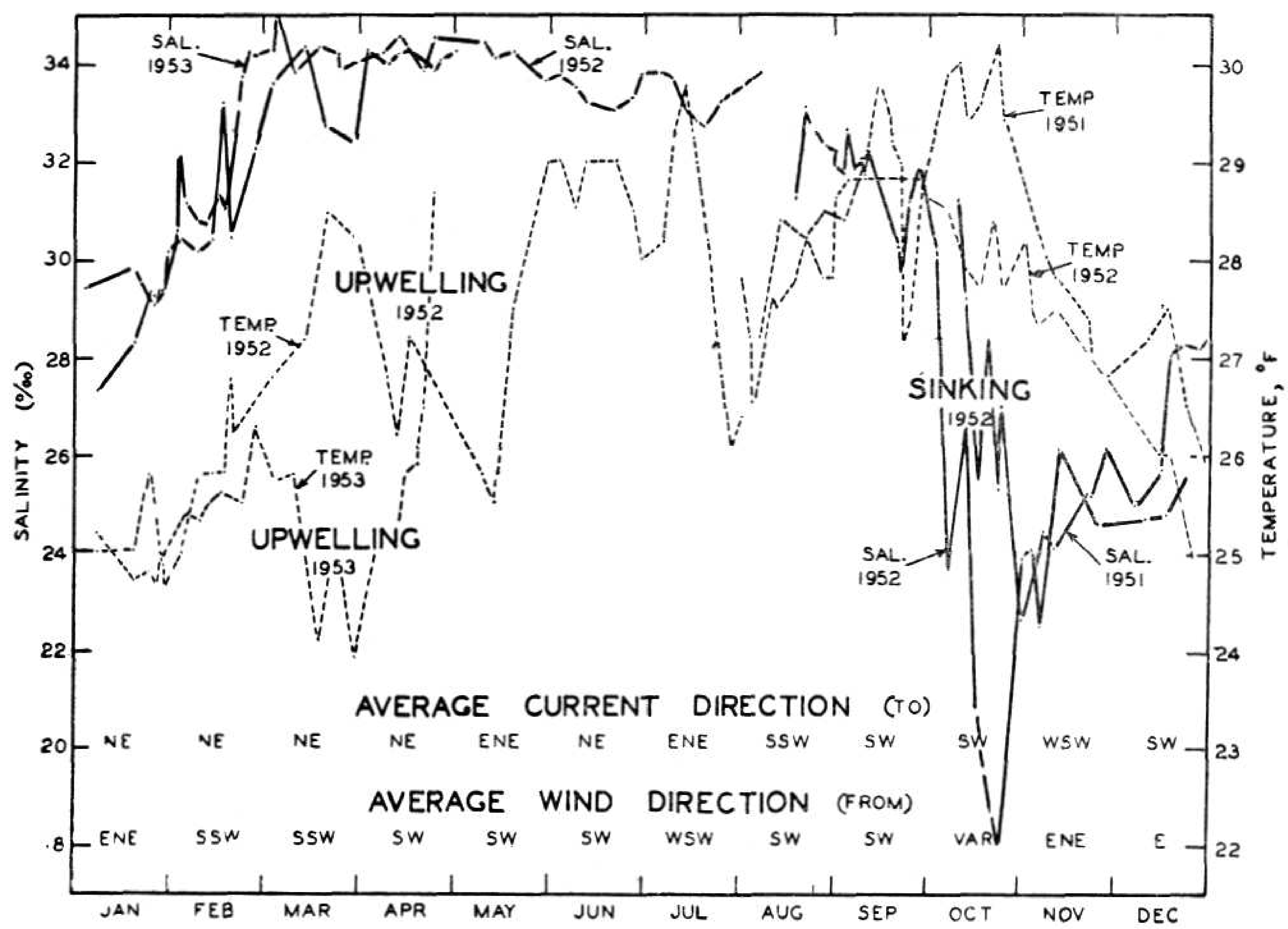

FIG. 14. Seasonal cycle of surface salinity (solid lines) and temperature (dash lines) off Waltair showing periods of upwelling and sinking, together with average monthly current and wind direction (1951–53).

extremely variable.[25] Off Waltair where most of the studies have been made the surface salinity is about 29‰ in January, increasing to 34‰ in March with the development of upwelling and the strong northerly flow,[26] Fig. 14. It decreases slightly during the summer and drops abruptly with the fall rains, even to as low as 18‰ (1952). The sinking circulation tends to confine the low values near the coast and over the continental shelf.[27]

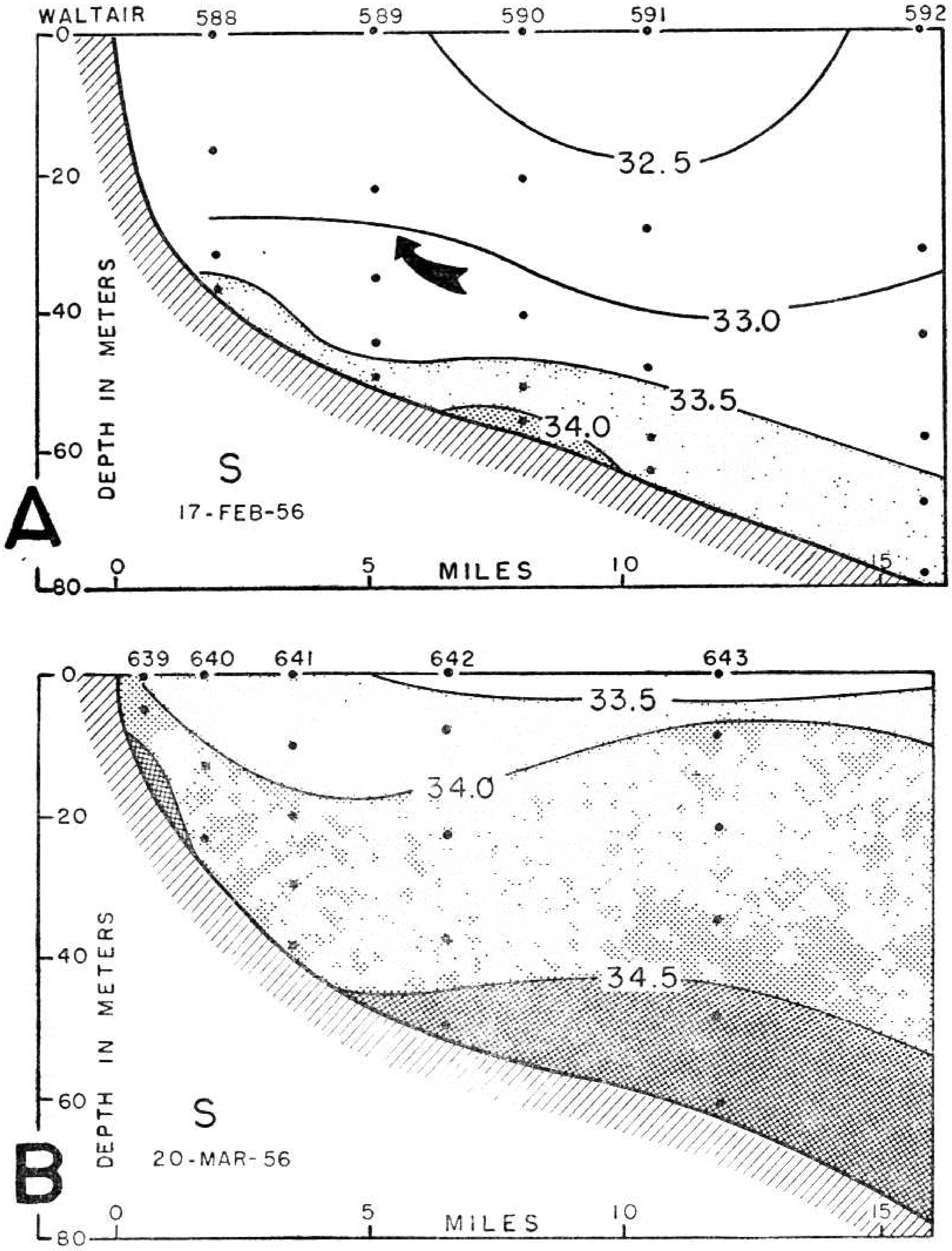

Fig. 15. Vertical salinity section across the continental shelf off Waltair at the onset of the upwelling period (1956). (A) February. (B) March. (Salinity in parts per thousand.)

Vertical salinity structure.—Vertical salinity gradients across the central shelf reflect the runoff and circulation.[28] In the fall the isohalines are tilted upwards when going away from the coast. The thick layer of low salinity water near shore is the result of both the runoff and sinking. In spring the isohalines are tilted downward when going away from the coast, similar to those of phosphate, silicate, oxygen, temperature, etc. A comparison of the vertical salinity across the continental shelf near Waltair in February and March is shown in Fig. 15 A and B. A rapid increase takes place with the onset of upwelling and the northern flow. In spring the vertical gradients of salinity are lower with surface and bottom values

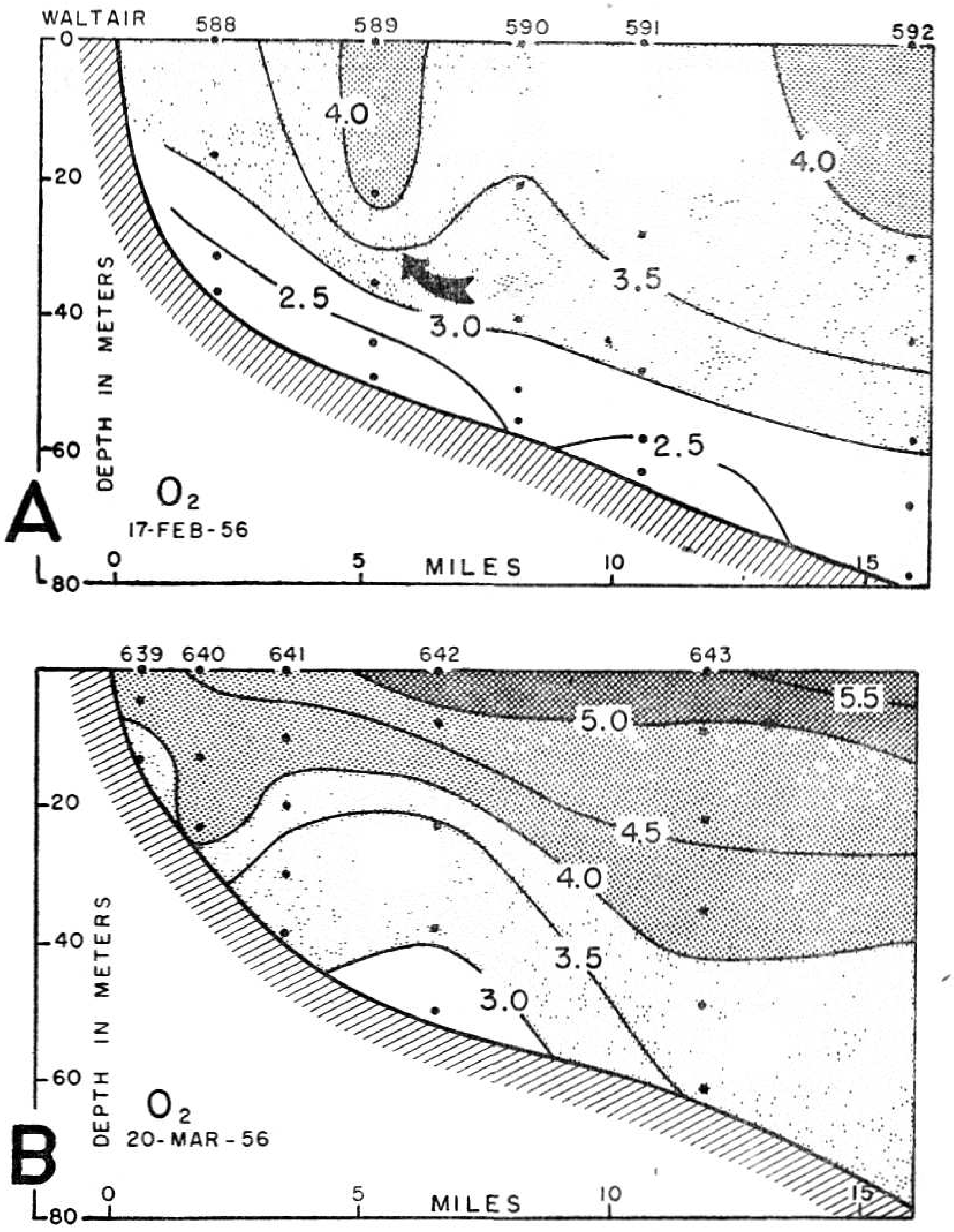

FIG. 16. Vertical oxygen section across the continental shelf off Waltair at the onset of the upwelling period (1956). (A) February. (B) March. (Oxygen in ml./L.)

of 32·5 to 34·0 and 33·5 to 34·5 over the shelf, than are those in the fall where the difference is as great at 18·0 to 34·0 (in 1952).

Oxygen structure.—The oxygen content of sea-water off Waltair varies somewhat with the season. In coastal shelf water the surface values range from 3·7 to 5·6 ml./L. in the spring and from 3·1 to 3·8 in the fall.[26] The bottom water is more uniform, 2·2 to 2·9 throughout the year. The rapid change in the vertical oxygen structure from February to March 1956 is shown in Fig. 16 A and B, and reflects the circulation of low oxygen water towards the surface and the production of oxygen by phytoplankton. The

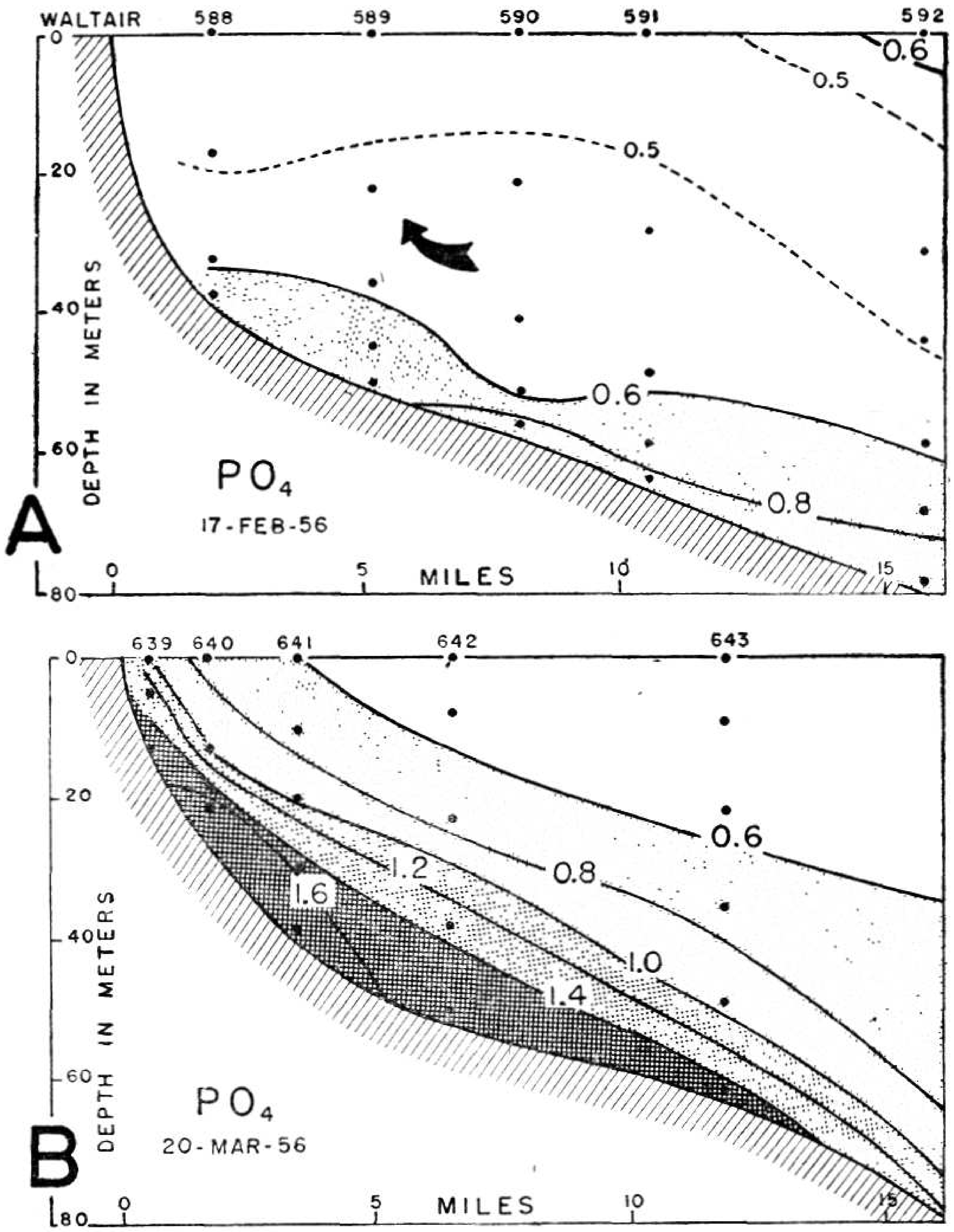

Fig. 17. Vertical phosphate section across the continental shelf off Waltair at the onset of the upwelling period (1956). (A) February. (B) March. (Phosphate in μg.-atoms/L.)

latter effect predominates and the oxygen content of the water increases about one ml./L in this one month.[28]

Phosphate structure.—Phosphate is considered one of the essential plant nutrients. With a high phosphate content and sunlight, phytoplankton are produced in abundance. A comparison of the same two months, February and March, shows the change in phosphate content of the water across the continental shelf off Waltair,[29] Fig. 17 A and B. When the high phosphate water reaches layers near the surface, as shown in Fig. 17 B, there is a large flowering of phytoplankton.

Silicate structure.—Silicate, like phosphate, is an essential nutrient salt for some types of marine plants and animals. And, as with the phosphates, its concentration is a measure of the initial growth of organisms. It can be seen in Fig. 18 A and B that the amount of silicate in the coastal waters increased greatly during a period of one month, due to upwelling and the northerly circulation. Consequently, spring silicate values are much greater than are the fall ones. As with phosphate, the greatest values are near the bottom, with isolines tilting upwards toward the shore.[29]

Marine Organisms

Plankton.—Plankton comprise an important link in the organic cycle of the sea. Near shore both phytoplankton and zooplankton collections were made from a catamaran. A minesweeper was used throughout the western Bay of Bengal for the offshore collections. The most important study in this field has been on chætognatha (arrow-worms). It was found that they bear a close relation to salinity (and other nutrients) in that they occur in greater abundance off shore when the salinity along the coast is low. Further, a study of the distribution of chætognatha in space and time has revealed the possibility of some species being considered as indicators of the different water masses.[30] Thus *Sagitta bedoti* is a common form of the inshore or nearshore waters while *Sagitta neglecta* is an indicator of shelf water. The occurrence of *Sagitta serratodentata* coincides with the incursion of oceanic waters into this area under the influence of the northerly current. Other studies on a variety of copepods bear a similar relationship with the environment.[31] For example, a near-shore peak of maximum abundance of both chætognatha and copepods occurs when the water temperature is lowered and the salinity is increased. This corresponds to the upwelling period, in which not only high salinity water is brought near the surface but also rich phosphate and silicate water as well. Some anomalies in the distribution of plankton still remain to be explained.

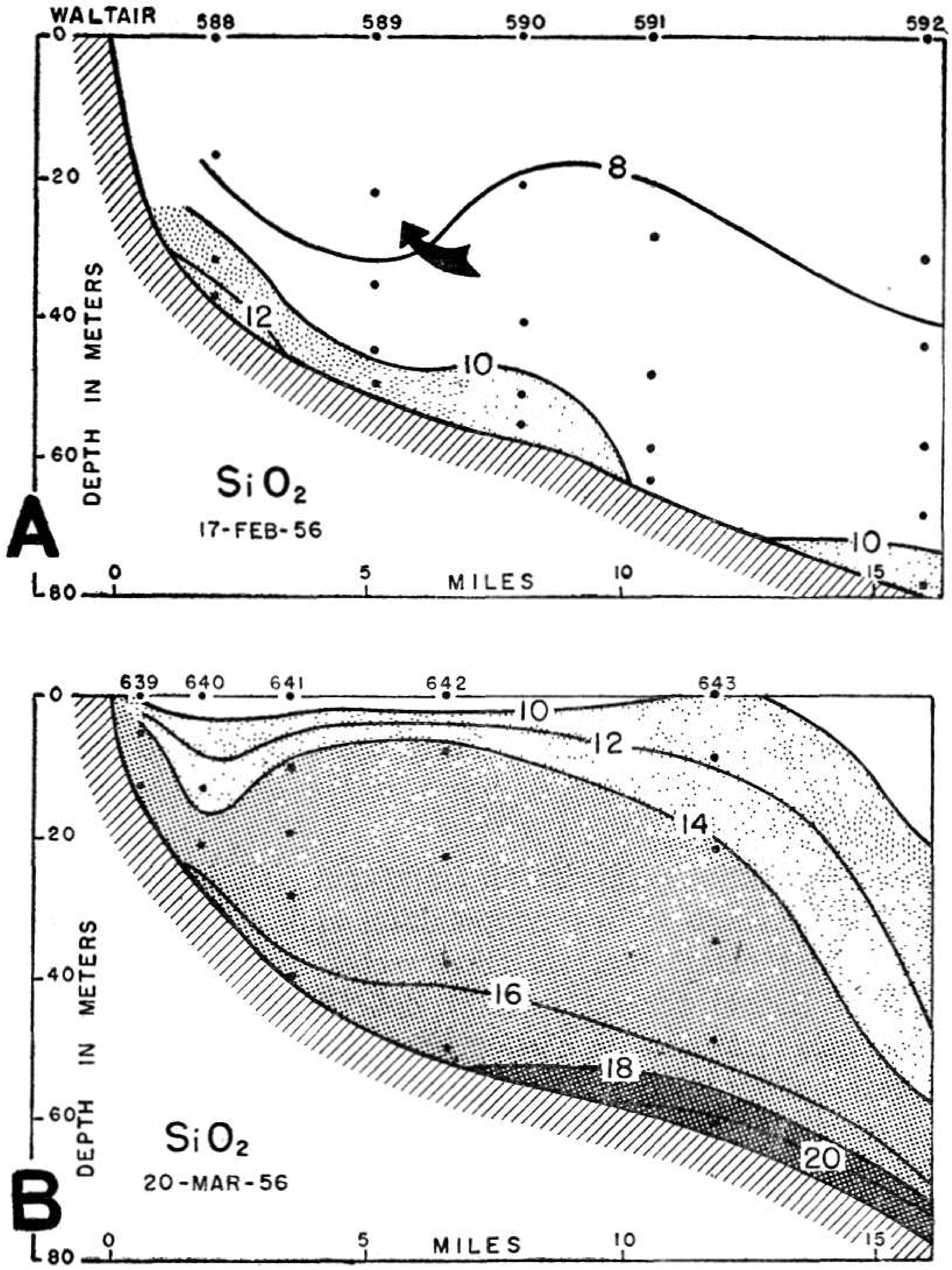

FIG. 18. Vertical silicate section across the continental shelf off Waltair at the onset of the upwelling period (1956). (A) February. (B) March. (Silicate in μg.-atoms/L.)

Benthonic organisms.—The bottom living organisms comprise the chief source of food for many fishes. To study this relationship and food it is essential to have a knowledge of their distribution abundance and the influence of the environment on these animals. Numerous dredge collections at 10 to 35 fathoms were made along the east coast of India from Puri (19° 40′ N) to Kakinada (17° 00′ N). These samples revealed the abundance of a variety of coelenterates, crustaceans, molluscs, echinoderms and a few flat fishes.[32]

From the observations made and samples collected it was found that the distribution and abundance of animals are chiefly influenced by the nature of the bottom. Three distinct types of bottom environment characterized the dredgings.

To the north of Vishakapatnam the dredgings were made on a bottom composed of a greater percentage of sand, and were dominated by the echinoderms. Some of the animals collected from this region were:

Coelenterata: *Lytocarpus* sp., *Trochocyathus* sp.

Annelida: Polychætes: tube dwelling forms, *Polydontes melanotes*, *Diopatra neopolitana*, *Hyalinœcia tubicola* and *Hesione* sp., *Armandia* sp. and *Sternaspis scutata*.

Arthropoda: Crustaceans:—*Callapa lophos*, and *Albunea symnista*.

Mollusca: *Sinum planulatum*, *Oliva oliva*, *Malius albus*, *Glycemeris tyllori*, *Solen truncatus and* developing eggs of squid *Loligo*.

Echinodermata: *Diadema* sp., *Echinodiscus biperforatus*, *Clypeaster* sp., *Ogmaster capella* and *Archaster typicus*.

Fishes: *Ctenotrypauchen microcephalus*, *Platyphyrys pantherina*, *Pseudorhombus* sp., and *Plyatycephalus insidiatrix*.

The form of particular interest from this region is *Diadema* sp. dredged off Kalingapatnam and Waltair. See Fig. 3 F.

The bottom south of Vishakapatnam towards Kakinada on which dredgings were made was largely an admixture of sand and mud and seems to be equally as productive as the preceding one. This region has a rich representation of coelenterates, crustaceans and molluscs. Echinoderms are sparsely distributed in this region. Coelenterates from this region were *Cavernularia* sp., *Sphenopus marsupialis*, *Flabellum pavonium* and *Gorgoniss*.

Dredgings beyond the 5 fathom line off Kakinada Bay had a surprisingly poor representation of animals, in comparison with either of the preceding areas or to the intertidal region of the Bay. For example, the only bivalve mollusc collected here was *Paphia textile*. The bottom in this region is composed of loosely packed fine sediment. This seems to be a striking example of the great influence that the oceanographic environment has on the distribution of the benthonic animals.

Fouling.—Fouling organisms in tropical waters are notoriously abundant and Visakhapatnam Harbour is no exception. Here the inevitable barnacles and serpulids (tube worms) are the chief foulers, followed in order of abundance by hydroids, amphipods, encrusting and erect bryozoa, simple and compound ascidians, bivalve molluscs, errant polychætes, anemones, and sponges. The peak of organism abundance varied with the season, barnacles flourishing in April and May and serpulids in January and February.[33]

Fisheries.—Although the actual study of fish populations has not been pursued at the University, the zoology studies are pertinent to fish production. From a food standpoint the upwelling circulation is favorable in that it supplies nutrients for phytoplankton. These in turn supply the zooplankton, etc., which, with the benthonic population, should offer sufficient food for abundant commercial fisheries.[34]

It may be pointed out here that even a cursory examination of the available data on the fish statistics reveals a great discrepancy in the total output between the two coasts of India. An analysis of the data collected during the year 1952 revealed that the total quantity of marine fish landed in India was about 500,000 tons and of this the west coast contributed 82 per cent.[35] An investigation into the causes of this discrepancy is an important marine biological problem and it is quite likely that there are vast areas of rich fisheries elsewhere in the Bay of Bengal as yet untapped.

It is possible that the high dilution in the fall may be detrimental to some species.[36] The Central Marine Fisheries has set up a unit in the Zoology Department to study this interesting and vital problem.

STUDIES IN PHYSICAL OCEANOGRAPHY

Physical oceanographic studies have been carried on under the leadership of Professor S. R. Savur, Head of the Geophysics Department, and are comprised of studies of the physical properties of the water such as its temperature and density. They also include investigations of water movements—currents, turbulence, tide levels, waves, slicks, sea-level, upwelling and sinking, as well as related meteorological factors. Physical studies are important to all branches of oceanography in that many of the biological, geological and chemical properties are influenced or controlled by the physical processes.

Sea Temperature and Density

Surface temperature.—The physical property most easily measured is the sea surface temperature. Generalized overall Bay of Bengal charts of surface temperatures show that the offshore areas are very uniform—with decreasing temperatures towards the north, and in the winter.[37]

Near-shore temperatures, like salinities, are more variable.[27, 28] Examples of seasonal cycles of temperature and salinity are given in Figs. 19

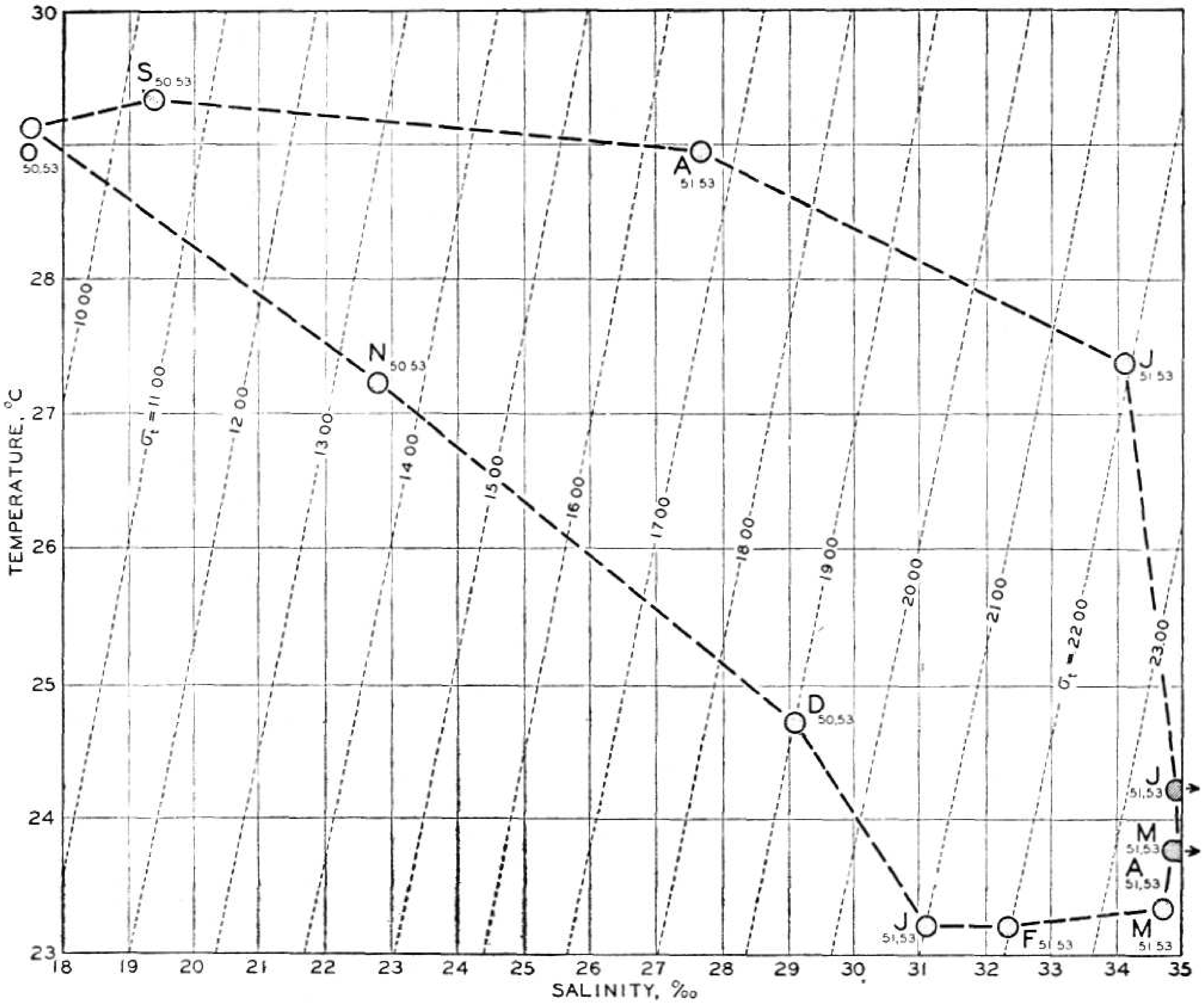

FIG. 19. Average monthly sea surface temperature, salinity and density (1950–53) at Saugor Island.

to 21. These are the average monthly values for three coastal stations —Saugar Island, Waltair and Mandapam. Monthly temperatures are plotted against salinity. Each monthly value is labeled with the first letter of the month. It can be seen that the seasonal range of surface temperature is still only 4 to 6° C. The salinity, especially in the north, reflects the influence of the fresh-water runoff in the fall season. These are discussed more fully under water masses.

Vertical temperature.—The vertical temperature structure of the sea can frequently be used to determine the physical processes going on in the sea.[39] Figure 22, for instance, gives six examples of the types of temperature-depth structure found in the Bay of Bengal.[40] The curve labelled A is isothermal water, or water that has been thoroughly mixed to the lower level of the trace. Curve B is typical of the usual three layer system (thermosphere, thermocline and psychrosphere) and the higher temperature at the surface

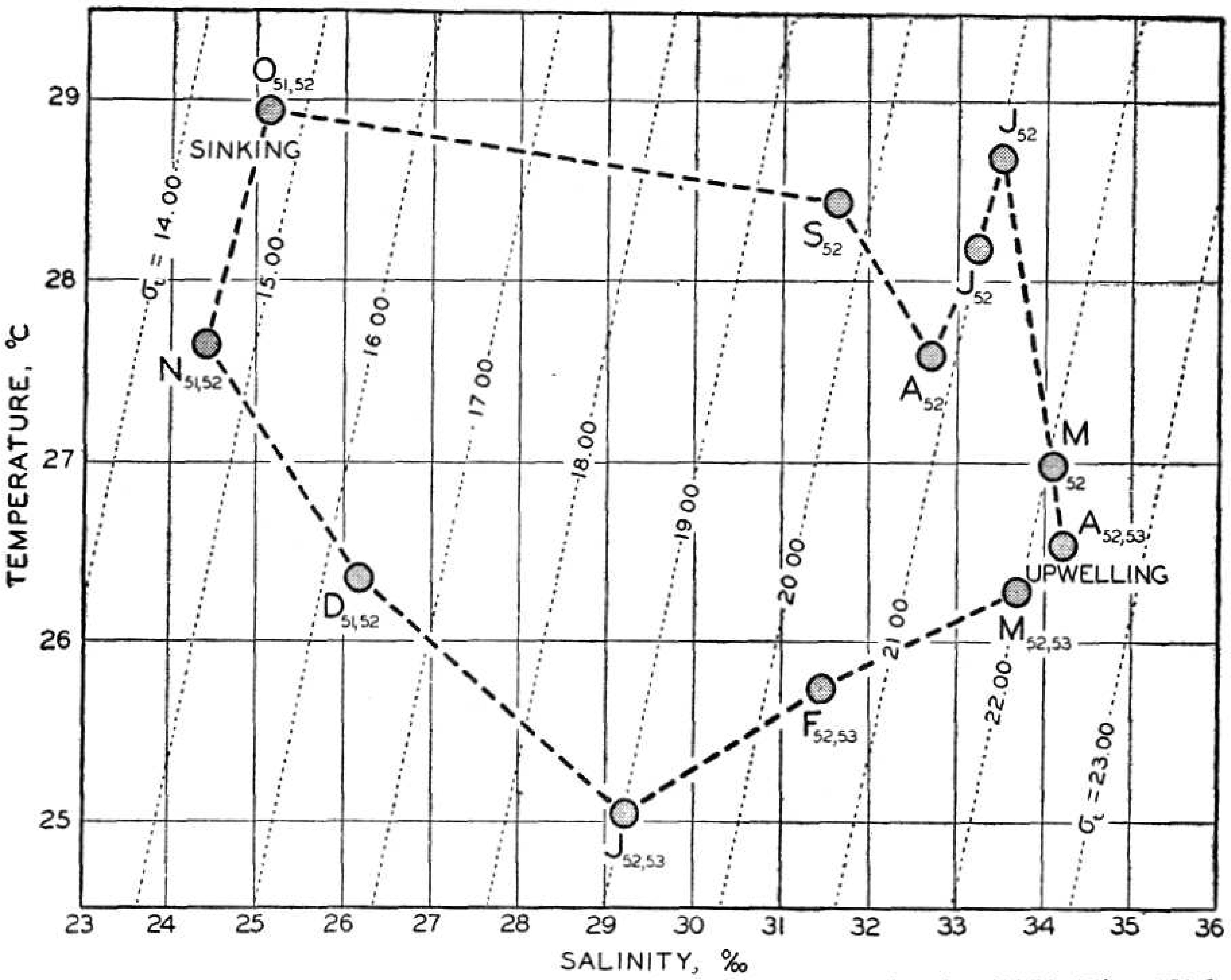

FIG. 20. Average monthly sea surface temperature, salinity, and density (1951–53) at Waltair.

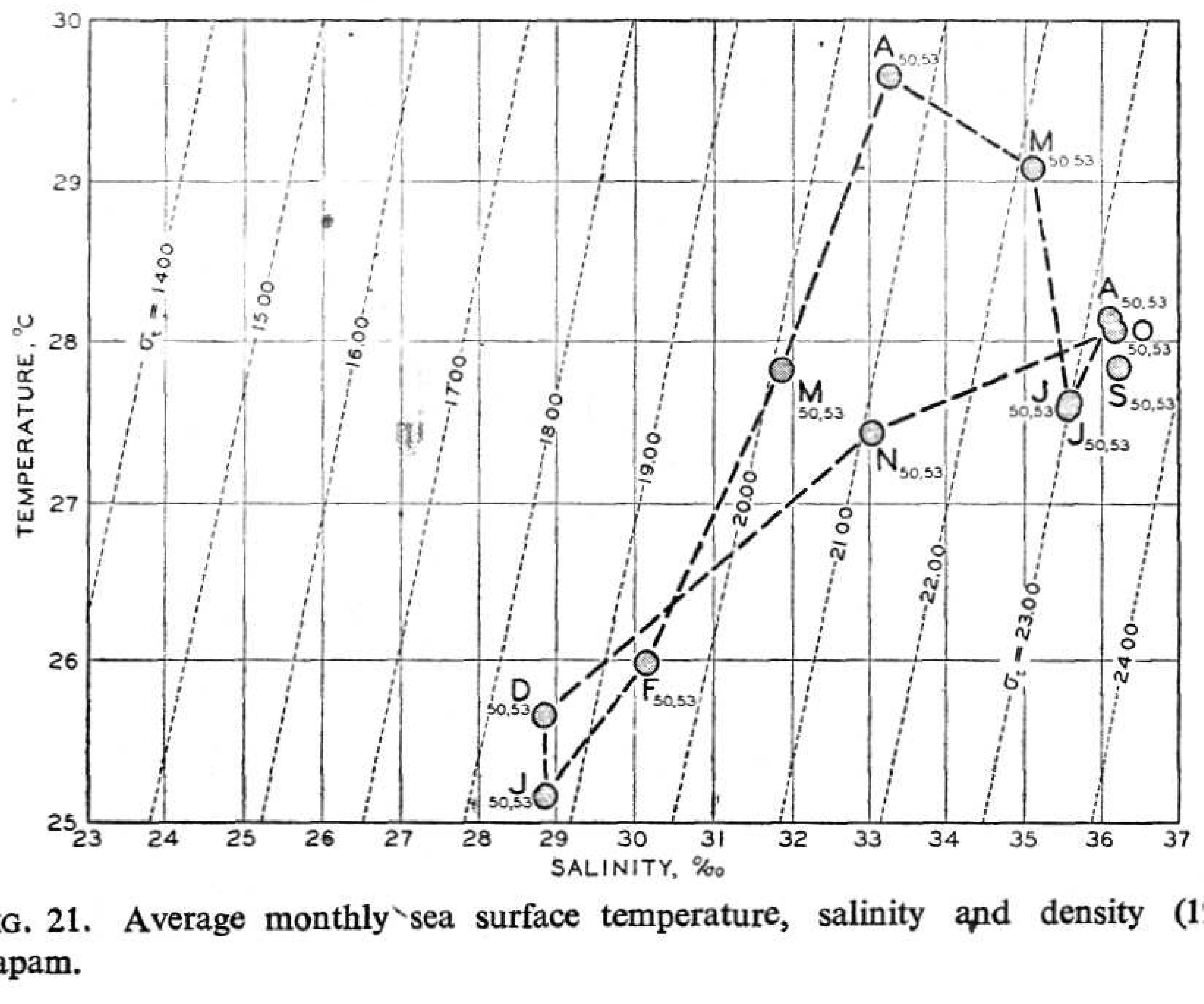

FIG. 21. Average monthly sea surface temperature, salinity and density (1950–53) at Mandapam.

represents conduction of heat to the water from the atmosphere under low winds. The step-like structure in **C** is usually the result of successive surface heatings and wind mixings, common in the spring. A sharp break in the bathythermogram, as in **D**, occurs when a water mass of a given temperature flows over another of a different and lower temperature. The boundary between the two masses remains sharp until later diffusion and mixing takes place. A strong wind may also mix the upper layer and produce a similar break in the curve. Irregular wiggles shown in **E** are the result of turbulence at strong current boundaries. An increase of temperature below the surface is usually the result of cooling at the surface. The surface layer under these conditions must contain water of low salinity in order that the vertical column may remain in stable equilibrium.

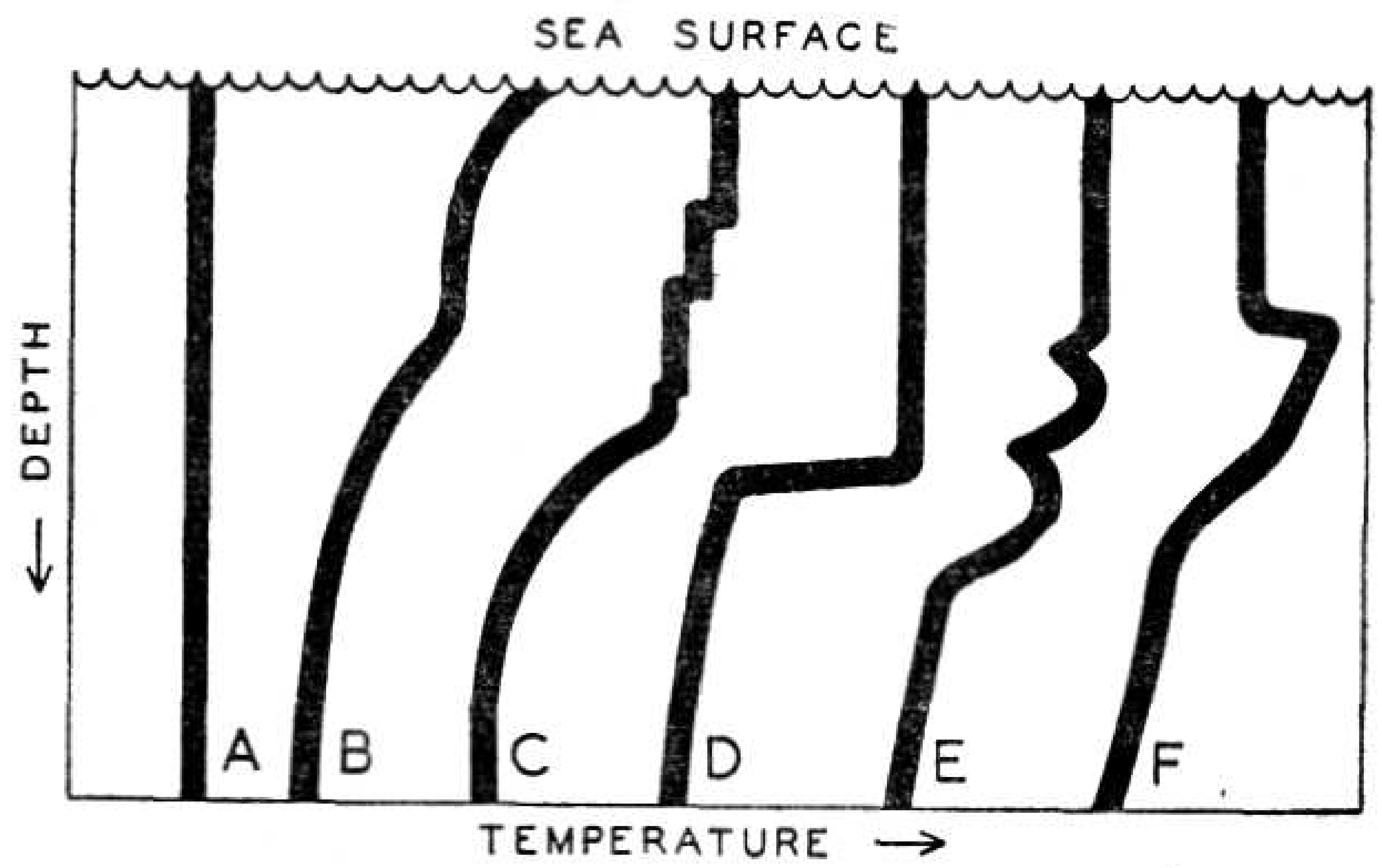

FIG. 22. Various types of bathythermograms observed in the Indian Ocean.

The most informative features of the vertical temperature structure of the water off the Waltair coast are those caused by upwelling and sinking. During upwelling the thermocline becomes weaker and rises towards the surface.[41] During sinking the thermocline becomes sharp and deeper—sometimes intersecting the bottom at the outer part of the continental shelf. This produces nearly isothermal water over the inner part of the shelf during fall and winter. All of these temperature patterns are clues used to solve the puzzles of circulation, mixing, and heat transfer in the sea.

Density and water masses.—Density is a function of temperature and salinity, and for convenience is expressed as σ_t, where $\sigma_t = (\delta - 1) \times 10^3$. By means of these T–S relations, water masses may be established which can be used to trace the direction of flow and other dynamic processes that occur in the ocean. In Figs. 19 to 21 the east coast surface density is also illustrated by diagonal dashed lines.

From the preceding T–S plot in Fig. 20, as well as from other subsurface T–S plots, it has been possible to assign names and σ_t limits to water masses for the purpose of discussing their distribution and circulation.[42] For example, water of low density ($\sigma_t < 19$), which occurs off Waltair, from October to December has been called *Northern Dilute* water, Fig. 23. A *Transition* water mass between $\sigma_t = 19$–21 encompasses January to February and August to September, and water with σ_t values of 21–22 has been called *Southern Bay of Bengal* water. The *Upwell* water mass has a σ_t of 22–23. Water having a σ_t greater than 23 is most always a subsurface water mass, therefore, σ_t of 23–24 has been called the *Subsurface Shelf* water mass. With greater density ($\sigma_t > 24$) it may be considered part of the *Indian Equatorial* water. These σ_t limits and the names assigned were based on distribution, origin and formation.

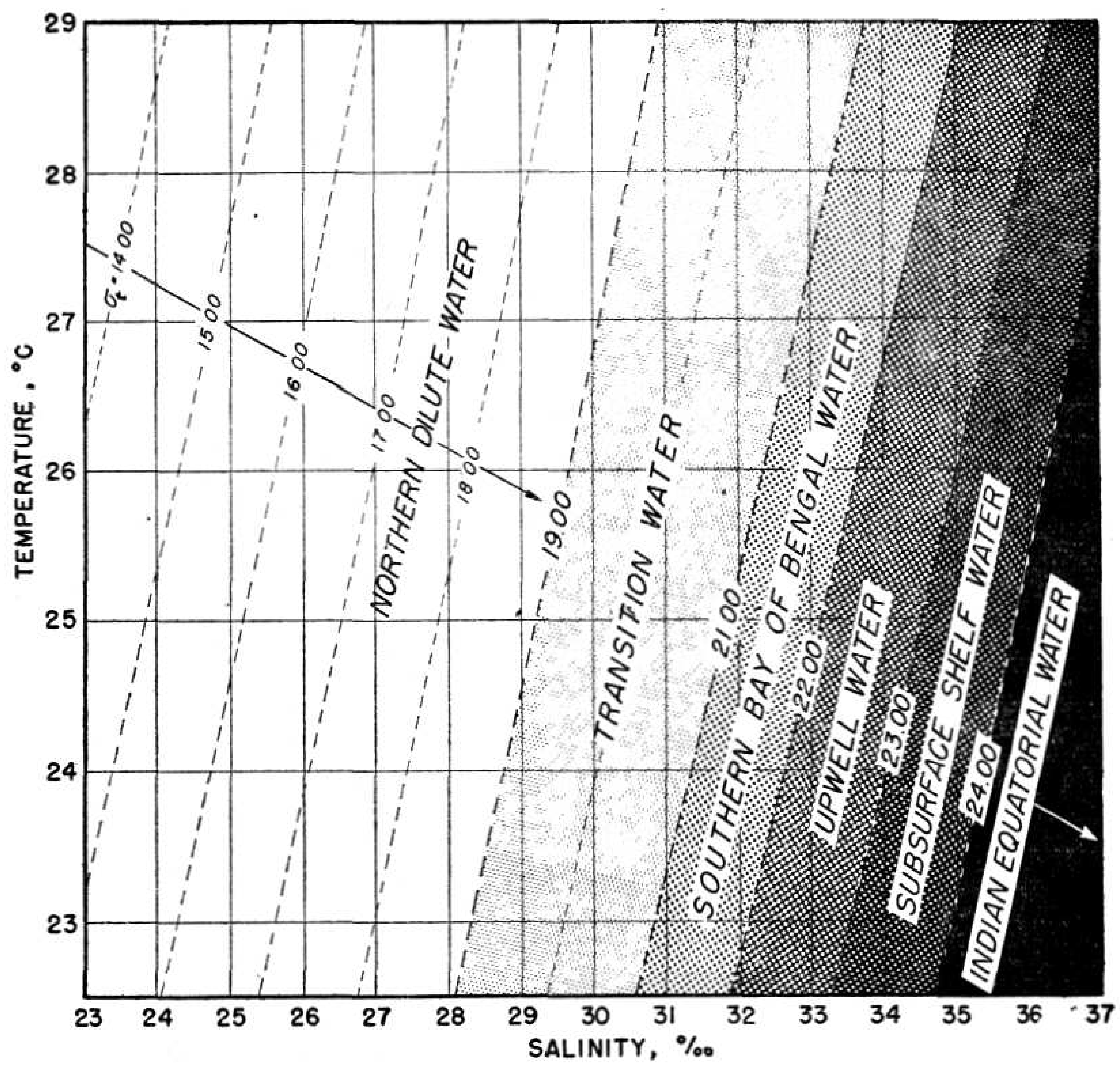

Fig. 23. Temperature-salinity diagram and related sigma-*t*. Shallow water masses for Bay of Bengal are named and assigned sigma-*t* limits as indicated by the shading.

From the observed temperature and salinity in the western Bay of Bengal, the horizontal and vertical distribution of density and water masses were determined for the months of October and March. These are illustrated in

Figs. 24 (October) and 25 (March). The area considered comprises two wedge-shaped sections running up and down the coast from Waltair, Fig. 24 A. The central part, Fig. 24 C, is an enlarged vertical section extending 30 miles out from Waltair. In the horizontal section, B of the block diagram, the scale at the northern end is compressed, as it is for the southern end of D.

On the horizontal and vertical sections (B, C, D) the water masses defined above have been represented by shadings. The lighter the water, the lighter the shading. In Fig. 24 B (October) the sea surface is covered with *Northern Dilute* water. It is formed in the northern end of the Bay by the mixture of runoff water with the more dense Southern *Bay of Bengal* water. River discharge into the Bay of Bengal is estimated at 4×10^{11} cubic meters of fresh water per year.[1] This mixture spreads out over a large portion of the north-eastern Bay and flows down the east coast.

At this time of the year all the above-defined water masses are present over the continental shelf, Fig. 24 C. The *Northern Dilute* ($\sigma_t < 19$) extends down to about 150 feet near the coast, whereas 30 miles off the coast it reaches only half this depth. The others are found as thin layers below the surface.

To the south the *Northern Dilute* water continues at the surface nearly to Ceylon, Fig. 24 D. However, its thickness becomes less with distance from its source.

The same projection is used in Fig. 25 to illustrate the distribution of water masses during the spring season. The surface densities are considerably greater in spring than in fall. The surface water mass is largely *Southern Bay of Bengal* water (σ_t = 21–22). This water mass is most always found in the central and southern part of the Bay. By spring it has now been transported up the coast by north-east flowing currents produced by the prevailing wind system which, in March, is mainly from the south-west.

The unique feature of the surface density is the band of *Upwell* water along the coast. Near Waltair it is initially only a few miles wide in March but increases by May to cover about half the width of the shelf. Off the Orissa Coast this width may be even greater.

At this season no *Northern Dilute* or *Transition* water is present off Waltair. The other water masses present over the shelf are in thicker layers than in the fall, thus making the vertical gradients weaker.

To the south some *Upwell* water extends to the neighborhood of the Godavari Delta but most of the surface is covered with *Southern Bay of Bengal* water.

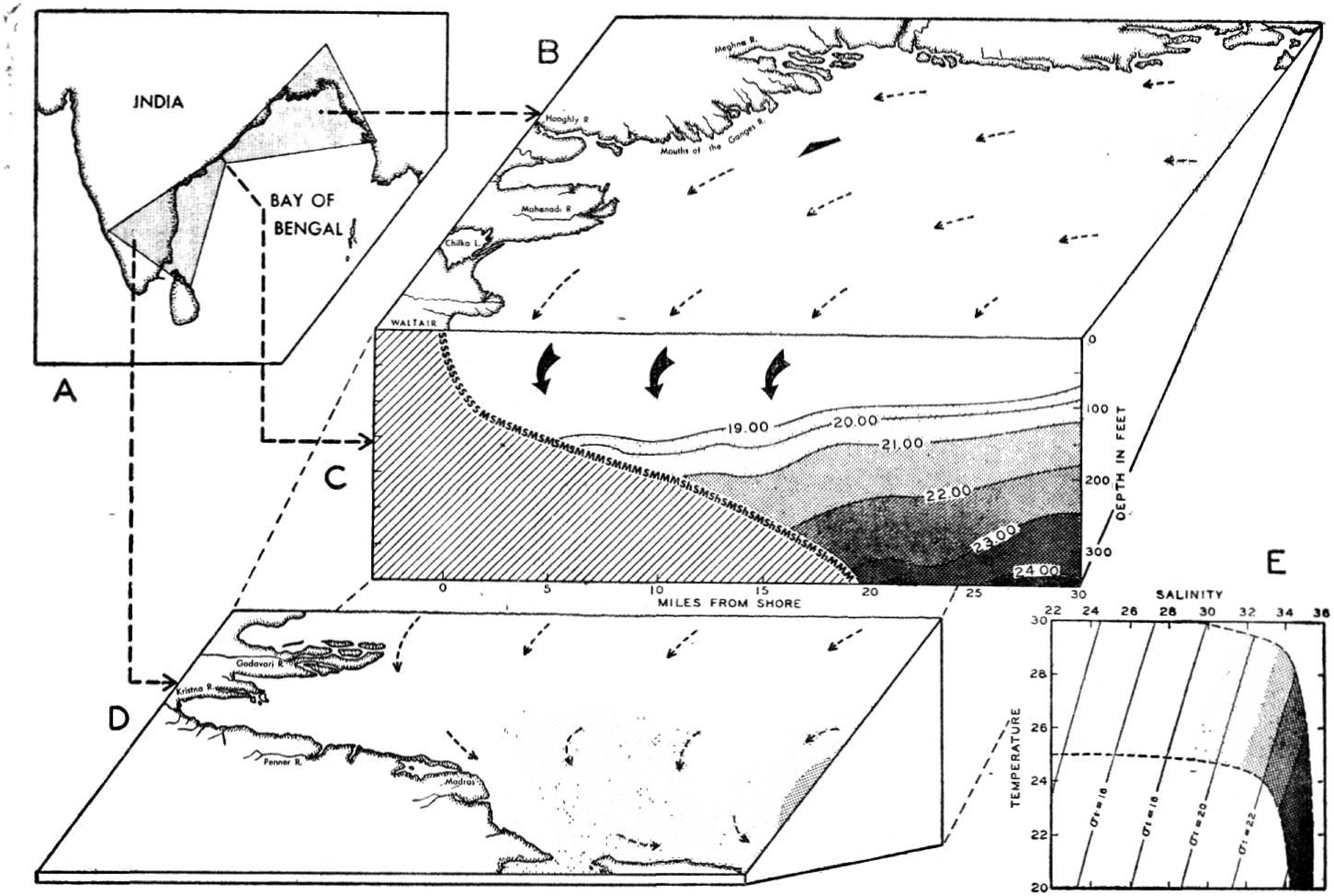

FIG. 24. *October* water masses (density distribution) and currents off the east coast of India (1952). (A) Areas used for projection. (B) Sea surface north-east of Waltair. (C) Vertical section off Waltair. (D) Sea surface south-west of Waltair. (E) T-S relations used for the water masses.

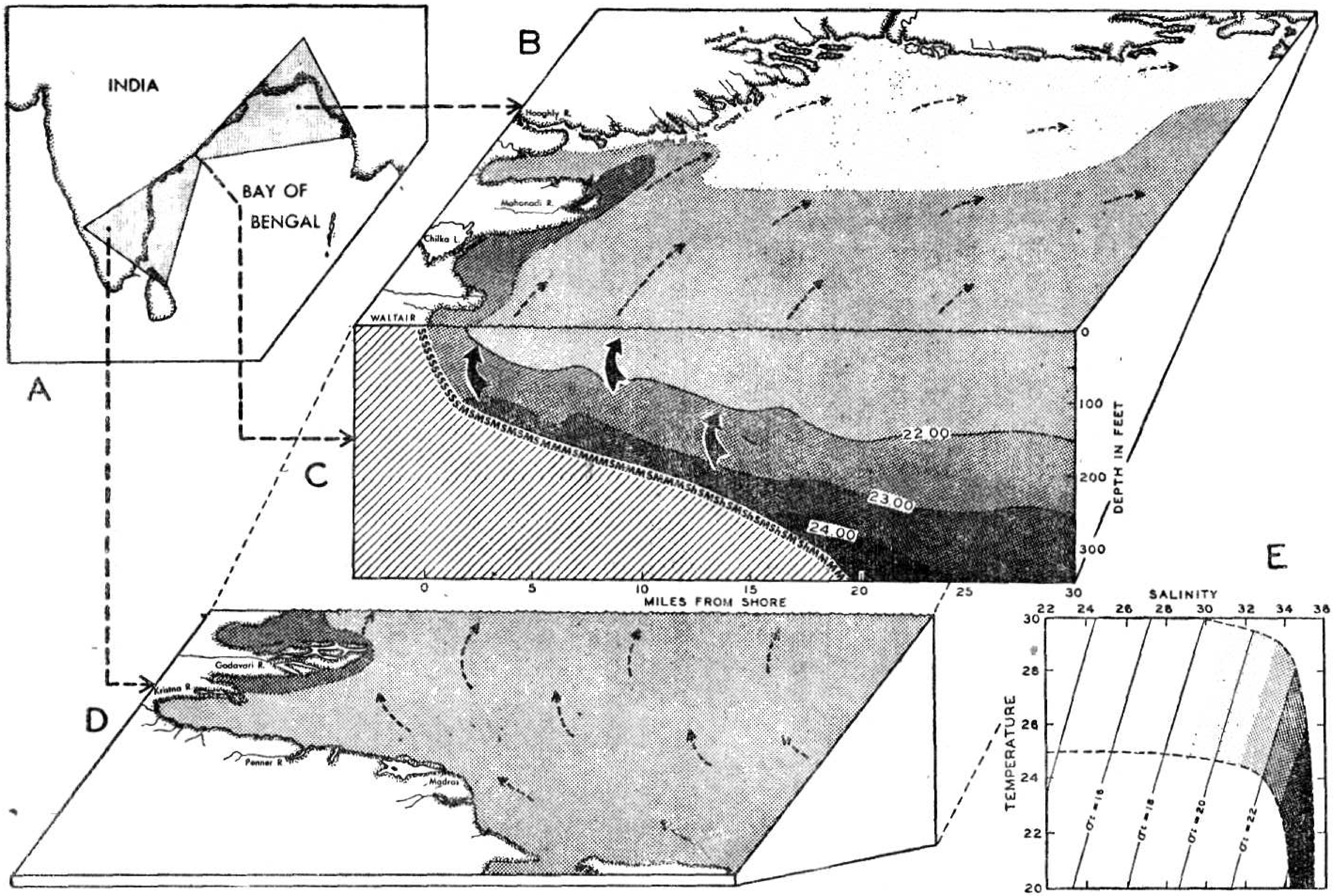

FIG. 25. *March* water masses (density distribution) and currents off the east coast of India (1953). (A) Areas used for projections. (B) Sea surface north-east of Waltair. (C) Vertical section off Waltair. (D) Sea surface south-east of Waltair. (E) T-S relations used for water masses.

Water Circulations

Currents.—From the distribution of the water masses described above, the circulation of entire Bay may be deduced. The surface circulation is generally clockwise from January to July and counterclockwise from August to December.[37]

This generalized circulation along the western part of the Bay is illustrated by dashed arrows in Figs. 24 and 25. During the transition periods it is believed that large eddies break off from the major flow patterns. The seasonal coastal flow in the vicinity of Waltair is shown in Fig. 8. This is purposely represented by a broad band because of the variability of speed, and sometimes direction. If the wind is strong for a few consecutive days its effect is manifested in the flow. However, currents to the north-east not only persist longer but flow at great speed. At times the currents off Waltair were observed to be as much as 3 knots to the north-east and off Sacramento Shoal (Godavari Delta) to be as much as 5 knots. Great quantities of *Southern Bay of Bengal* water are consequently advected from the south, only to be displaced a few months later by the *Northern Dilute* mass from the north.

Upwelling and sinking.—One of the most unique features of the Bay of Bengal is the fact that both upwelling and sinking exist off the east coast.[24] Upwelling is the process in the sea whereby the subsurface layers move up towards the surface. The reverse is possible when surface water is concentrated or piled up, usually against the coast, Fig. 24 C, thus displacing subsurface water downwards and causing sinking. The phenomena are not as extensive as observed on the Arabian Coast and are here confined to the inner shelf area.

Off the east coast the wind systems associated with the N-E and S-W monsoons not only blow the water along the coast but displace it offshore at different seasons. The forces involved and the direction of motion can be measured by the density distributions shown in Figs. 24 C and 25 C. Another relation has been developed whereby the south-west wind component bears a high correlation with the salinity.[43] In other words, the water (of high salinity) upwelled is proportional to the wind force which blows the low salinity water north and east and to the rainfall, which replaces the low salinity water. Off Waltair an empirical expression for salinity is

$$S = 32 \cdot 59 + 0 \cdot 35 \text{ wind force} - 0 \cdot 0016 \text{ rainfall.}$$

Other effects related to upwelling are shown in Fig. 14 where the sudden drop in surface temperature indicates that cold layers have upwelled to the surface. Sinking is indicated by a period of high temperatures in the fall. The best indication of upwelling is shown in Fig. 23 C, where the isopycnals are tilted upwards towards shore. Further evidence of this upwelling is the presence of weaker vertical gradients. Still other effects of upwelling are shown in Figs. 17 and 18, where the chemical properties of the water are changed by the rise of high nutrient water towards, or to, the surface. These high nutrients can come only from subsurface levels, since the surface nutrients to the south from which the current is flowing, are lower.

The old axiom of " what goes up must come down " applies to the dense upwelled water near shore. It not only goes down, but down below a neutral plane, causing sinking. The S-W wind forces on the sea, which were partly balanced by the tilting of the density field, reverse in the fall. Consequently, the density field must also reverse. During sinking along the coast the isopycnals are tilted downward towards shore as shown in Fig. 24 C. Downward motion is further brought out by the compactness of the isopycnals. Since this water displaced shoreward and downward in surface water, its nutrient content is low.

The change-over of wind systems takes place in September and October (Fig. 8). When the strong S-W winds cease blowing, the forces maintaining the horizontal unstable density distribution terminate, and a " relaxing " current is set up. The dense water near shore will gradually flow down the slope. Its speed must be very slow but it takes place along the bottom and in a seaward direction. Any depression such as the Swatch of No Ground would funnel and speed up the flow. At the head of the Bay it is conceivable that surges in these relaxing currents are strong enough to influence the down slope flow of newly deposited sediment. This might possibly be the trigger mechanism for turbidity currents which may flow the length of the Bay.

Since the general circulation at the head of the bay is counter clockwise and the relaxing current is down slope the resultant combination would be a southwesterly flow as in the direction of the Swatch.

Ano'her interesting phenomenon related to the upwelling is an unusual isothermal temperature layer which develops at the bottom over the central part of the shelf.[44] The mixed water first appears in February as a thin layer 5 to 10 feet thick along the bottom. It thickens until by March it is 5 feet thick seven miles off shore, Fig. 26. The water has a slight

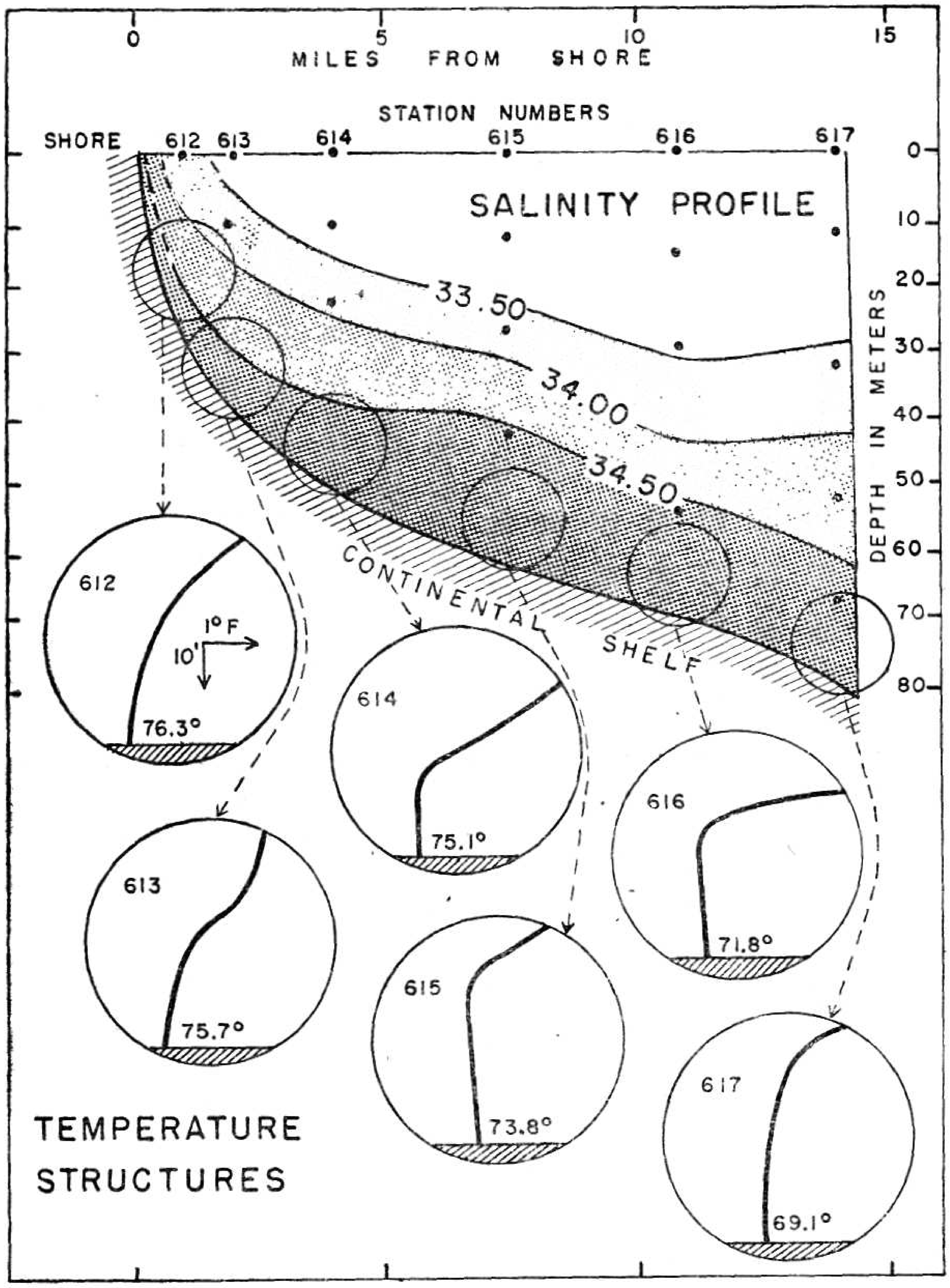

Fig. 26. Salinity profile and vertical temperature structures of the coastal waters off Waltair (March 7, 1956). Upper part: Salinity profile over the continental shelf indicating the upward tilting of isohalines towards shore produced by upwelling. Lower part: Enlarged temperature structures showing the virtually isothermal bottom water found at the indicated locations near the bottom along the central part of the continental shelf.

negative gradient near shore and at the outer edge of the shelf. The maximum mixed water is found where the water depth is between 30 and 45 fathoms. Although the water is nearly isothermal vertically, it possesses horizontal gradients. The bottom temperatures increase shoreward, as shown by the numerical values in the insets. This unique formation of an isothermal layer at the bottom seems to be caused by two agencies. The first is upwelling, which introduces water of nearly the same density and perhaps creates instability in a layer near the bottom. The second, and the more important, is turbulent mixing resulting from relatively strong currents flowing over a rough sea bottom (probably rock or coral). From the location and thickness of the layer, the position of maximum along-shore, bottom currents on the continental shelf might be deduced. Again, this is another of the inexplicable characteristics of the Bay of Bengal.

Sea-level.—In addition to water-level changes due to waves and tide' the average sea-level itself varies throughout the year. To obtain the mean sea-level the hourly tide heights are averaged over any given period. For example, the daily mean sea-level (average for 24 hours) from the conveniently located tide gauge in Visakhapatnam Harbour is shown in Fig. 27. During 1950 it was low in February and March and high in June and again in the fall.[45] However, August was low. The range in this annual cycle is surprisingly high—and the highest in the world is found in the Bay of Bengal. The oceanographic and meteorological factors suspected of contributing to these changes were examined—namely, atmospheric pressure, wind, rainfall, density and currents.

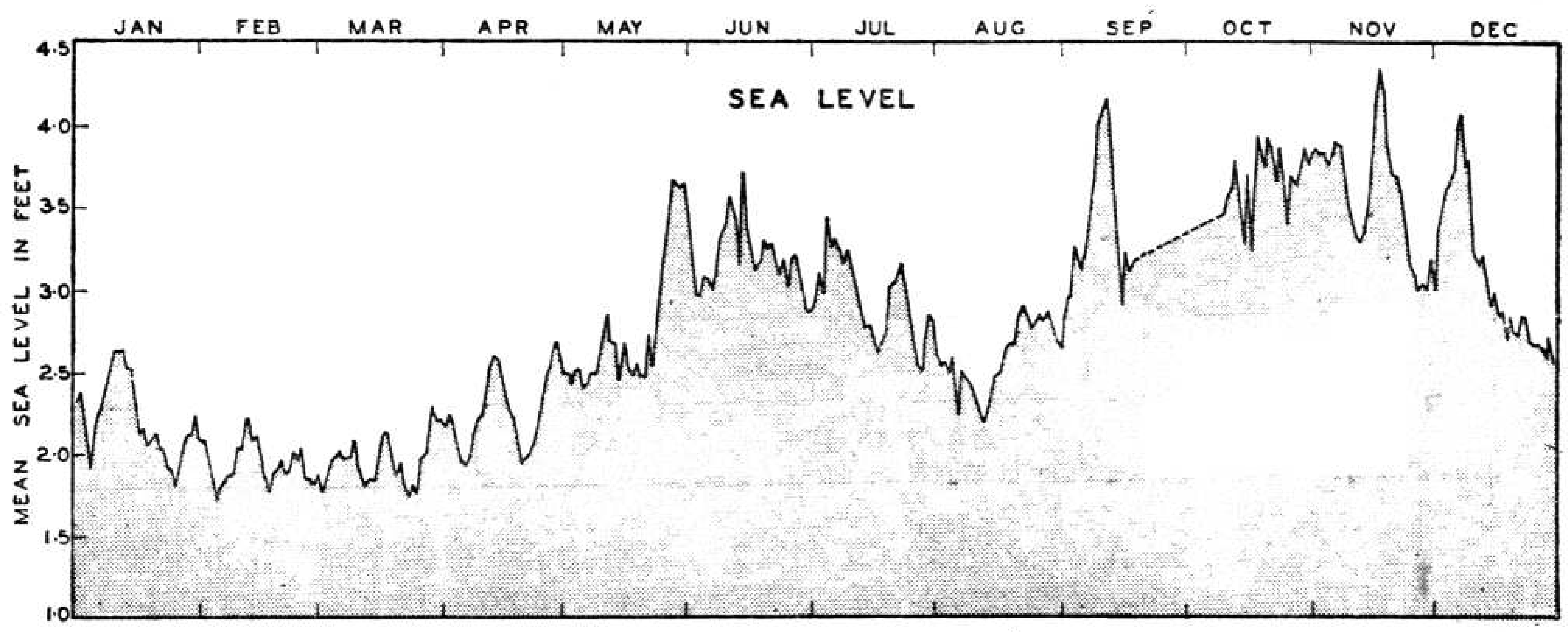

FIG. 27. Mean sea-level in Visakhapatnam Harbour for each day for the year 1950.

By calculating the dynamic heights (0/200 meters) based on the density of the vertical water column, it was found that the difference between April and October was 0·548 dynamic meters, or 22 inches. This, then, will account for approximately 90% of the annual change. In addition, the atmospheric pressure difference between Visakhapatnam and the opposite side of the Bay of Bengal was found to account for 2 inches more of water-level, or approximately 10% of the observed range in sea-level. The other factors could not be evaluated and apparently are not in themselves significant. However, the drop in sea-level in August still remains a mystery—possibly a low rainfall in that month?

Seiches.—One feature brought out in the tide records is small waves superimposed on the smooth semi-diurnal tidal cycles. A few are illustrated in Fig. 28. They are usually more pronounced when the tide range is

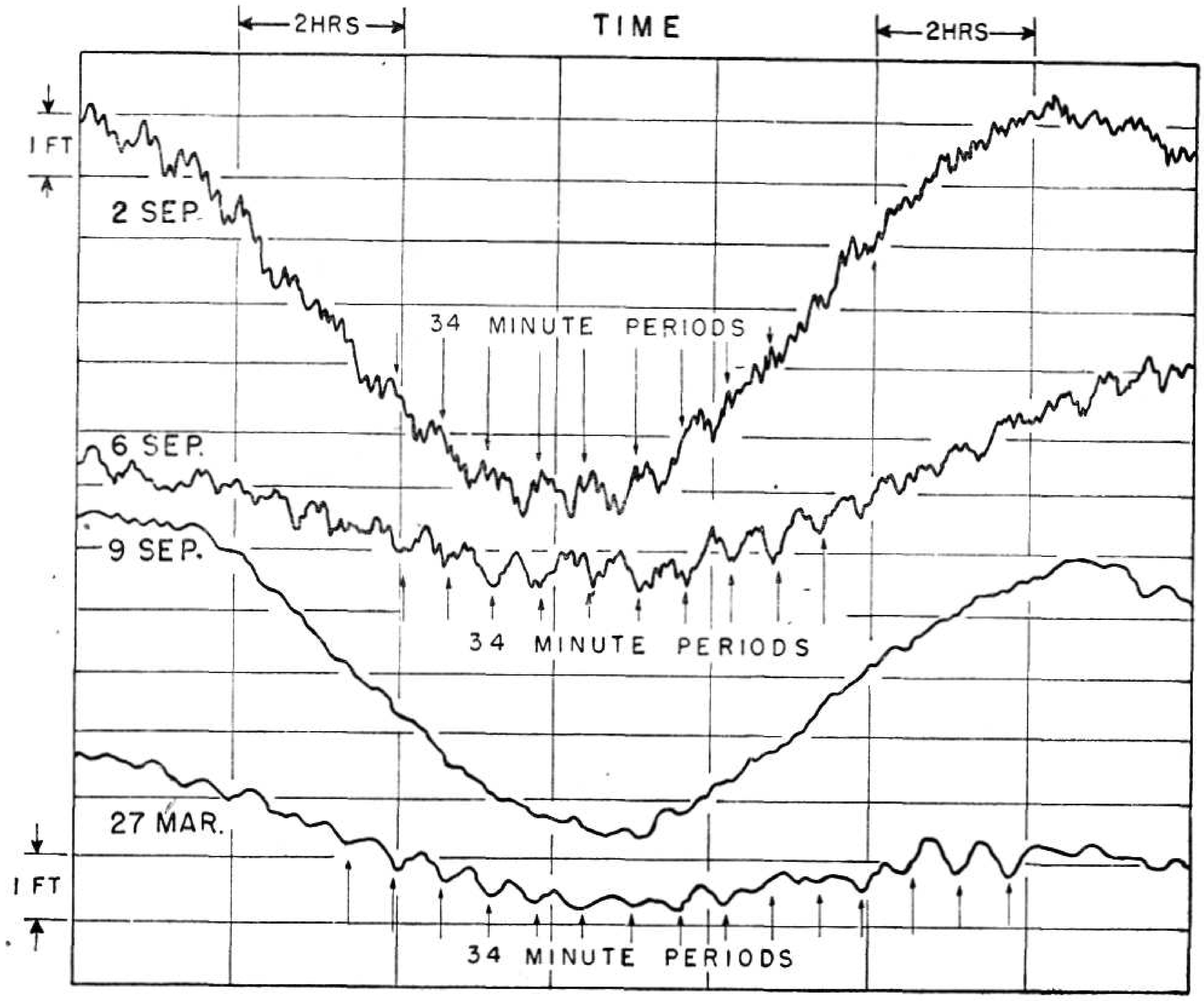

FIG. 28. Parts of the tide record for the days 2,6, 9 September and 27 March 1950, showing 34 minute seiches and other smaller vertical oscillations superimposed on the semi-diurnal tide.

low. Their heights vary from 2–6 inches and they have a surprisingly consistent period of 34 minutes.

This 34-minute period is too long for a harbour oscillation which should be about 8 minutes. Also, if a standing wave oscillated from the harbour to the edge of the continental shelf, the period should be 64 minutes. The wave must then have some other dimensions, which makes the 34-minute seich another enticing mystery.

Internal waves.—Vertical oscillations in the sea known as internal waves, also exist in the Bay of Bengal. These were investigated by means of repeated bathythermograph lowerings at single locations and revealed temperature fluctuations with time.[46] The oscillations, when taken over a long period of time, appear to have a semi-diurnal cycle, especially at the thermocline. The most promising force creating these internal waves was that of the tide, consequently harmonic analysis was performed on two sets of repeated temperature data collected at the edge of the continental shelf. The depth of an isotherm, with respect to tide, in the thermocline of each of the sets of data can be expressed as follows:

I.O.1, $$Z_{820} = C_0 + 12{\cdot}8 \cos(\theta - 51) + 9{\cdot}2 \cos(2\theta - 103)$$
and

I.O.2, $$Z_{780} = C_0 + 8{\cdot}6 \cos(\theta - 91) + 16{\cdot}4 \cos(2\theta - 12)$$
where

Z = depth of isotherm, C_0 = constant and θ = phase angle.

It was found that the phase lag of the second harmonic, corresponding to the semi-diurnal tide, was $3^h\ 31^m$ for one case and $-\ 2^h\ 31^m$ in the other case, or completely out of phase. These data when plotted with other similar data taken in the Atlantic and Pacific Oceans indicate that although an internal wave of tidal period exists, the phase lag between surface and internal tide varies widely, Fig. 29. The majority of the 17 sets of data examined show that the "internal" high tide usually occurs 3 to 5·5 hours after the surface high, or $a_{IHT} = 4{\cdot}5^h + a_{MHW}$.

Shallow internal waves.—If the internal waves described above are of short periods and the thermocline is nearly at the surface, they produce a surface disturbance. The crests of the shallow internal waves ruffle the surface as they move along. The troughs, on the other hand, tend to smooth the surface, producing a slick band. Thus, the sea becomes a series of slicks and ruffled waves over shallow internal waves as shown in Fig. 12 I.

This phenomenon has been observed all along the east coast shelf.[47] On one occasion the thermal structure was examined in detail by repeated bathythermograph lowerings. From the measured thermal structure and the drift of the ship, the circulation in the zones was deduced as shown in Fig. 30. It was concluded that the wave motion was cellular in nature,

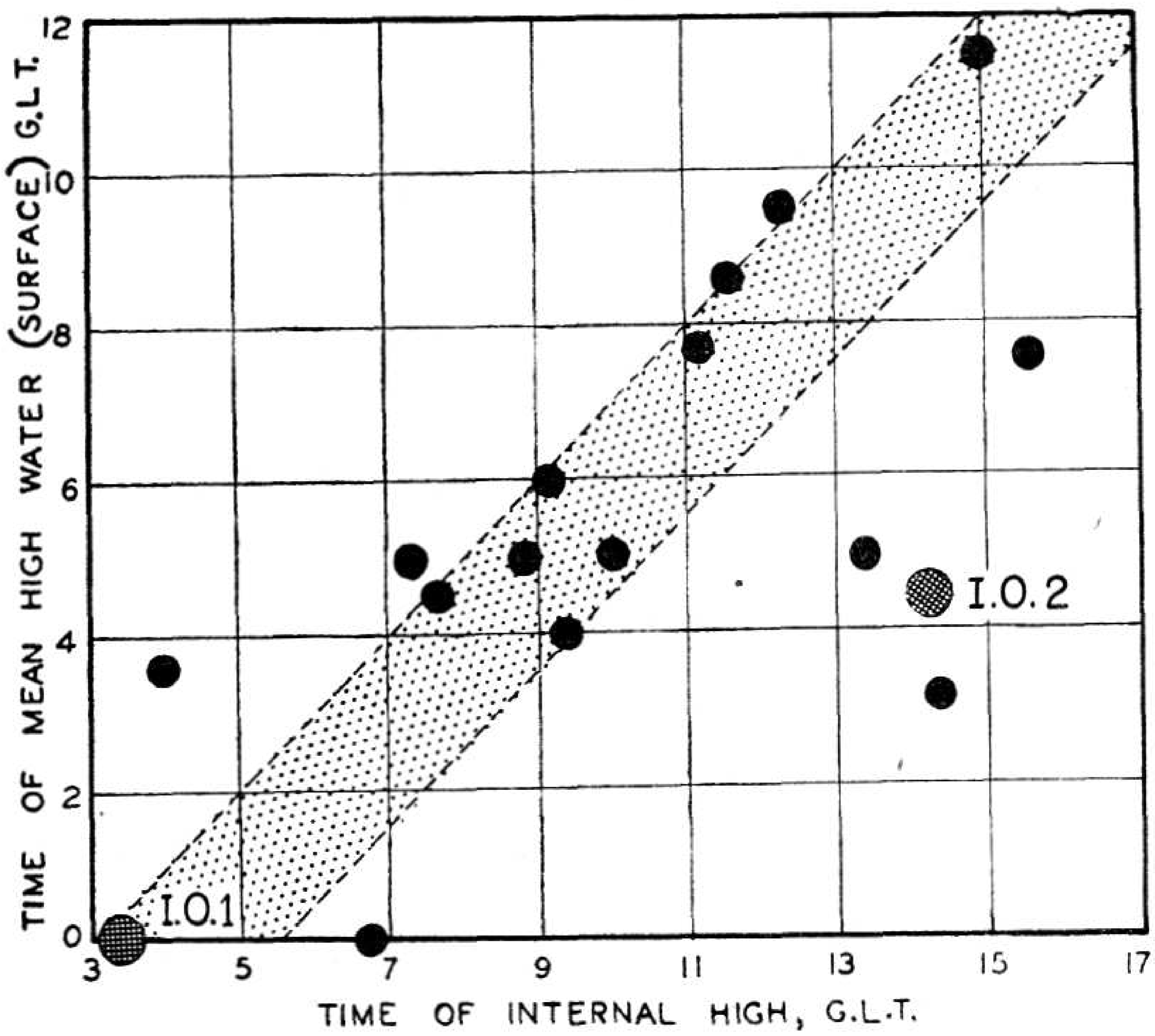

FIG. 29. Relationship of time of surface high tide and internal high tide (shaded band) for 15 stations in Pacific and Atlantic Oceans (dots) and 2 in the Indian Ocean (I.O.1 and I.O.2).

Consequently, they were termed rotary currents. The motion was further substantiated by the nature of the bathythermograph traces in which layer depths were both deeper and sharper in the trough than on the crest of the waves—a feature characteristic of sinking or downward motion. In other words, the rotary currents are a wave motion consisting of zones of convergence and divergence. They appear to develop in the turbulent region where the offshore tidal currents come in contact with the prevailing coastal currents. The development and maintenance of this boundary comprises another of the many complex phenomena of the Bay of Bengal.

CONCLUSIONS

The preceding review points out the progress that is being made in studies at Andhra University. It reveals that the secrets of the sea are many and varied.

It is probably apparent from these studies that an interrelation exists between the various fields of oceanography. For example, it is not possible to discuss plankton population or beach erosion without reference to currents and waves. All are interrelated. Consequently, the solution of

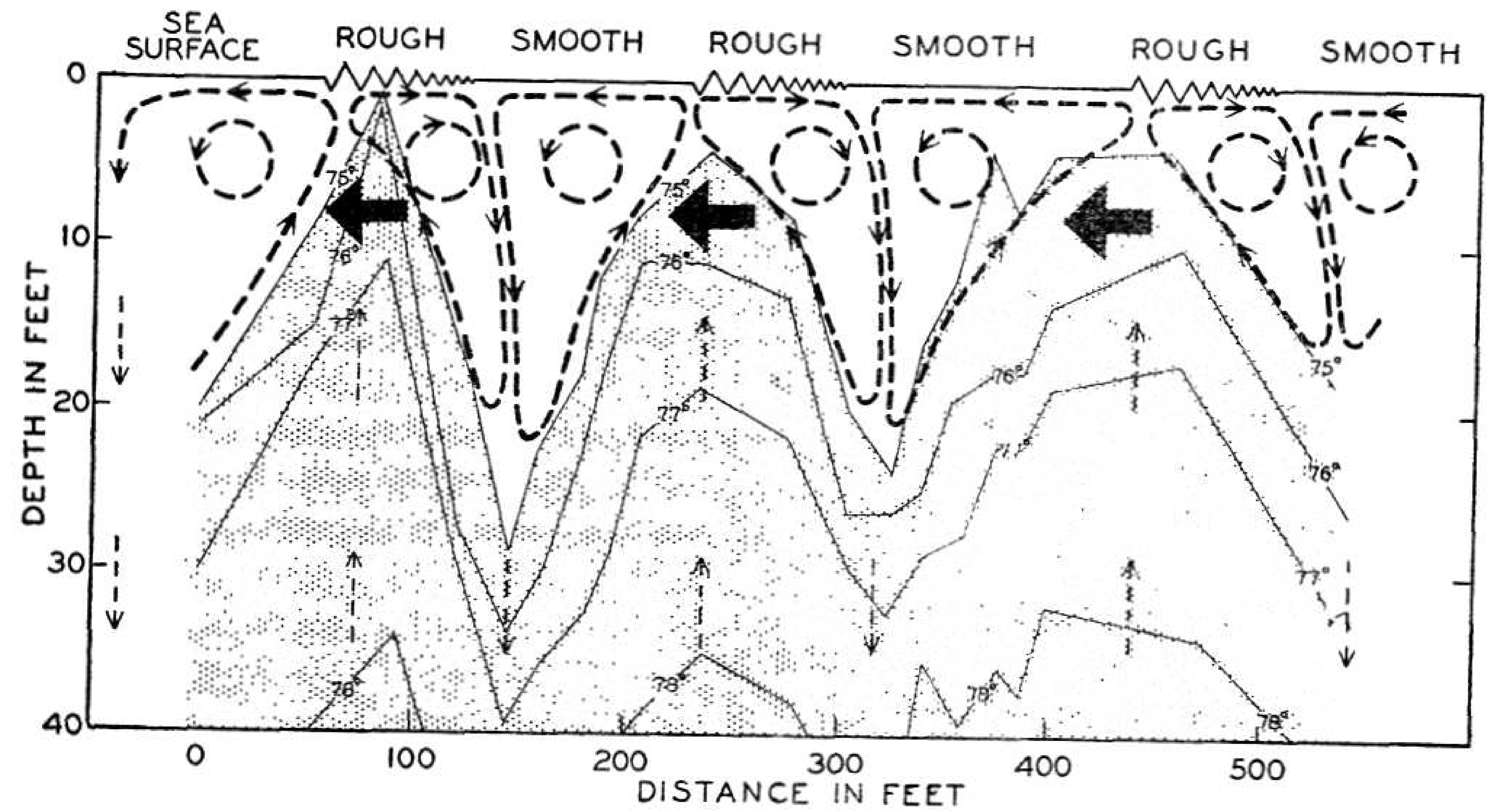

FIG. 30. Horizontal temperature section (fine lines), showing shallow internal waves which move from right to left (broad arrows), the probable turbulent (rotary) circulation (dashed arrows); and the rough and smooth bands at the surface (see Fig. 12 I).

the many unsolved problems must be a cooperating-team approach, whereby experts in one field work jointly with experts in another. This has been accomplished at Andhra University, as evidenced by the progress made on the many problems.

This summary also points out how interesting and thought-provoking the problems of the sea can be. The Bay of Bengal is literally a gold mine of intriguing problems for an unlimited number of future students in oceanography.

ACKNOWLEDGMENTS

The writer is grateful to the Heads of the three Departments, Professors C. Mahadevan, S. R. Savur and P. N. Ganapati, for continued friendly co-operation, and to the students of oceanography at Andhra University for their work at sea and in the laboratory, which is summarized here. Thanks is also extended to Dr. J. N. Nanda for his helpful interest in the work, especially for obtaining ship facilities and reviewing reports, and finally to Sir C. V. Raman who suggested the preparation of this report.

REFERENCES

1. Sewell, R. B. Seymour .. "The oceans around India. An Outline of Field Science in India," *Indian Science Congress*, 1937, 17–41.

2. Anonymous .. "Flood damage and flood control activities in Asia and the far east," *Flood Control Series No.* 1, Bureau of Flood Control, Economic Commission for Asia and the Far East, United Nations, Bangkok, 1950.

3. Dietz, R. S. .. "Possible deep-sea turbidity-current channels in the Indian Ocean," *Bull. Geol. Soc. An.*, March 1953, **64,** 375–76.

4. Kiilerich, A. .. "The Ganges Submarine Canyon," *Andhra Univ. Mem. in Oceanog.*, 1957, **2** (in press).

5. Kukkuteswara Rao and La Fond, E. C., "The profile of the continental shelf off Visakhapatnam Coast," *ibid.*, 1954, **1,** 78–85.

6. Sewell, R. B. Seymour .. "Geographic and Oceanographic research in Indian Waters," *Mem. of Asiatic Society of Bengal*, 1925, **9** (2), 27–50.

7. Mahadevan, C. and Poornachandra Rao, M. "Study of ocean floor sediments off the east Coast of India," *Andhra Univ. Mem. in Oceanog.*, 1954, **1,** 1–35.

8. Mahadevan, C. .. "Some recent results on oceanographic research at Andhra University," 1955 (in Press).

9. Poornachandra Rao, M. .. "Some aspects of marine geology in the Waltair parts of Bay of Bengal," *Doctorate Thesis*, Andhra University, 1954.

10. Mahadevan, C. and Poornachandra Rao, M. "Studies on the ocean bottom samples from the Bay of Bengal Indian Ocean," *Proceedings of XX International Geologica Congress*, Mexico City, 1956 (in Press).

11. Poornachandra Rao, M. and Mahadevan, C. "The collections on the continental shelf off the Visakhapatnam area. A.I.O.P.," *Proc. Verb.*, 1955, No. 6, 292–93.

12. Mahadevan, C. and Aswathanarayana, U. "Radioactivity of sea floor sediments off the east coast of India," *Andhra Univ. Mem. in Oceanog.*, 1954, **1,** 36–50.

13. Borreswara Rao, C. and LaFond, E. C. "Sand sorting on the east coast beaches," *Curr. Sci.*, 1956, **25,** 77–78.

14. Rao, B. S. R. and Bhimasankaram, V. L. S. "Magnet metrical tracing of the heavy mineral concentrates of the Visakhapatnam Beach," *Indian Minerals*, 1956, **9** (4), 305–08.

15. LaFond, E. C. and Borreswara Rao, C. "Deposition and sorting of heavy mineral sands on the east coast beaches of India," *Proceedings of XX International Geological Congress*, Mexico City, 1956 (in Press).

16. ———— and Prasada Rao, R. "On the erosion of the beach at Uppada," *The Port Engineer*, 1956, **5** (2), 2–9.

17. ———— .. "Beach erosion cycles near Waltair on the Bay of Bengal," *Andhra Univ. Mem. in Oceanog.*, 1954, **1,** 63–77.

18. Prasada Rao, R. .. "Further studies of sand movement across Waltair Beach," *Curr. Sci.*, 1954, **23,** 48–49.

19. LaFond, E. C. and Prasada Rao, R. "Beach erosion cycles near Waltair on the Bay of Bengal," *Andhra Univ. Mem. in Oceanog.*, 1954, **1,** 63–77.

20. ———— "On the swatch and backwash," *Oceanography of Bay of Bengal, Central Board of Physics*, May 1956, pp. 18–19.

21. Bhavanarayana, P. .. "Foam on the sea," *ibid.*, Calcutta, May 1956, p. 17.

22. Satyanarayana Rao, T. S... "Studies of the penetration of light in the Bay of Bengal, Part 1. Transparency of the waters on the east coast of India and its significance," 1957 (in Press).

23. LaFond, E. C. and Sastry, J. S. "Turbidity of waters off the east coast of India," *Indian Jour of Met. and Geoph.* (in Press).

24. Sewell, R. B. Seymour .. *Memoirs of the Asiatic Society of Bengal*, 1929, **9** (5 and 6), 207–423.

25. LaFond, E. C. .. "Seasonal cycle of sea surface temperature and salinity along the east coast of India," *Andhra Univ. Mem. in Oceanog.*, **2** (in Press).

26. Ganapati, P. N. and Murty, V. S. R. "Salinity and temperature variations of the surface waters off the Visakhapatnam coast," *ibid.*, 1954, **1**, 125–41.

27. LaFond, E. C. .. "On upwelling and sinking off the east coast of India," *ibid.*, 1954, **1**, 117–21.

28. Ganapati, P. N., LaFond, E. C. and Bhavanarayana, P. V. "On the vertical distribution of chemical constituents in the shelf waters off Waltair," *Proc. Ind. Acad. Sci.*, 1956, **44 B** (2), 68–72.

29. Bhavanarayana, P. V. and LaFond, E. C. "On the replenishment of some plant nutrients during the upwelling period on the east coast off India," *Indian Jour. Fish.*, 1957, **4** (1), 75–79.

30. Ganapati, P. N. and Satyanarayana Rao, T. S. "Distribution of the Chætognatha in the Waters off Visakhapatnam Coast," *Andhra Univ. Mem. in Oceanog.*, 1954, **1**, 143–50.

31. ——— and Rama Mohan Rao, V. "Studies of plankton copepods. I. Seasonal fluctuations in the distribution with reference to salinity and temperature," *ibid.*, 1954, **1**, 151–62.

32. Sastry, A. N. .. "The littoral bottom fauna on the Coromandal Coast," *Oceanography of Bay of Bengal, Central Board of Geophysics*, Calcutta, May 1956, p. 25.

33. Ganapati, P. N., Lakshmana Rao, M. V. and Nagabhushanam, R. "A preliminary account of the fouling organisms of the Visakhapatnam Harbour area" (in Press).

34. LaFond, E. C. .. "On upwelling and fisheries," *Curr. Sci.*, August 1955, **24**, 258–59.

35. Panikkar, N. K. .. "Annual Report of the Chief Research Officer, 1953," *Indian Jour. Fish.*, 1953, 377.

36. Ganapati, P. N. and Satyanarayana Rao, T. S. "The scope of fisheries in the Bay of Bengal," *Indian Science Congress Abst.*, 1956.

37. Anonymous .. *Indian Ocean, Oceanographic and Meteorological Data*, Koninklijk Nederlands Meteorologisch Institut No. 135, 2nd Ed., 1952.

38. LaFond, E. C. .. "Sea surface density at four stations along the east coast," *Indian Jour. of Met. and Geoph.* (in Press).

39. ——— .. "Environmental factors affecting the vertical temperature structure of the upper layers of the sea," *Andhra Univ. Mem. in Oceanog.*, 1954, **1**, 94–101.

40. ——— .. "Bathythermograms—an oceanographic tool," *Curr. Sci.* 1956, **25** (9), 40–41.

41. ——— and Borreswara Rao, C. "Vertical temperature structure of the upper layers of the sea off the east coast of India," *Defence Science Organization Publication No.* 4/55, 1955, 1–89.

42. LaFond, E. C. .. "On the circulation of the surface layers off the east coast of India," *Andhra Univ. Mem. in Oceanog.*, **2** (in Press).

43. Poornachandra Rao, C. .. "Meteorological factors affecting sea temperature and salinity off Waltair," *Curr. Sci.* (in Press).

44. LaFond, E. C. and Bhavanarayana, P. V. "On a thermal feature of bottom water during upwelling on the east coast of India," *Indian Jour. of Met. and Geoph.*, 1956 (in Press).

45. Prasada Rao, R. and LaFond, E. C. "Changes in sea-level at Visakhapatnam on the east coast of India," *Andhra Univ. Mem. in Oceanog.*, 1954, **1**, 86–93.

46. LaFond, E. C. and Poornachandra Rao, C. "Vertical oscillations of tidal periods in the temperature structure of the sea," *ibid.*, 1954, **1**, 109–16.

47. ——— and Borreswara Rao, C. "Rotary currents in the Bay of Bengal," *ibid.*, 1954, **1**, 102–08.

FIG. 2. Oceanographic equipment and measurements. (A) I.N.S. Rohilkhand used for oceanographic work. (B) Level-winding wire rope on electric winch drum. (C) Retrieving Phleger corer. (D) Extracting sea floor sediment core from corer. (E) Examining marine samples. (F) Retrieving sea floor sediment snapper. (G) Extracting sediment from snapper. (H) Placing glass slide in bathythermograph for temparture. (I) Lowering bathythermograph off stern of ship.

FIG. 3. Oceanographic equipment and measurements. (A) Lowering Secchi disc for determination of transparency of water. (B) Lowering plankton net to collect small plants and animals. (C) Examining plankton collection. (D) Making chemical analysis of sea-water. (E) Lowering dredge to scoop up benthonic organisms. (F) New sea urchin—*Diadema* sp.—dredged off Kalingapatam. (G) Retrieving Nansen bottle with water sample. (H) Reading hydrophotometer meters on deck. (I) Drawing water samples from Nansen bottles. (J) Lowering hydrophotometer to measure water transparency.

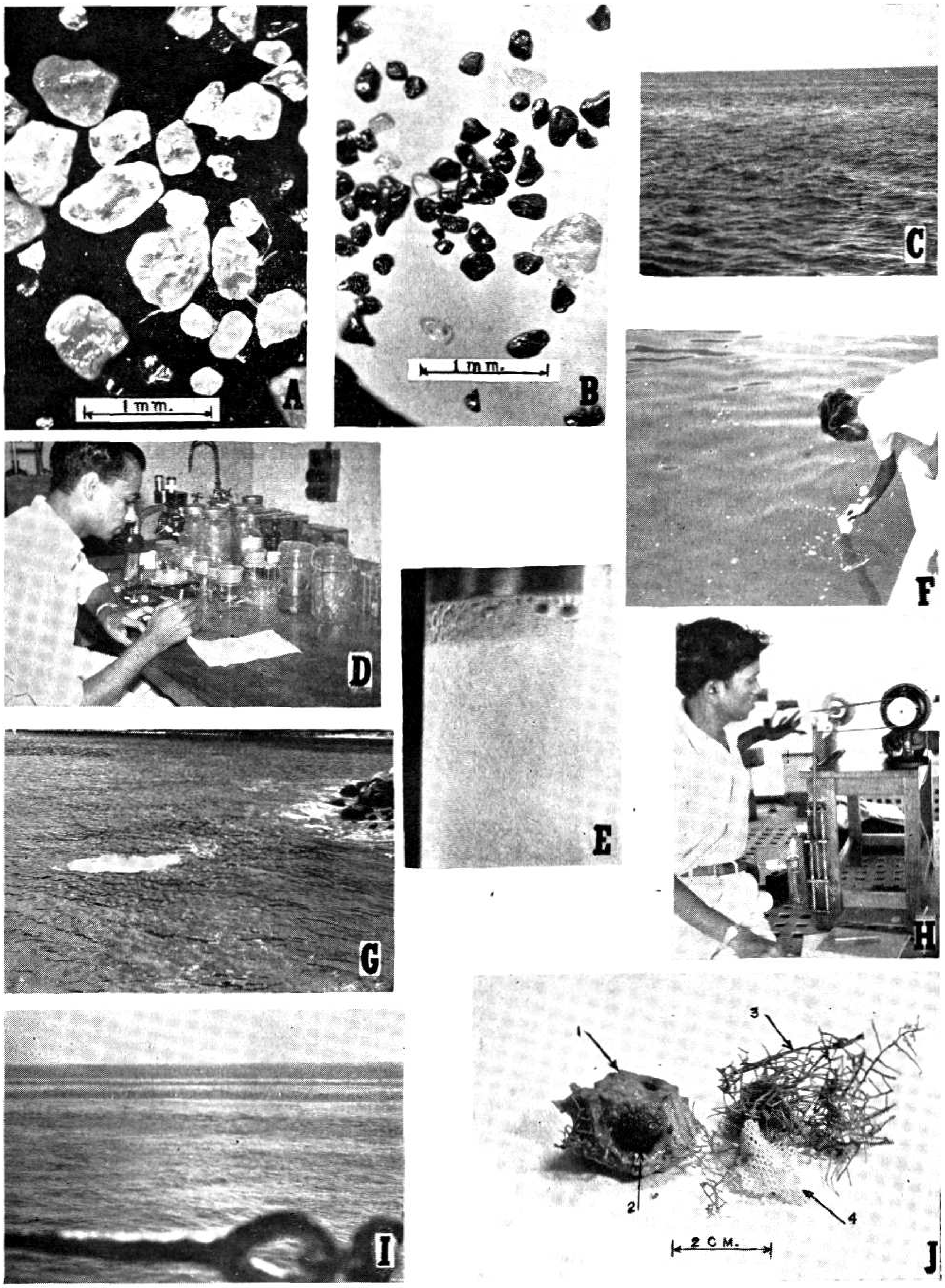

FIG. 12. Oceanographic samples, equipment and procedures (A) Sample of normal beach sands. (B) Sample of heavy mineral beach sands. (C) Sea surface slicks. (D) Examining biological samples in Laboratory. (E) Foam layer produced by shaker. (F) Sampling film from sea surface slick. (G) Persistent foam patch on sea. (H) Shaking samples of water for foam study. (I) Surface appearance of shallow internal waves (rotary currents). (J) Dredge sample (sta 704, depth 35 fms). (1) Sponge, (2) Pecten, (3) Hydroid, (4) Bryozoa.