A REVIEW OF OCEANIC FRONTS

by

Ola M. Johannessen
Geophysical Institute
University of Bergen
Bergen, Norway

ABSTRACT

This paper will start with a brief account of oceanic frontal research. The definition of oceanic and acoustic fronts and the distinction between them will be discussed. Examples of frontal structure dynamics, correlation with bottom topography influence of local wind effect and examples of vertical and horizontal scales will be demonstrated. Finally some recommendation for further research will be suggested.

I INTRODUCTION

In recent years an increased interest has been paid to frontal research in different world oceans and continental shelfs. Several of the earlier investigations were "oportunity studies" in the sense that during a cruise an oceanic front was unexpectedly discovered, resulting only in a brief investigation of the phenomena. However, during the last 10 years more systematic investigation have been carried out using higher resolution instruments and station spacing adapted to the finer scales of the fronts. In the coming years the frontal research covering dynamical, acoustical, biological and chemical problems will probably be intensified and it was therefore felt that a brief account of frontal research up to present might be useful. It whould be mentioned that an extensive bibliography for oceanic fronts and related topics has been produced by Moors et al. (1974).

In part II of this paper brief comments to some of the major contributions will be given. However, it is stressed that this is not meant to be a critical review, but rather more of informative nature such that the interesting reader can go back to the original paper for detailed informations. In part III the definition of oceanic and acoustic fronts will be discussed and examples will be shown to demonstrate that an oceanic and acoustic front might not necessarily coincide. In part IV the dynamic of front will be dealt with. Examples from the literature will be used to illustrate frontal structure, velocity shear, correlation with bottom topography and local wind effect. Finally scales and the order of magnitude of ranges in oceanographic parameters in different frontal regions will be commented on. In part V recommendations for further research are suggested.

II FRONTAL RESEARCH

The investigations of oceanic fronts defined in Ch. III were started in the seas around Japan, Uda (1938), Quoting Uda (1959, p.13) frequent occurence of fronts were to be found;

"1. at the boundary between a cold and warm current, a warm and cold front.
2. at the boundary between coastal and oceanic water masses, at a coastal front
3. around banks, reefs, shoals, an island shelf, along a shelf edges
4. off estuaries
5. along the margin of areas of upwelling."

To illustrate the outcrop of an oceanic front at the surface, a photograph of the Sargasso Sea front is shown in Fig. 1, Voorhis (1969) while Fig. 2 demonstrates the temperature structure across a similar front in the Sargasso Sea. Two surface water masses are separated by a sloping interface. The horizontal temperature difference across the frontal interface was approximately 1.5°C while the salinity difference was reported to be 0.05-0.1 $^{o}/oo$, implying a change of 4.5m/s in the speed of sound structure. Horizontal changes of this order might have significant effect on the propagation of sound across fronts. Searching the literature it is difficult to find investigations of acoustic propagation in frontal regions; however, Hanson (1975, p. 231) recently reported the following findings: "The thermal front between water masses of the Greenland Sea and Norwegian Sea was located, and an acoustic propagation experiment was performed across the front. Data analysis revealed a 10 decibel lower acoustic transmission loss for propagation northward through the front (warm to cold) than southward (cold to warm)." It therefore appear that oceanic fronts or more correctly acoustic fronts (defined in Ch. III have an important effect on sound propagation.

Detailed investigations of the Gulf Stream Front started in U.S.A. with studies of the surface temperature with Air Radiation Thermometer (ART) equipped airplane, closed spaced BT (5-10 n.mi spacing) and horizontal shear current measurements with the towed GEK system in the beginning of the 1950's;see for example Stommel et al. (1953), Von Arx et al. (1955), Ford et al. (1952) Fuglister (1951, 1955)and Fuglister and Worthington (1951). However, the Gulf Stream system as well as the Kuroshio are strong western boundary current, and such parameters as for example the slope of the interface, horizontal gradients of the variables, horizontal and vertical scales are an order of magnitude larger, when compared with other frontal systems such as for example the Sargasso front, Voorhis (1969), Katz(1969) or the Maltese front in Mediterranean, Johannessen et al. (1971), Briscoe et al. (1973). It is therefore suggested that the strong western boundary currents should be classified as a separate class within the frontal systems. Further comments to this class is out of scope of this paper, but the interesting reader is referred to the papers by for example Stommel (1958), Fuglister (1963), Hansen (1970), Hansen et Maul (1970, 1971), and to a recent paper by Robinson et al. (1974) which is dealing with the intermediate-scale variability or meandering of the Gulf Stream.

Some of the first detailed temperature sections across fronts in the open ocean were obtained in the Central Pacific, Cromwell and Reid (1956) and Knauss (1957). Knauss reported BT dips every 30 m in the horizontal as the ship drifted through the front and he was able to picture "cold water overrunning the less denser water and plunging downward". The unstable zone was less than 100 m wide. It was also noted that the frontal surface boundary was moving with approximately one knot along a line normal to the boundary. High biological activity was observed in the frontal zone.

The equatorial front between Peru and Galapagos was investigated by Wooster (1969) and Pak and Zaneveld (1974)by use of classical techniques. Zaneveld et al. (1969) also performed optical measurements in this frontal region and by use of radar observed that typical waves with wave length of 10 km was present at the surface boundary of the front.

La Fond (1971) used a 250 m deep towed thermistor chain and obtained detailed temperature sections in the California Front. Frequent temperature inversions were observed and believed to be the result of two water masses intermingling,resulting in local sound channals, probably effecting propagation of the sound.

Roden (1974) investigated the trade wind region between California and Hawaii, and found good relationship between the spatial fields of air/sea interaction parameters such as wind stress, heat, salt and buoyancy flux fields at the sea surface and the meridionally temperature and salinity structure, which was sampled with STD at 20 n.mi interval, and the position of the doldrum and subtropical fronts. Frontal studies were also carried out in the Mid-Pacific and the Subartic-Subtropical transition zone in the western Pacific, Roden (1970, 1972). The front of Cape San Lucas, Lower California, was studied both physical and biological, however, in this case accumulation of biota at the front was not conclusive, Griffiths (1965).

Recently studies off the Oregon coast, U.S.A. and Cape Town, South Africa, have thrown light on frontal formation under upwelling periods where it was demonstrated that the pycnocline surfaces resulting in a strong front, located in a direction parallel to the coast, Stevenson et al. (1974) Bang (1973). Bang and Andrews (1974).

In the Sargasso Sea, oceanic fronts are normally observed between latitude 22-32°North, however, not during summer time when little frontal activity is present. The first use of a towed thermistor chain in frontal research was carried out in the Sargasso Sea, Voorhis and Herzy (1964), and it was shown that the vertical scale of the front was of the same order as the thickness of the 100 m mixed layer. Surface current across the frontal boundary was measured by the towed GEK and the velocity profile showed a jet like structure, with a maximum current of 60 cm/s along the frontal edge. Voorhis (1969) continued the investigation and studied the horizontal extent of the front from air by use of a ART system. It was shown that the front at least extended 500-600 n.mi in a west/east direction and was persistent in time over at least a 3 months period. Voorhis indicated that the fronts in this region was the end product of large scale wind field and seasonal, meridional heating and cooling of the sea surface, Katz (1969) performed the first STD observations across a segment of the Sargasso front. By the higher resolution temperature-salinity correlation obtained by the STD probe it was demonstrated that no mixing within the resolution of the instrument took place across the frontal interface, which was taken as an indication of water transport along the frontal surface. Both the ART survey by Voorhis (1969) and the study by Katz (1969) was interpretated by Beckerle (1972) to be associated with a slow moving westward Rossby wave. Colton et al. (1975) demonstrated a strong evidence of a faunal change across a front in the Sargasso Sea.

A study of the Oceanic Polar Front was carried out during the Geophysical year and reported by Diterich (1964, 1969). However, this was a study of the whole North Atlantic on a rather large scale, giving the general location of the Polar Front during the summer and winter season.

Recently two studies of the Polar Front in the Barents Sea were carried out, Foster et al. (1974, 1975). The first one dealt with the average position and its variation over several years while the second one was a detailed study, using ART, STD current measurement and XBTs. The XBT grid covered an area of 50 by 50 n.mi with launching each km and grid line separated by 5 n.mi A very high correlation between the location of the front and the bottom topography was established.

In the Mediterranean Woods (1970) started the investigations of fronts on the continental shelf and slope east of Malta on the border to the Ionian Sea. Both ART and ship observations were carried out simultaneously, however, only the temperature field was sampled. Rather than fixing the grid of observations in space, Woods used a moving framework by dropping drogues in the surface layer across the front. In this way, at least to a first approximation, the same part of the front was investigated, although a slow distortion of the framework took place caused by the horizontal current shear. Some detailed temperature sections were obtained both by use of a microstructure probe and later by XBTs from a fast moving vessel, Woods (1972), Briscoe (1972), clearly demonstrated up and down-welling processes along the frontal interface.

While the studies by Woods were carried out over a limited area covering only a fragment of the front, Johannessen et al. (1971) and Briscoe et al. (1974) performed a large scale investigation to determine the horizontal extent of the frontal zone. A good correlation between the location of the front and the edge of the continental slope was shown. In addition simultaneous STD dips with station spacing of few hundred metres and current measurement from a moored array in the frontal zone were performed, to be further commented on in the next chapter.

A front located over deep water in the Ionian Sea was investigated during the early winter by the use of the Naval Undersea Center's 250 m. deep towed thermistorchain. Some spectacular temperature sections of the frontal structure were obtained, see Fig. 8. Johannessen (1972), Johannessen et al. (1975). From the location of the Maltese front and the one over deep water in the Ionian sea it was suggested that perhaps the Maltese front undergoes seasonal variation and is propagating eastwards from the continental slope area and out into the Ionian Sea from summer to winter.

Levine and White (1972) from observation of BTs and a towed thermistor probe in the eastern Mediterranean, suggested that two major frontal systems existed, one in the Ionian Sea and another in the Levantine Basin; however, the location of the Maltese front and the one in the Ionian Sea was not coinciding with their suggestion.

An attempt to study the seasonal variation of Oceanic fronts on a world wide scale was done by applying the second directional derivative operator to the synoptic sea surface temperature field on a daily basis, Lavastu and LaFond (1970). However, since several oceanic fronts are determined by the salinity field rather than the temperature field, see for example Amos et al. (1972), Roden (1974), Johannessen (1975) a large number of fronts will be excluded. Smaller scale fronts will not be discovered because of the scarity of the observations and the grid size used. The result indicated that a large fraction of the world oceans were covered by frontal zones.

III DEFINITION OF OCEANIC AND ACOUSTIC FRONTS

In the literature the most frequent term used in association with fronts in the ocean is the "thermal front", the reason beeing that in many of the first investigations, only the temperature field was sampled. In recent investigations, salinity observations have also been included, thereby introducing the term "salinity front", where appropriate. Several definitions of oceanic fronts have been suggested, Cromwell and Reid for example suggested that "A front will mean a band along the sea surface across which the density changes abruptly". However, in many cases the horizontal gradients in the temperature and salinity fields compensate each other resulting in a very weak or no change in the horizontal density field, and accordingly will not classify as an oceanic front after Cromwell and Reid's definition. Another important class of front which will not be included is the subsurface front. The following more general definition is therefore suggested "A front in the ocean is a zone where abrupt horizontal changes in the temperature and/or salinity fields take place".

A simple situation of a front is shown in Fig. 3, where two water masses with two different densities are separated by a sloping interface. This simple situation is, however, seldom found in nature, and a realistic situation is shown in Fig. 4, which demonstrates the density structure in a frontal zone located over deep water in the Ionian Sea, Johannessen et al. (1975). The slope of the interface is $0.5 \cdot 10^{-2}$ and the horizontal density change across the interface is in the order of 0.3-0.5 sigma t. Figs. 6 and 7 exhibits the temperature and salinity structure. Strong horizontal gradients are established between stations 3 and 4 at the 50 to 100 m level. However, they compensate each other, resulting in no horizontal density gradient in this region, Fig. 4.

When dealing with sound propagation in frontal region, it is suggested that the term acoustic front should be introduced and defined "as a zone where abrupt horizontal changes in the speed of sound take place". It should be stressed that in the case the salinity is the dominating parameter for the density field in a frontal region, the acoustic front will be very weak or none existent because of weak or none-horizontal gradient in the temperature field, and the dominance of the temperature on the speed of sound calculation.

This point is illustrated in Fig. 5, which shows the speed of sound field for the same section as in Fig. 4. As mentioned, Fig. 4 was used to demonstrate an oceanic front, while on Fig. 5 a corresponding acoustic front is not present in the surface layer, because the salinity (Fig. 6) is dominating the density field, with very weak horizontal temperature gradient (Fig. 7).

Comparison of Figs. 4 and 5 also illustrates that the oceanic and acoustic fronts coincide between station 1 and 3; however, at station 3 a splitting occurs. The oceanic front is rising towards the surface, while the acoustic front is changing slope and is inclined downwards toward station 4.

Some comments should also be offered to the variation of the sign of the horizontal gradient of speed of sound. In Fig. 2, the sign of this gradient will not change across the acoustic front (the temperature field will reflect the speed of sound field because the salinity variation is small), while this will be the case for Fig. 5 where the gradient will change sign between station 2-3 and 3-4. How complicated the structure of an acoustic front can be is seen in Fig. 8 which is a detailed temperature section obtained with a towed thermistorchain across the same front as the STD dips in Figs. 4-7, Johannessen et al. (1975). As mentioned the acoustic front will be determined by the temperature field, and acordingly the acoustic front (expressed by the temperature field) will show large variation in slope, of horizontal gradients, while the oceanic front will be rising through the mixed layer, roughly following the slope of the 18.5°C isotherm.

In the next chapter it will be shown that both up and downwelling occurs along the frontal interface. In the case of upwelling, this will bring nutrients up into the surface layer, which will cause the biological activity to increase implying an increase scattering of the propagations of the sound.

IV DYNAMICS OF FRONTS

Few theoretical investigations have been carried out in the field of oceanic frontal dynamics when comparing with the intense research carried out by the meteorologists on atmospheric fronts. However, Welander (1963) investigated the dynamics and upwelling feature along a frontal interface for a two layer model of a stationary front. Orlanski (1969) and Orlanski and Cox (1972) studied the baroclinic instability and applied their models to the Gulf Stream Front. It was shown for the range of parameters of the Gulf Stream that baro-cline unstable waves could be generated. Comparison between the theory and observed manders of the Gulf Stream between Miami and Hatteras. Rao et al. (1971) indicated that these waves probably were unstable baroclinic waves. Rao and Murthy(1973) investigated upwelling of fronts in the open ocean and used as input observations of fronts in the Pasific, Cromwell and Reid (1956) and in the Atlantic Ocean, Voorhis and Hersey (1964). Their model predicted average vertical motion of the order of 0.1 cm/s with maximum values up to 1 cm/s.

In this paper, however, examples of observations in frontal regions will be used to demonstrate some of the dynamical features, but before doing so Fig. 3 will be used to illustrate the simplest situation of a two layer model.

The sloping interface in Fig. 3 implies that a current shear will be present between the two water masses, and the shear will depend on the slope of the interface, the Coriolis parameter and the difference in density, and can as a first approximation be expressed by the Witte-Marquels equation:

$$\Delta V = \frac{g}{f} \frac{\Delta\rho}{\rho} tg\alpha$$

where ΔV is the shear, $\Delta\rho$ density difference, g gravity, f Coriolis parameter and α the slope of the interface.

If a real situation can be approximated in this way and the slope and density difference can be estimated from hydrographic data, which is much easier to obtain than current measurements, a rough estimate of the shear can be obtained.

In Fig. 3 the outcrop of the front at the surface was a straight boundary, while in nature this seldom occures. Fig. 9 shown the observed outcrop of the Maltese front in the Ionian Sea, Johannessen et al. (1971) and Briscoe et al (1974). The figure shows the surface isotherms obtained by an ART equipped airplane. The zone of the strongest temperature gradient represents the surface boundary of the front, because from simultaneous observations by ship, Johannessen (1975) established a high correlation between the temperature and the density gradients, although it is actually the salinity which dominates the density field while the temperature acts to decrease the density gradient across the front. Since the ART picture was obtained during a period of 2.5 hours the observed feature is nearly synoptic, and the very slight distortion caused by horizontal shear over this period is in the same order of the accuracy of the position determination of the aircraft. One purpose of this detailed flight track was to investigate the waviness of the front. Meanders of 15 n.mi and perhaps 30 n.mi wavelength seemed to be present. (The aim of investigation of this nature should be to obtain both a frequency and wave number spectra of the frontal waves; however, this would require a much more extensive observational program. It can be mentioned that the author is at present involved in planning such an experiment).

The other interesting feature is the cold patches of water located west of the frontal boundary, the major one centred at latitude 35°40'N and smaller patches at 35°20' and 36°20' North. This is strong indication of upwelling, which is verified by subsurface observations in a vertical section across the front (see Fig. 11) to be discussed later. On "wavey fronts" both in the atmosphere and in the ocean it is expected that up and downwelling will be present. Strong downwelling patterns are for example shown in Fig. 10 which represent an XBT section obtained at 10 knots speed (and therefore nearly synoptic) with a dip every 0.5 n.mi across the front shown in Fig. 9 at 36°North. The subsurface structure of the front is clearly seen and the downwelling is indicated by the large lobe of warm water, which is penetrating down into the colder water, for example shown by the 15°C isotherm. Fig. 11, which is a detailed STD section perpendicular to the front at the same location as Fig. 10 carried out in a very calm period demonstrates that upwelling along the upper part and downwelling along the lower part of the frontal interface is simultaneously present resulting in an inversion layer with a secondary sound channel along the frontal interface. It should be noted that the interpretation of the vertical circulation in Figs. 10 and 11 is based on the temperature structure and is justified in Figs. 12 and 13 which shows that the salinity is the dominant parameter controlling the density field. This implies that the temperature loses some of its dynamical significance, such that it can be used to get an idea of the vertical circulation.

Fig. 12 illustrates very clearly that the frontal interface indicated by the 37.6 to 38.3 ‰ isohalines is dividing the lower salinity water to the west from the more saline eastern Mediterranean water to the east.

The patch of surface water of salinity less than 38.0 east of the front might express that cross frontal mixing take place. The density field is expressed in Fig. 13 and the frontal interface with vertical thickness of about 10 m can in this case be approximated with a straight plane with a slope of $0.25 \cdot 10^{-2}$. Smaller perturbations on the interface are also present caused by internal waves.

Fig. 3 showed schematically the shearing current across the interface, while few detailed vertical shear measurements across frontal boundaries have been reported in the litterature. However, direct current measurements over a 3 days period at 5-15-30-60 m was carried out across the frontal boundary of Fig. 11 to 13, Johannessen(1975).The three upper current meters were located above the interface and the 60 m one below. The average current for the upper and lower layers were respectively in the order of 40 and 7 cm/s, both southwards. By inserting the different parameters known from observations, the Witte Marquels equation was tested and was found in good agreement with the data set, which implied that the front was geostrophic balanced within the acuracy of the measurement.

Vertical shear in the order of 2 cm/s/m was present across the frontal boundary. The shear combined with the density difference across the boundary allows calculation of the Richardson number, which was estimated to be in the order of 1. This was an average bulk value and it is believed that when higher resolution measurements can be carried out, this will be lower with strong possibilities that shear instabilities resulting in that overturning and mixing can take place. Another instability on larger scale which probably also will occur is the baroclinic instabilities, which when triggered will cause the frontal wave to grow and eventually cause eddies to be formed.

While Fig. 14 showed the current from 4 discrete depths, Fig. 15 exhibites the geostrophic calculated flow across a front located over deep water in the Ionian Sea, Johannessen et al.(1975). The horizontal and vertical shear is well established, with current running in opposite direction on each side of the front. The horizontal difference is 75 cm/s over a distance of 25 n.mi giving an average horizontal shear of 3 cm/s/n.mi or about 1/5 of the Coriolis parameter. The vertical shear is in the order of 0.5-0.8 cm/s/m or less than half the value given by the direct current measurement in Fig. 13.

The acoustic implication of strong horizontal and vertical shear in the velocity field might be that the principle of reciprocity will break down, bearing errors will be introduced, and if small-scale shear and larger scale baroclinic instabilities will occur, resulting in turbulence and eddies, scattering of the sound from these inhomogenities will be another problem.

<u>Correlation of frontal location and bottom topography</u>;
Some major frontal zones are located over deep water with no correlation to bottom topography, while other locations correlate very well with the continental slope, as a matter of fact so well that this can be used for prediction purpose.* Probably one of the most detailed data set to investigate this matter was recently sampled in the Polar Front zone in the Barents sea, Foster, Johannessen, de Strobel (1975). Several ART flights were performed, with track spacing of 5 n.mi An XBT grid with track spacing of 5 n.mi and dips for every 1 km along these lines revealed an outstanding correlation with the zone of maximum horizontal gradient

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* The position of the fronts in the open ocean is difficult to predict.

in the temperature and the continental edge. Fig. 16 shows the topography and Fig. 17 the surface isotherms. The correlation is better in the eastern part of the area, while in the western part the waves indicated by the isotherms,had larger "amplitude" than the "amplitude in the bottom topography",perhaps indicating that baroclinic instability is present.

<u>Effect of local wind mixing:</u> An example of frontal structure in a calm weather condition was shown in Figs. 11 to 13. However, during the same investigation the wind suddenly increased as a step function from calm to force 7-8, and a STD section was obtained 2.5. days after the wind had started to blow. Figs. 18 and 19 represent respectively the calm and the windy condition of the speed of sound structure. As expected the mixed layer or the duct had increased from an average value of 10 m to about 20 m. The horizontal change of the speed of sound across the front in the calm condition in the surface layer between station 58 and 61, Fig. 18 was 4 m/s, while this change had decreased to half between station 126 and 128 in the windy case, Fig. 19 indicating that horizontal mixing occurs across the frontal boundary in the mixed layer. The sound channel below the thermocline west of the acoustic front in the windy case had increased significantly in vertical thickness, represented for example with the 1510 m/s contour. Furthermore the acoustic front below the mixed layer appeared to be more regular in structure for the windy case, the reason being that upwelling along the frontal interface had stopped; however, a pronounced downwelling had developed.

Scales of fronts: In determining the scales of fronts, several characteristics such as vertical and cross frontal scales can be given to good accuracy. However, estimates of horizontal extension, typical wave lengths, vertical and horizontal shear can be associated with considerable errors due to the lack of appropriate observations and the difficulties in obtaining such observations. The Sargasso Sea front, the Maltese front and the Polar front in the Barents Sea are frontal region where extensive observations have been carried out, and Table 1 shows as an example.estimates of the scales involved as well as changes in the oceanographic parameters for these 3 frontal zones.

V. RECOMMENDATION FOR FUTURE RESEARCH

To understand frontal dynamics the oceanographers can certainly benefit greatly from theoretical and experimental investigations carried out on the atmospheric front problem. Realistic theoretical models based on some of the "descriptive physical models" observed in the ocean should be formulated.In the formulation two important cases should be taken into consideration: the open ocean condition with no topographical effects (land and bottom) and case where the front is topographically controlled by for example the continental slope. Furthermore since many of the fronts observed manifest themselves in the surface layer, atmospheric forcing should be included. In some cases this forcing might actually be the reason of the formation of the front. In other cases when the front is topographically controlled, for example by the deformation field associated with the continental slope, short term strong atmospheric forcing will only modify the frontal structure temporarily.

Most of the fronts observed in nature are meandering, but at present our knowledge of the spectral form of these meandering is rather poor. As one way of attacking the problem it is suggested that the theories should attempt to predict the spectral form of the frontal waves (in frequency and wavenumber domain) and at the same time the experimentalists should aim to describe the frontal waves in the same way, such that a testing of the theory(s) can be performed.

From an observational point of view it should be stressed that obtaining a "synoptic data set" of parameters in a frontal region where the shearing effect of the velocity field will distort the scalar fields as sampling is in progress will be a challenge to the oceanographers for many years. New "thinking" of experimental design is certainly needed in this field. Given the resources,"computer experiments" for "optimum synoptic interpretation" should be performed using as input expected range of parameters in the frontal region to be investigated.

At present the studies of fronts in the ocean is at its beginning, perhaps at the same stage as the atmospheric frontal research was at the time the Bergen school with Bjerknes and his co-workers went "into action". However, with the present state of ocean and space technology and the experience gained in atmospheric frontal research, by for example, advanced numerical computer techniques, the oceanic frontal problems should be a challenging and fundamental research area to move into, and certainly deserves more attention in future.

TABLE 1

Name	Sargasso Sea	Maltese	Polar Front Barents Sea
Vertical scale m	200-400	100	100
Interface thickn. m	∿ 5	∿ 5-10	5-10
Slope $(\cdot 10^{-2})$	0.4-1	0.25-0.5	0.1-0.5
Horizontal scale n.mi			
cross frontal	15	20	15-20
along front	500	90	400-500
typical wavelength	40-240	15-30	30
Horizontal changes acorss the front			
$T\,^{o}C$	2	1-2	2-3
$S\ ^{o}/oo$	0.05	0.5	0.3
σ_t	0.5	0.5	0.3
ν m/s (sound)	6	4-8	6-9
Vertical shear $s^{-1}\cdot 10^{-2}$		2	
Horizontal " $s^{-1}\cdot 10^{-4}$	∿0.2	∿0.5(?)	
Depth Limited	No	Yes	Yes
Persistence in time	Months	Months	Permanent
Latitude North	27^{o}	36^{o}	74^{o}

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FIG. 1
AERIAL PHOTOGRAPH OF A FRONT TAKEN IN FEBRUARY 1965 NEAR 26°N-66°W
[From VOORHIS (1969) p.332]

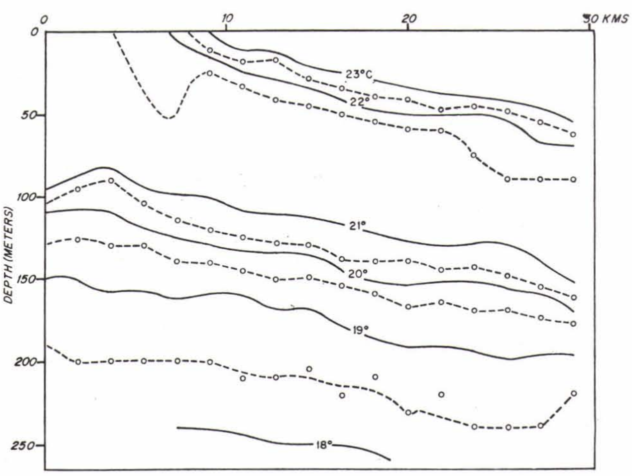
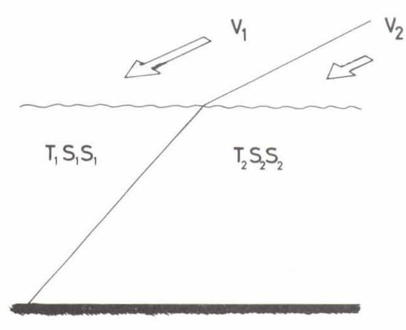


FIG. 2
VERTICAL TEMPERATURE SECTION ACROSS THE FRONT NEAR 26°30'N-68°30'W FROM CLOSELY SPACED BATHYTHERMOGRAPH STATIONS
[From VOORHIS (1969) p.335]

FIG. 3



STD SECTION I

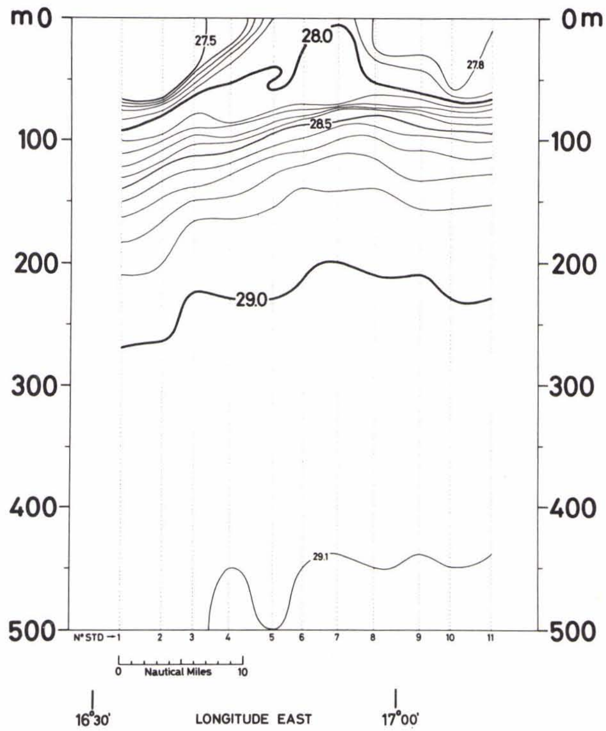


FIG. 4

STD SECTION I

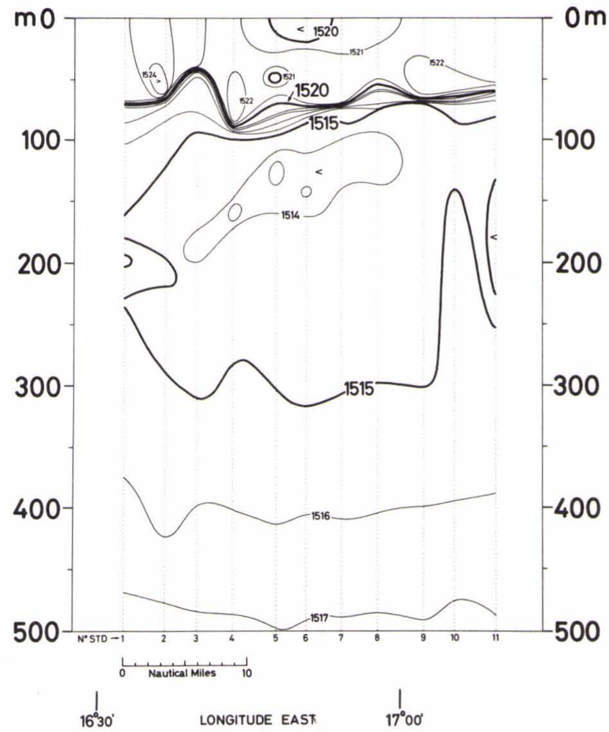


FIG. 5

STD SECTION I

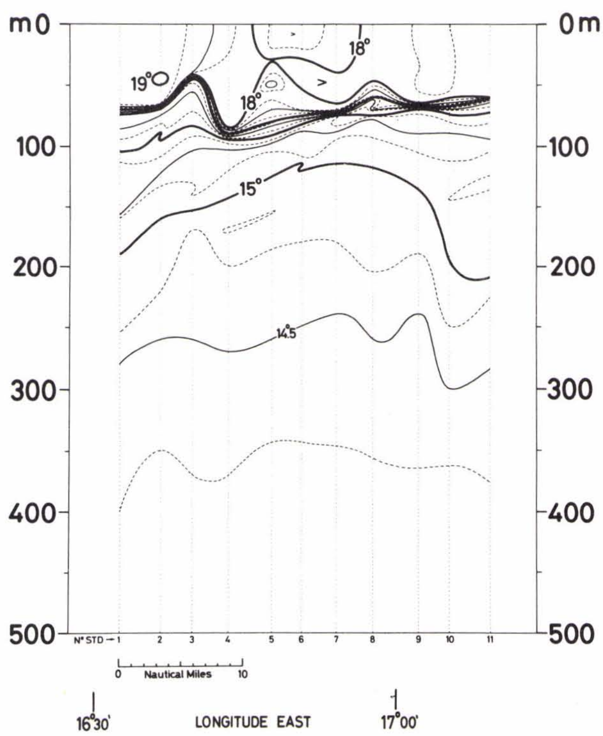


FIG. 6

STD SECTION I

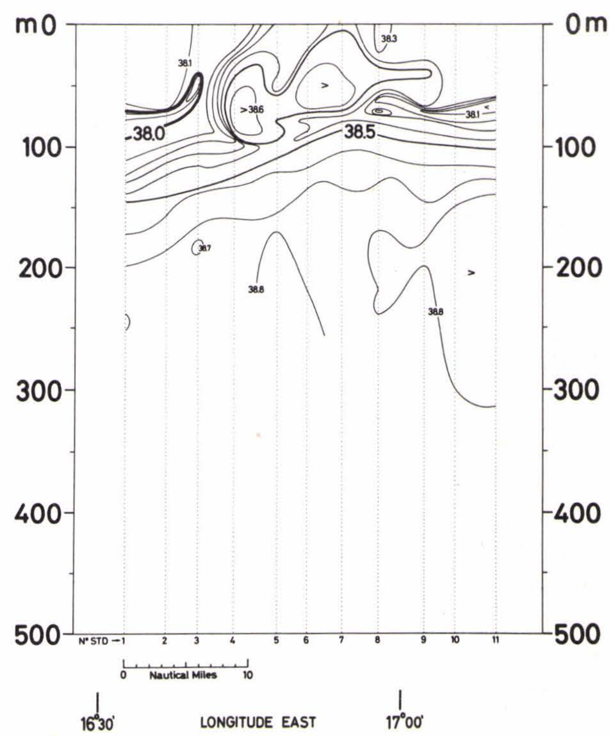


FIG. 7

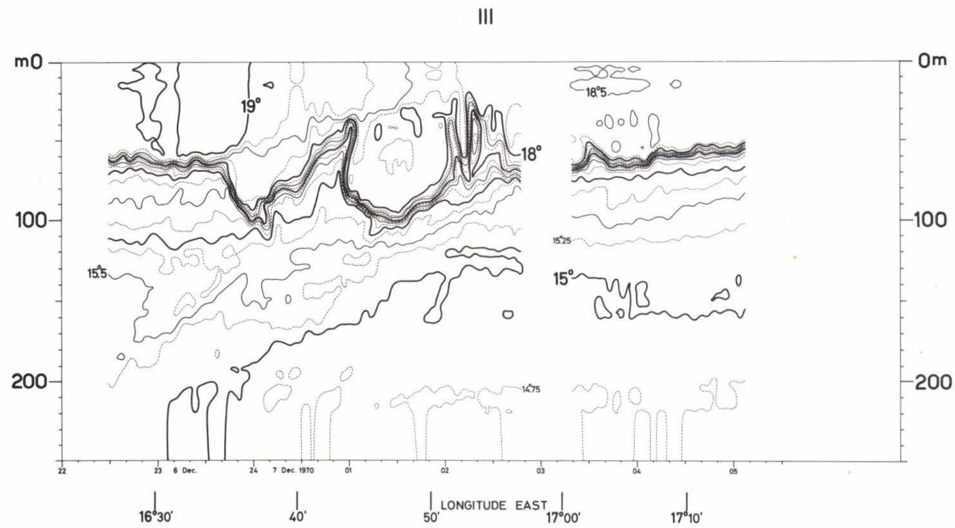


FIG. 8

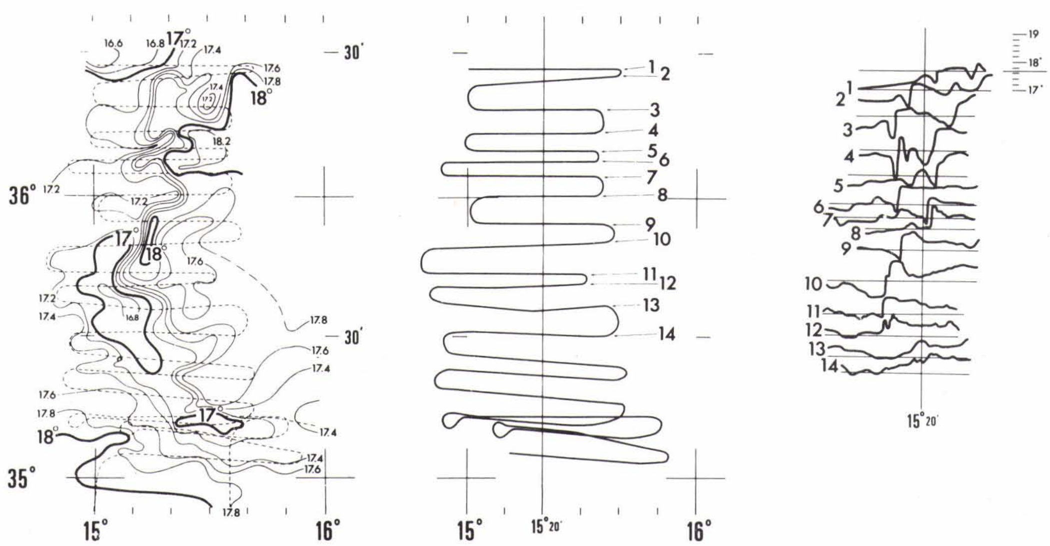


FIG. 9

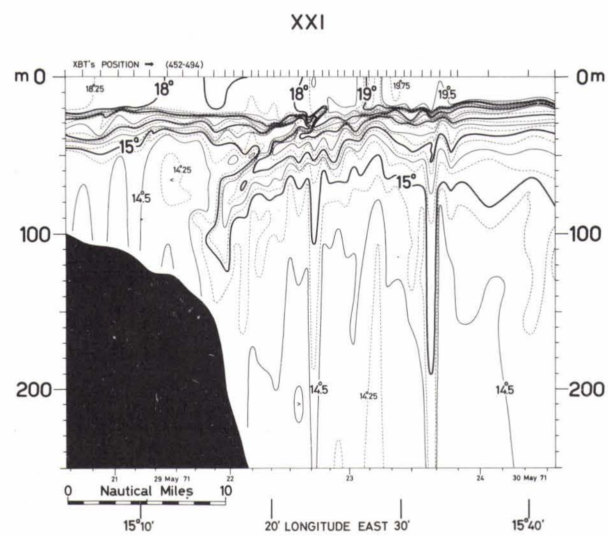


FIG. 10

SECTION A TEMPERATURE

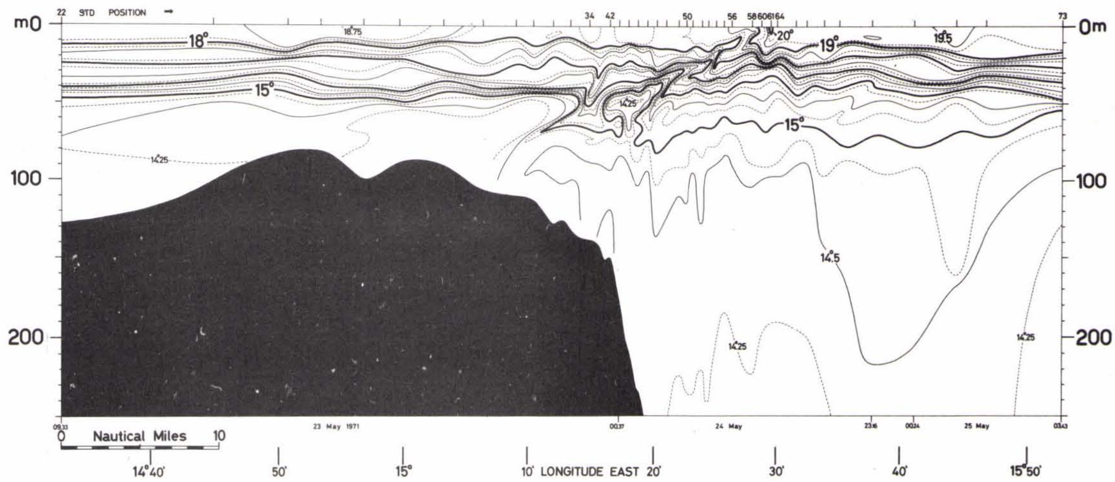


FIG. 11

SECTION A SALINITY

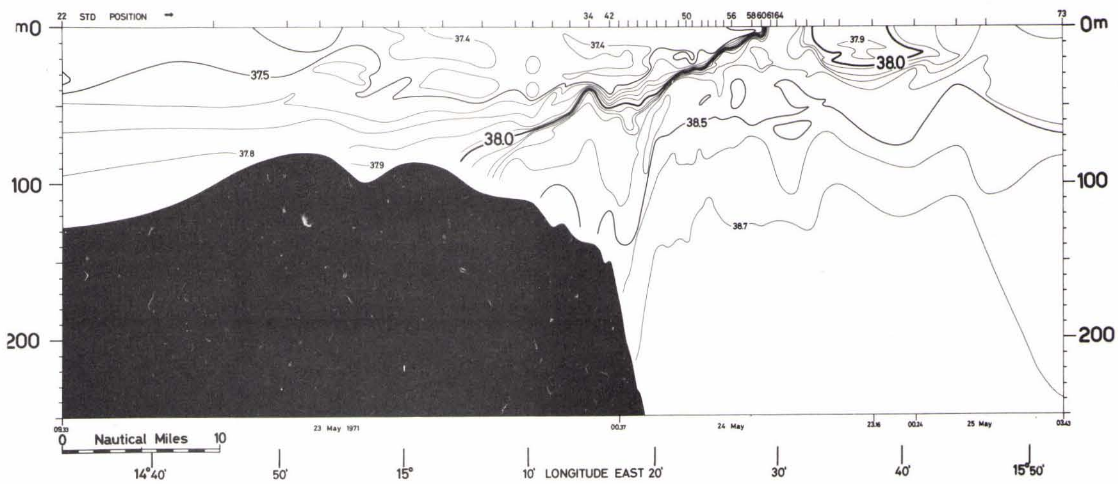


FIG. 12

SECTION A DENSITY

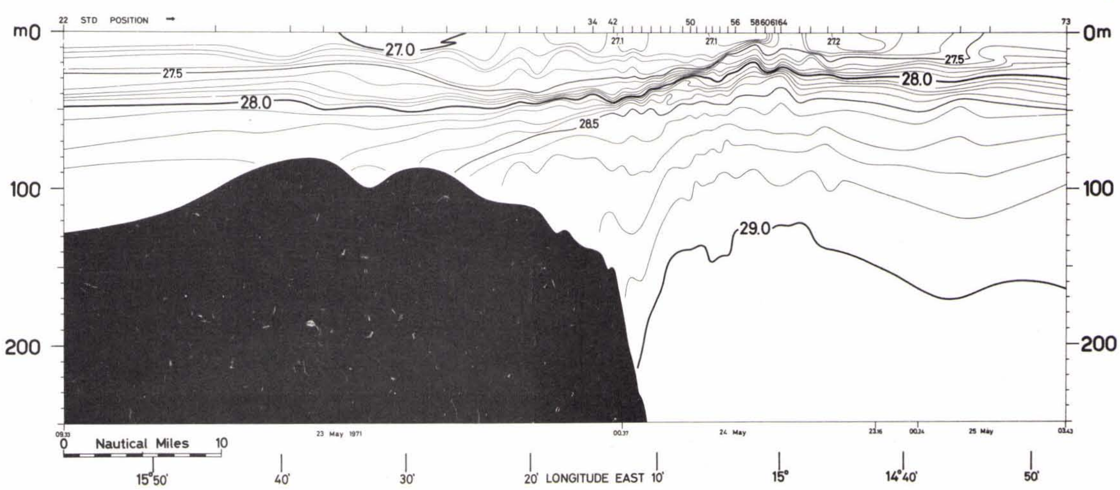


FIG. 13

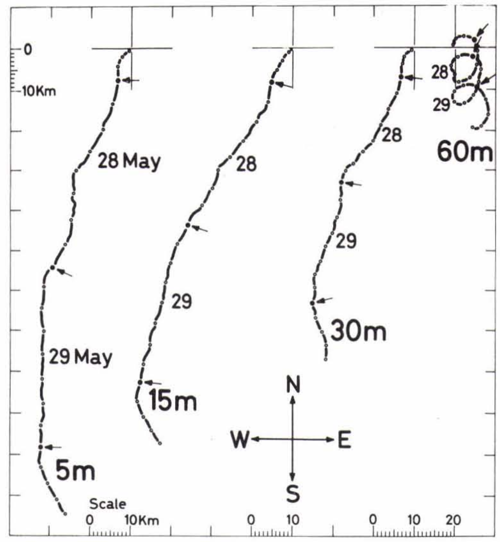


FIG. 14

SECTION I

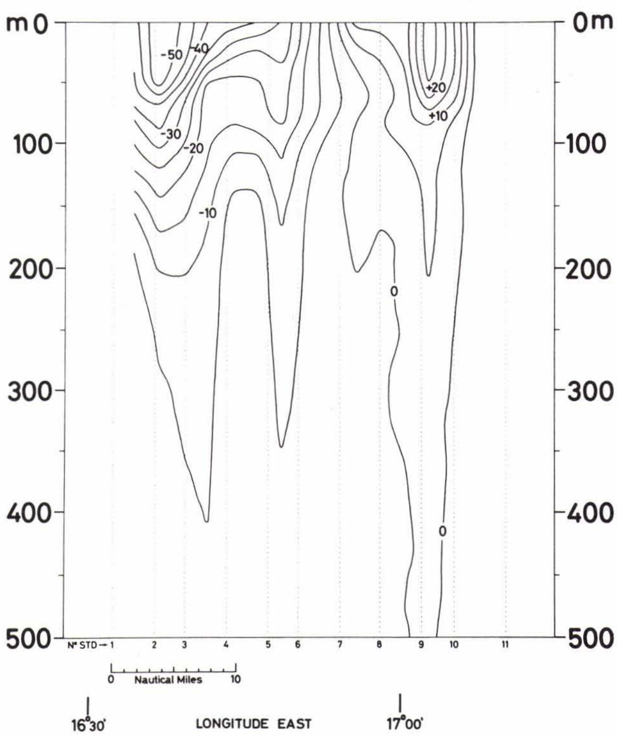


FIG. 15

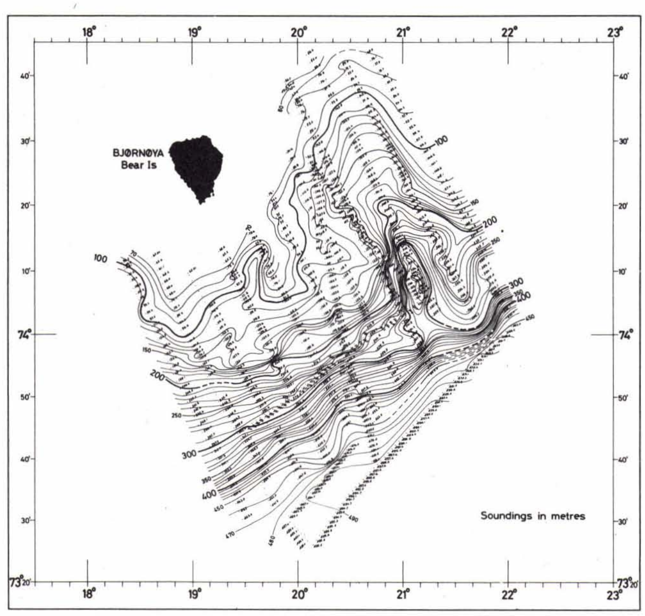


FIG. 16

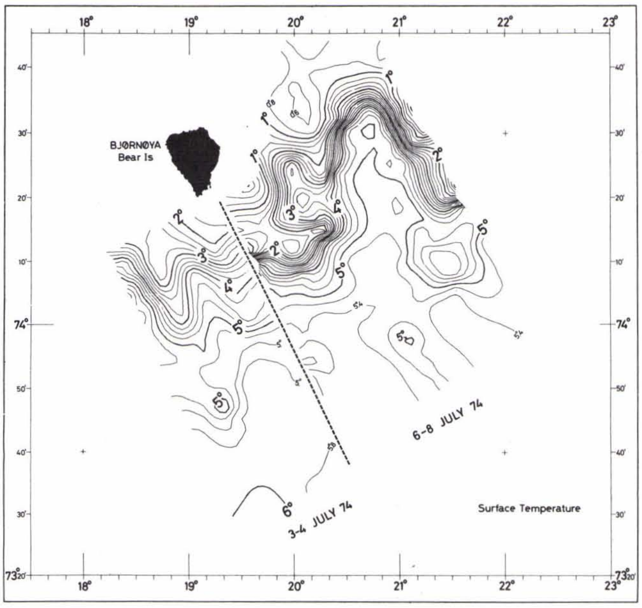


FIG. 17

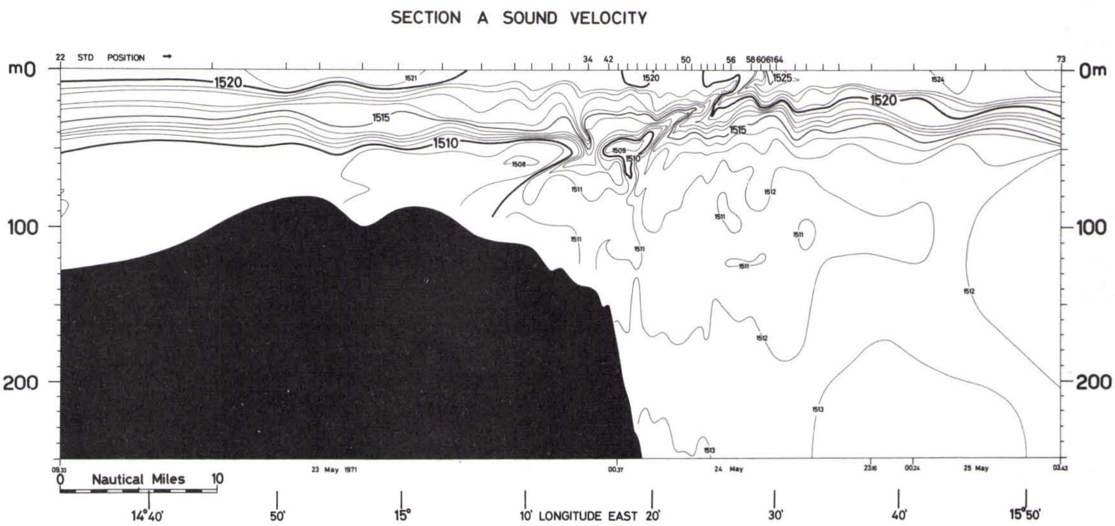


FIG. 18

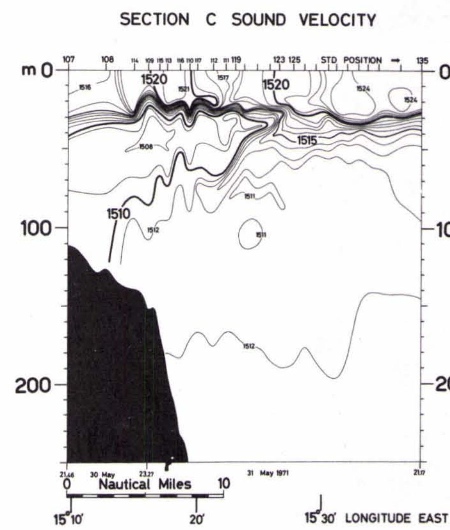


FIG. 19