OCEANIC LAYERED MICROSTRUCTURE AND FRONTS

by

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INTRODUCTION

This talk is divided into two parts: one deals with oceanic microstructure, with particular attention to the so-called "layered microstructure"; the other part is concerned with oceanic fronts. As an example of the latter I am going to describe in some detail a front east of Malta, which the Oceanography Group of this Centre is studying.

The intention of giving this paper in this Ray Tracing Conference is to remind you that the vertical profiles of temperature and salinity, and hence speed of sound, are not a continuous and smooth curve as a function of depth, but rather consist of a large number of nearly homogeneous layers separated with interfacial regions where strong gradients with values as high as 0.5°C/10 cm are present. The reported work on the front east of Malta will show you that very high horizontal gradients of the oceanographical parameters, and hence sound speed, are established, with values as high as 6 m/s over a horizontal distance of 1 km, when passing through the frontal region.

OCEANIC LAYERED MICROSTRUCTURE

The acousticians have been aware of thermal microstructure for about 20 years [see, for example, Refs. 1 & 2]. A recent review by Gostev and Shvachko [Ref. 3] on "random inhomogeneities of microstructure of temperature and sound velocity profiles" summarized the results of Russian investigations as well as mentioning some of the more important contributions from "western scientists". However the acousticians have paid more attention to the so-called "patch size" microstructure of temperature and speed of sound fields [see, for example, Refs. 2, 4, 5, 6, 7, 8] than to the layered microstructure. Indication of the layered microstructure, however, was reported by Piip [Ref. 9], who measured some detailed vertical speed-of-sound profiles in the Bermuda area. Figure 1 shows an example of one of these profiles. Actually two velocity meters are shown, one displaced 25 cm/s to the left. Thin layers, a few metres thick, of lower speed are seen in the main thermocline. Piip referred to these layers as "strange layers of water" and we shall see that this is what we today call layered microstructure.

The study of layered microstructure has only recently attracted the attention of physical oceanographers. Such investigations have been possible due to the invention of the STDV system, which continuously records temperature, salinity and speed of sound versus pressure, and to the specially designed free-falling microstructure probes. Observations with these instruments have shown that the vertical profiles of the oceanographical parameters are not smooth curves, as normally seen by traditional Nansen cast technique, but rather exhibit a number of both regular and irregular homogeneous layers with typical thickness of metres or less, separated by interfacial regions or transition zones where large gradients are present.

Figure 2 shows a typical example of layered microstructure in the thermocline observed east of Malta by Woods [Ref. 10] with a free-falling microstructure probe. Both temperature and the gradient between two thermistors separated by 25 cm in the vertical are recorded. The layering effect is clearly established in the thermocline. Separating the nearly isothermal layers, which are of the order of 2 m - 4 m thick, are interfacial region, or as Woods calls them "thermocline sheets", only 20 cm - 50 cm thick where changes of 0.2°C - 0.4°C occur.

The investigators who are studying microstructure experimentally can be divided into two main groups; one which is using commercially available STDV systems which have a vertical resolution of about 0.5 m - 1 m depending on the sea state, and the other using prototype free-falling microstructure probes, not available on the commercial market, with vertical resolution of a cm or less. This vertical resolution enables one to study the finest structure in the temperature field. In the "western world" the latter group is, for example, presented by Woods [Refs. 10 & 11], Woods and Wiley [Ref. 12], Cox et al [Ref. 13], Grant et al [Ref. 14] and Nasmyth [Ref. 15]. The papers by Stommel and Fedorov [Ref. 16], Cooper and Stommel [Ref. 17], Grafe and Gallagher [Ref. 18], Siedler [Ref. 19], Tait and Howe [Ref. 20], Howe and Tait [Ref. 21] are examples of the STDV group. A modified XBT system has also been used by Neal et al [Ref. 22] in studying microstructure in the Arctic ocean. However, in the light of the results from the first group it becomes clear that the STDV group only shows the larger scale layered microstructure, because of the limited vertical resolution of this type of measurement.

I am now going to show you some typical observations of layered microstructure from different ocean regions. Figure 3 shows a recent profile after Woods and Wiley [Ref. 12] east of Malta, however with increased vertical resolution when compared with the profile in Fig. 2. The gradient is now measured 10 cm apart, and we see that both the temperature trace and the gradient are somewhat more irregular than the previous figure. The interfacial region between the isothermal layers which was thought previously to consist of one "thermocline sheet" [Ref. 10], now appears to consist of several sheets, and the thickness of the nearly isothermal layers are of the order of 1 m - 2 m or less. Figure 4 shows a temperature and speed of sound profile for the same area obtained by an STDV instrument suspended from a ship (SACLANTCEN, unpublished observations) and the finer detail shown on Fig. 3 is not resolved. However, the layering effect is clearly established in the thermocline region, decreasing with increasing depth. It should again be emphasized that finer structure is present, but not resolved with this instrument.

The last three figures were all from the Mediterranean. Figure 5 shows some successive STD analogue traces in the upper part of the main thermocline from an area south of Bermuda in the Atlantic Ocean [Ref. 17]. The arrows indicate the direction of the probe, and it is seen that some details are lost when the probe is on its way up, caused by unequal exposure of the sensors in opposite directions. Rather regular, homogeneous layers about 5 m thick separated by transition regions of 10 m - 15 m where temperature and salinity (not shown) change by 0.3°C - 0.5°C and 0.04‰ - 0.10‰ respectively. From several STDV dips in the area it was generally found that about one hundred of these layers were "filling up" the main thermocline.

Observations from the Pacific [for example, Refs. 16, 18, 13, 15] show the existence of layered microstructure. Furthermore, large numbers of unpublished STDV observations held by different laboratories around the world show that the layered microstructure is a common phenomenon in the thermocline region.

However, rather few investigations deal in detail with the horizontal extent, variability and generation of layered microstructure. Some preliminary results show that the same layers can extend from a few hundred metres to tens of kilometres in the horizontal. Furthermore the layers move up and down with the internal waves which are always present in the thermocline region. Several mechanisms for the generation of layered microstructure have been proposed such as breaking internal waves, formation of layers at boundaries (such as an oceanic front) followed by spreading along density surfaces and a double diffusion process, also referred to as the "salt fingering" process. At present, however, the generation mechanism(s) is not fully understood.

So far I have been talking about the layered microstructure in the thermocline region (seasonal and permanent). However, even more regular and pronounced stepped structure has been established in the deep part of the ocean, well below the thermocline region.

Figure 6 shows such stepped structure in an area between Gibraltar and Madeira in the north east Atlantic [Ref. 20], located just below the intrusion of the high saline Mediterranean water. The thickness of the layers was of the order of 15 m - 30 m and changes across the interfaces between the layers were of the order of 0.25 °C and 0.044‰, respectively, for the temperature and salinity. Unfortunately no observations were made below 1500 m, but probably the layering will extend to larger depths. A more detailed study of the variability of the layers was performed in the same area by Howe and Tait [Ref. 21]. The upper part of Fig. 7 gives some results of the average thickness of the layers and the interfaces and also the changes in oceanographic parameters across the interfaces. The lower part of Fig. 7 shows the time variability at one location over a 33-hour period. It is clearly seen that the layers are taking part in the internal-wave oscillation. Spatial investigation showed that the layers extended for about 20 n.mi in the horizontal.

Similar deep stepped structure has been observed in the Tyrrhenian Sea by Owen S. Lee from NUC, San Diego (unpublished data). Figure 8 shows one of the STDV stations and the stepped structure starting to form just below the high saline Levantine water. In the upper part the layers are of the order of 15 m - 20 m thick, but increasing their thickness with increasing depth, to as much as 200 m between 1100 m and 1300 m. Below 1600 m - 2000 m the stepped structure is not clearly seen. Figure 9 shows a magnification of the profiles and the change, for example, in the speed of sound across the interfaces is of the order of 0.2 m/s to 0.4 m/s. (The profiles in Fig. 9 are slightly displaced vertically with respect to each other due to the crossing of the three pens on the recorder). Deep stepped structure has also been established west of the Strait of Sicily (Johannessen, unpublished data) as shown in Fig. 10, however, the structure is not as pronounced when compared with the two previous mentioned cases. All these profiles show that the stepped structure started to form below the region in the profile where maximum salinity occurred and where the temperature was decreasing, an oceanographic condition which favours the so-called "salt finger mechanism" which may be the reason for formation of the layers [Ref. 23]. Stepped structure of a similar kind has also been established in the Arctic Ocean [see Fig. 11 after Neal et al (Ref. 22)].

In summary one can say that this deep stepped structure has so far been established only in special areas, and it is by no means as common as the smaller scale layered microstructure in the thermocline region.

One can now ask the question: what is the acoustical effect when sound is propagated through the layered microstructure in the thermocline region? In order to get some qualitative understanding of this effect we (Johannessen and Mellberg, unpublished work) carried out a very simple-minded simulation experiment using ray tracing on profiles with and without microstructure and compared the results. Using the results from Cooper and Stommel [Ref. 17, Fig. 5], from the Bermuda area, we simplified a Bermuda profile as shown in Fig. 12. Layered microstructure was inserted in the main thermocline, using layer thickness of 5 m and transition zone of 10 m where the temperature changed by 0.3°C. For simplicity the salinity was held constant, which, however, is not the case in nature because similar steps also occur in the salinity profile. The ray tracing was carried out for source depths of 5 m, 125 m, 890 m and 1200 m. Comparing the results from the two profiles, no significant changes in the intensity contours (for example the 75 dB one) for the 5 m and 125 m source was established. However, for the source located in the microstructure region, significant changes occurred. Figure 13 shows that for the linear profile the 75 dB contours are smooth for all the ray families, but when microstructure is inserted [Fig. 14], no smooth intensity contour can be drawn for the vertexing rays. Similar results were obtained for the source at 1200 m, below the microstructure. We also performed a similar simulation experiment on some real observed microstructure profile in the Mediterranean and compared it with the result when smoothing on the same profile was done. Again only the vertexing rays were significantly affected. Thus it seems that the layered microstructure has the effect of "scattering" the sound in the vertexing regions.

OCEANIC FRONTS

Oceanic fronts in general develop in areas where two or more water masses meet. When passing through a frontal zone one will observe a strong horizontal discontinuity in the oceanographic parameters. Typical horizontal changes in the few upper metres of the ocean are of the order of 0.5°C - 1.5°C in temperature, 0.5‰ - 1‰ in salinity and 1 m/s - 2 m/s in the speed of sound over 1 n.mi - 2 n.mi distance. However, at the deep level in the thermocline region, the horizontal changes are much larger when crossing a frontal region.

Oceanic fronts have, for example, been studied in the Atlantic by Voorhis and Hersey [Ref. 24], Voorhis [Ref. 25] and Katz [Ref. 26], by Cromwell and Reid [Ref. 27], Knauss [Ref. 28], Wooster [Ref. 29], LaFond and LaFond [Ref. 30] in the Pacific and by Woods and Watson [Ref. 31] in the Mediterranean. Laevastu and LaFond [Ref. 32] studied the surface location of the frontal areas for the northern hemisphere and Fig. 15 (after Laevastu and LaFond) shows that large areas, say 25%-30% of the ocean are covered with frontal regions.

Woods and Watson [Ref. 31] had previously reported on a frontal study east of Malta in shallow water during the summer, however, our first study [Johannessen, Good and Smallenberger, (unpublished work)] was carried out in deep water in the Ionian Sea during December 1970 jointly with the Oceanography Group of NUC, San Diego. Figure 16 shows the cruise track of the US SP LEE and the shaded line indicates the location of the front. The NUC thermistor chain was used, sampling temperature at 45 levels down to 230 m for every 37 m in the horizontal. Figure 17, which is a copy of the analogue output of the recording unit of the thermistor chain, shows the depth variation of each degree isotherm for a section perpendicular to the front. The thermocline is dramatically affected and entirely folded in the frontal region. The temperature structure is at least influenced by the front in the upper 230 m and it is seen that warmer water is located on the western side of the front. Figure 18 shows a section through the same area a few days later. The western edge of the front where the folding of the isotherms occurs has not moved more than 1 n.mi - 2 n.mi, however, the internal structure of the front has changed dramatically. In addition to the folding of the isotherms in the western part, the thermocline shows a "spiking" feature further east indicating upwelling. The thermocline is furthermore distorted for about 20 n.mi - 25 n.mi in the horizontal. Figure 19 presents the vertical profile for the same section as Fig. 18. The profiles are plotted for every 2/3 of a nautical mile. The lower part of the figure shows a magnification of the central part of the section with profiles given every 270 m. A large number of the vertical profiles show strong inversion, which is one of the typical characteristics of a frontal region. Figure 20 gives the horizontal temperature variation at three typical levels. As pointed out earlier, the largest variations or the strongest discontinuity is found at sub-surface levels, clearly illustrated in the figure. The calculated speed of sound field is shown in Fig. 21. Studying the figure in detail, horizontal changes can be seen to amount to as much as 6 m/s over less than 1 n.mi in the thermocline region.

In a recent study during the summer, Johannessen et al [Ref. 33] found that the frontal system had propagated from the deep water into the shallow water. Figure 22 shows the surface salinity, and that north of 35°30' the salinity changes rapidly from 37.40‰ to more than 38.0‰ along longitude 15°20' east, clearly indicating the frontal surface boundary. It appears that the front has been broken up by the east flowing surface Atlantic water, indicated by a region of low salinity water. Typical horizontal variation of the surface temperature is shown on Fig. 23 when passing through the front (perpendicular) along latitude 36° north. The slight minimum temperature region located just west of the strong temperature discontinuity, indicates that upwelling is present. A typical STDV station for the same area is shown in Fig. 24. The inversion is located at 40 m depth with more than 1°C in temperature and about 5 m/s for the speed of sound. The two principal water masses also stand out clearly from the salinity profile.

In summary, oceanic fronts cover a large area of the world's oceans, and in general the features shown in Figs. 23 and 24 with, respectively, a strong horizontal discontinuity in the surface layer and inversions in the thermocline region are characteristic of a frontal zone.

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DISCUSSION

In response to a question the author said that ray tracing had been performed through fronts, by Allan and Gerrebout of SACLANTCEN using the range-dependent ray-tracing facility at the Fleet Numerical Weather Central, Monterey, California.

Some discussion ensued concerning the use of ray tracing through fronts, when the results are available only well after the event. However, most people seemed to feel that such tracings were useful in anticipating the effect of similar events, and indeed were of operational significance.

It was noted that there were many examples in the past of oceanographers rejecting the evidence of layered microstructure as an artifact.

Asked about the scale size of the fronts, the author described them as being of the order of 20 n.mi across and hundreds of n.mi long; though further investigation was needed to reveal their true extent.

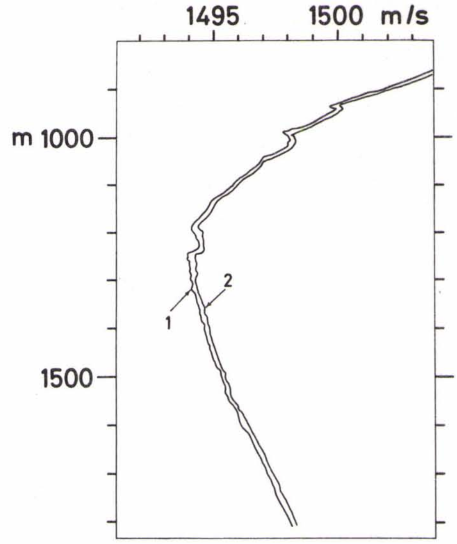
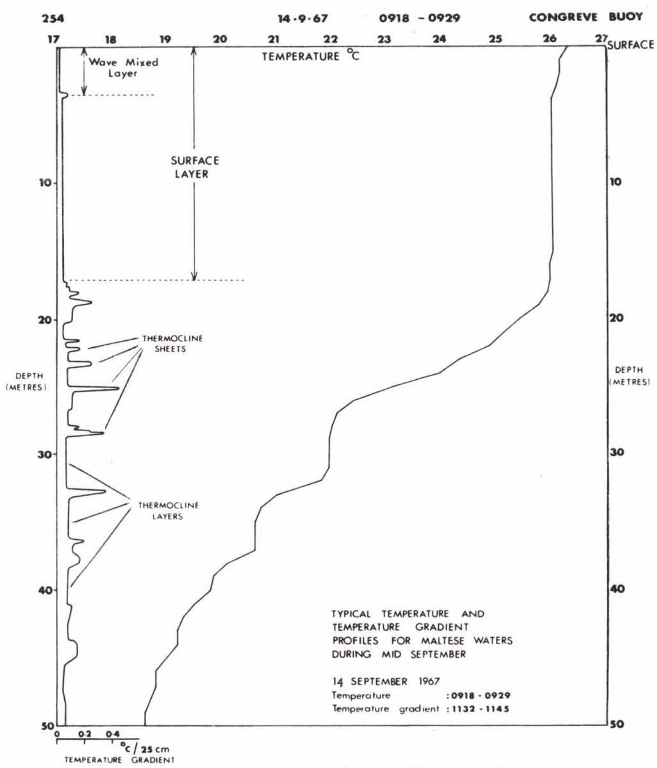


FIG. 1



A typical sounding through the summer thermocline off Malta during mid September

FIG. 2

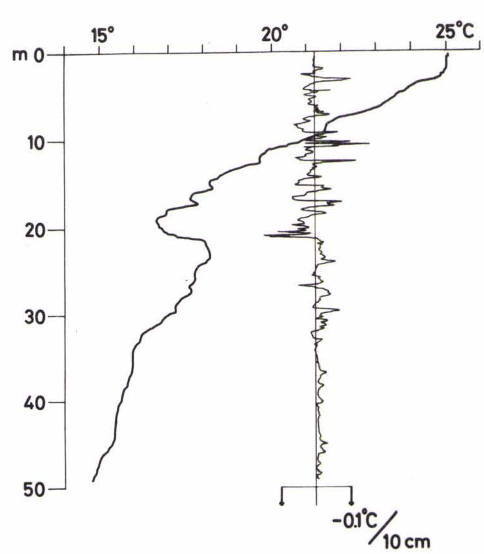


FIG. 3

FIG. 4

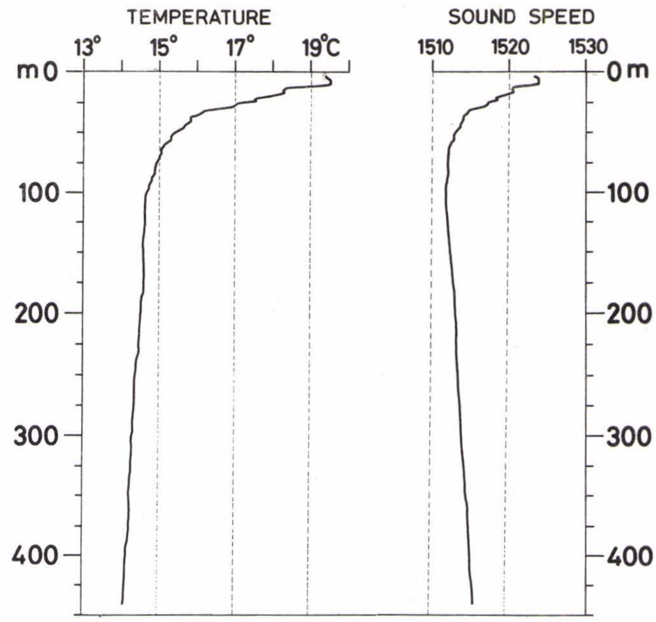


FIG. 5

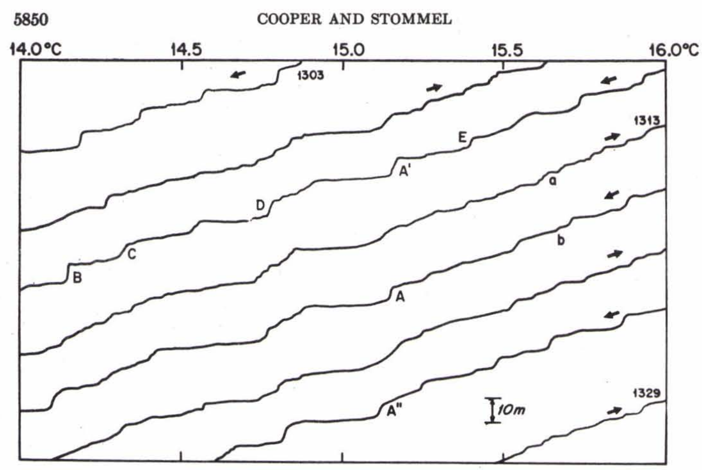
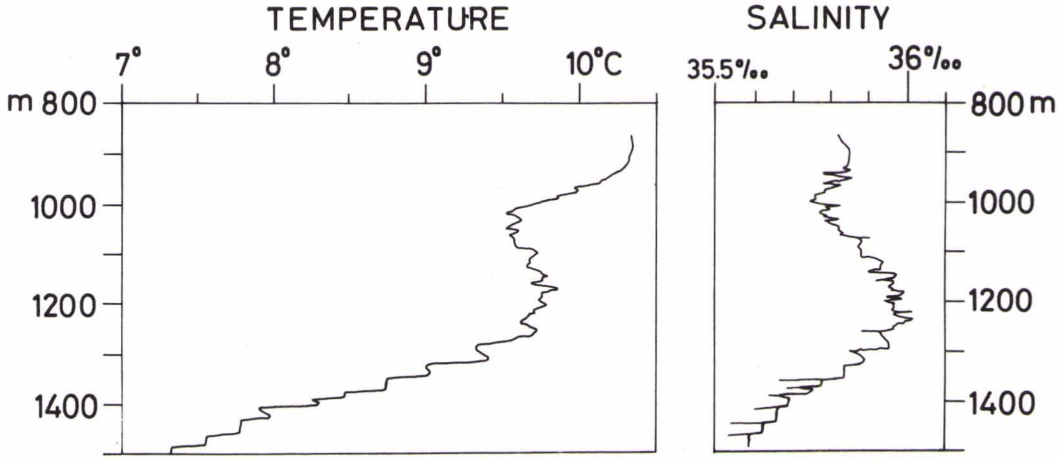


FIG. 6



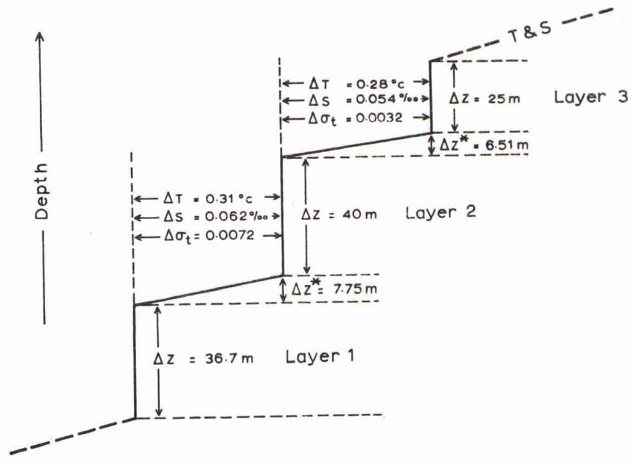
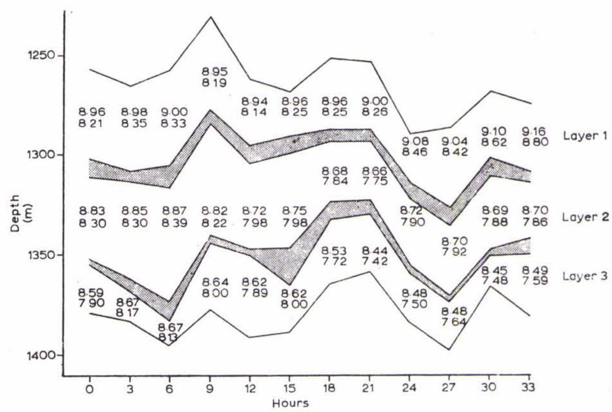


FIG. 7

Average parameters for the 3 layers considered in the analysis, computed from 33-hr of observation at a single station.



Depth variations of the layer system for Series A. Shading denotes interfaces and mean values of T and S within each layer also shown (S to three decimals after 35‰).

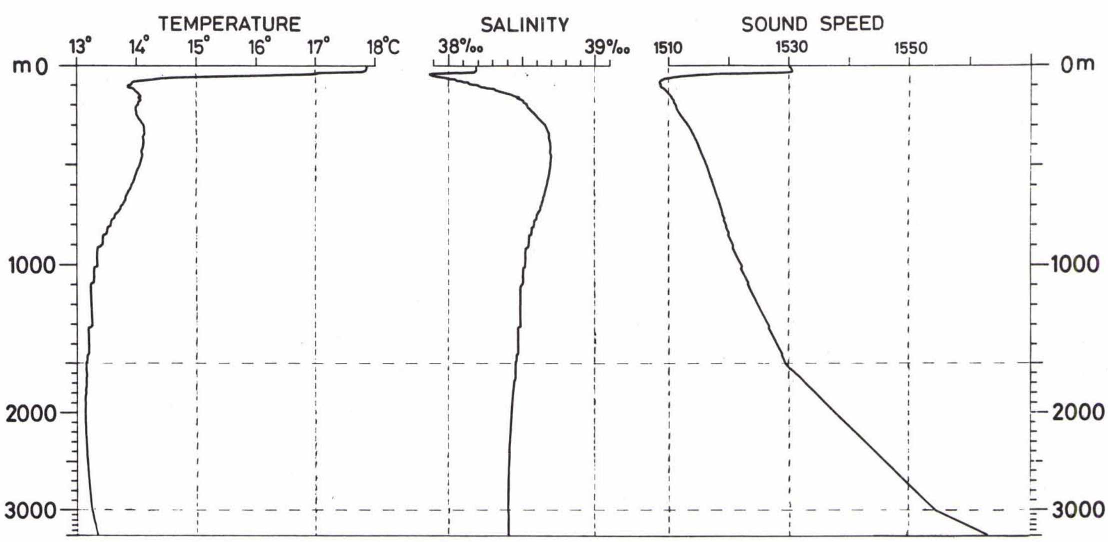


FIG. 8

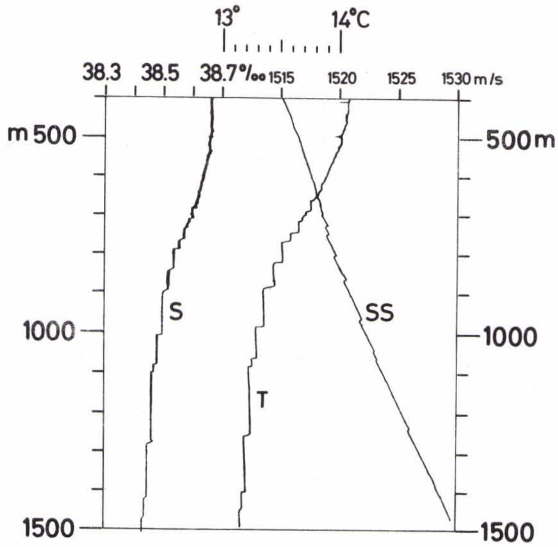


FIG. 9

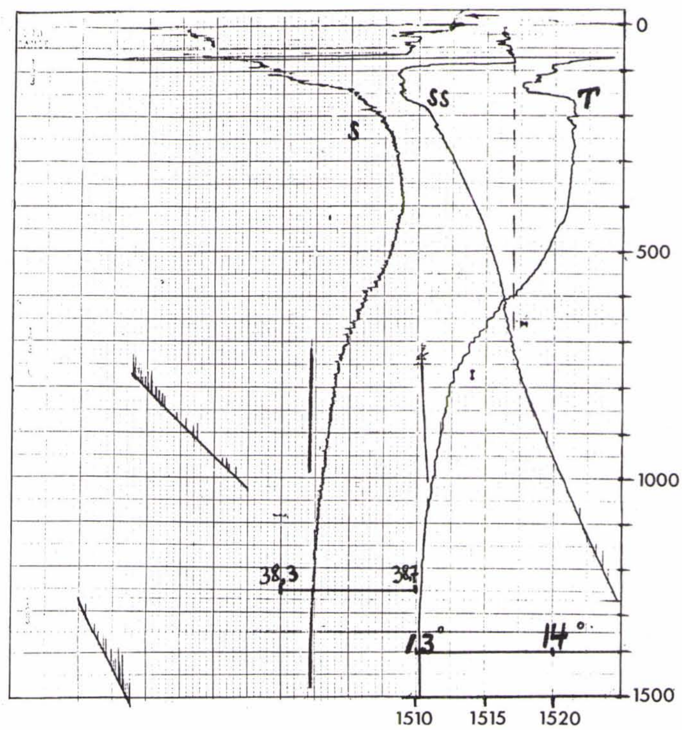
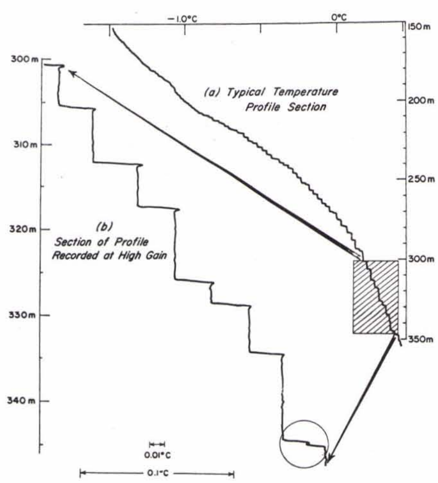


FIG. 10



Vertical profile of temperature under T-3 (84°38'N, 128°21.6'W, 19 March 1969). Shaded section of profile (a) shown as observed in profile (b) to left.

FIG. 11

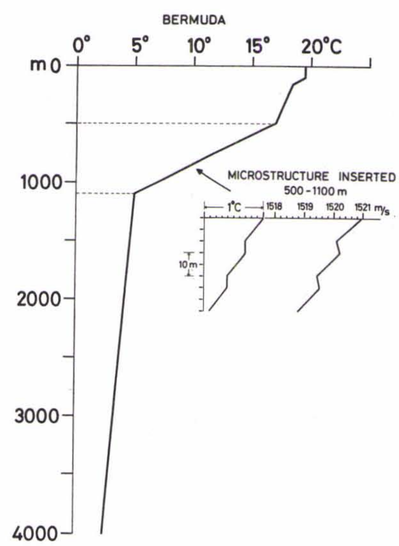


FIG. 12

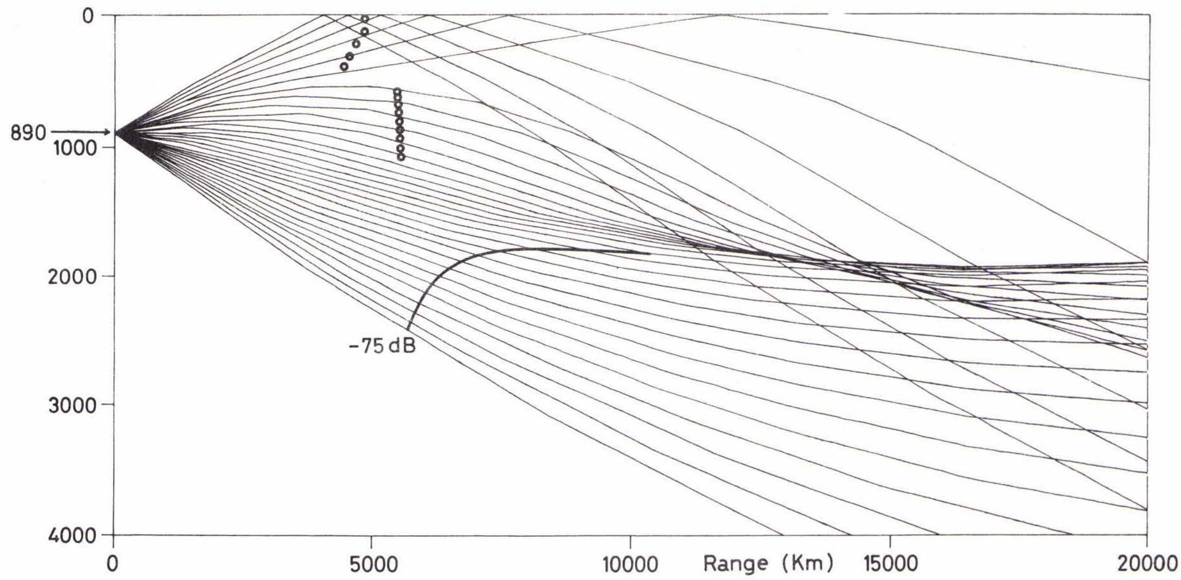


FIG. 13

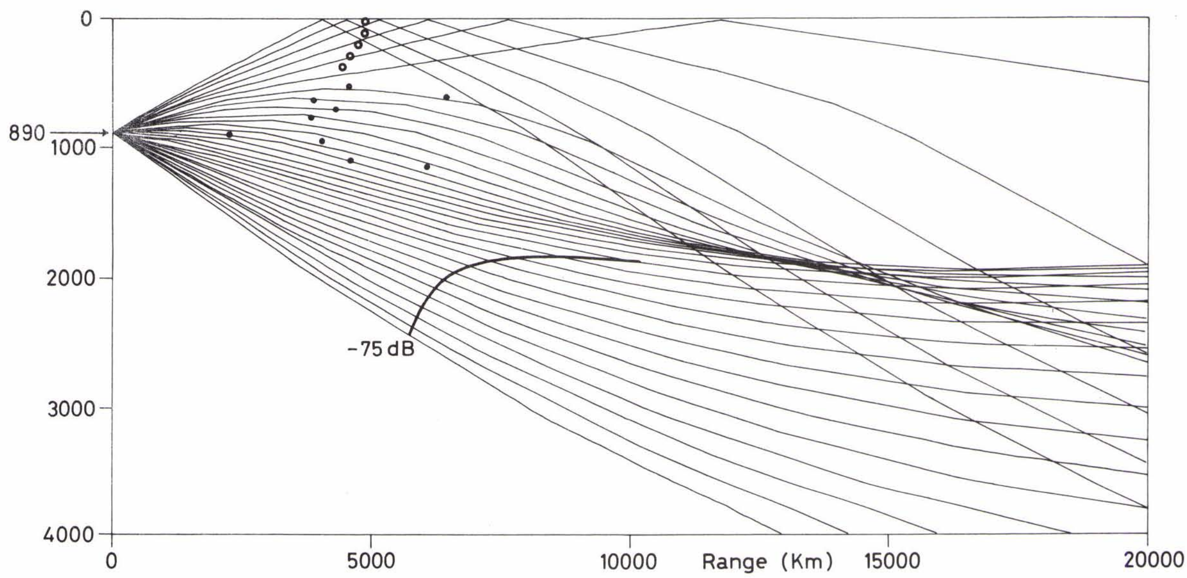
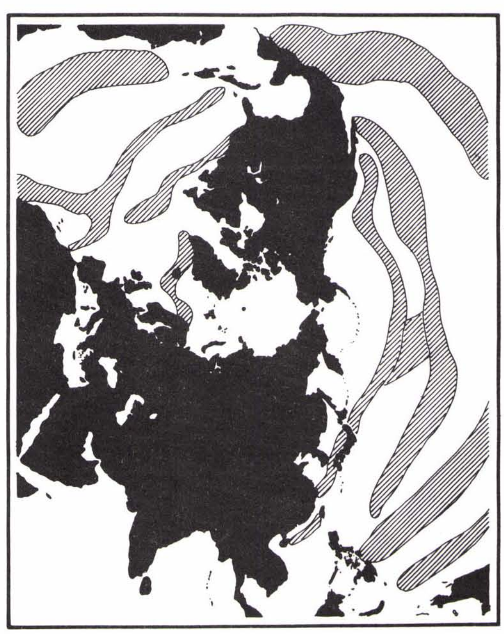


FIG. 14

FIG. 15



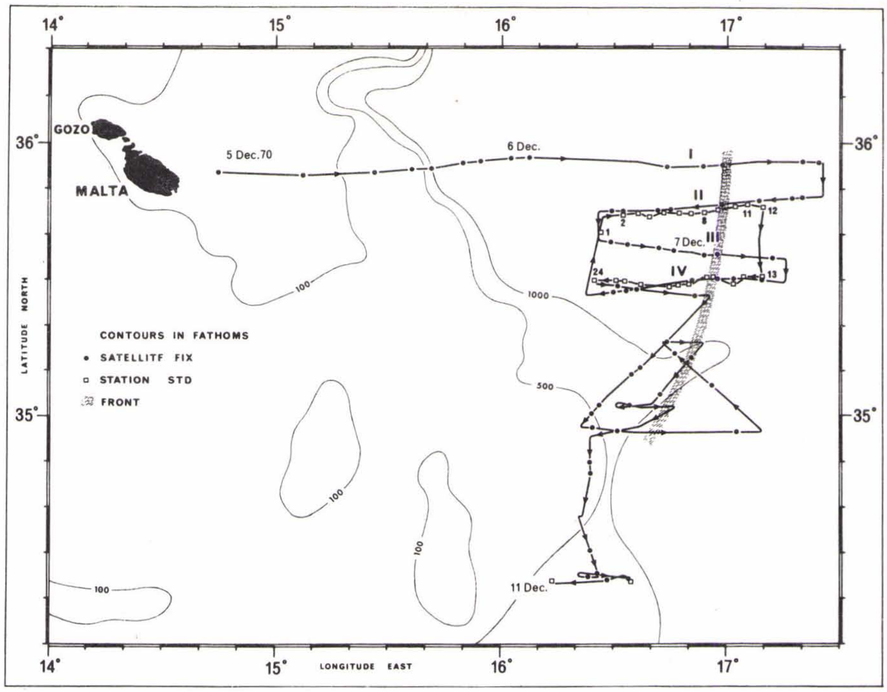


FIG. 16

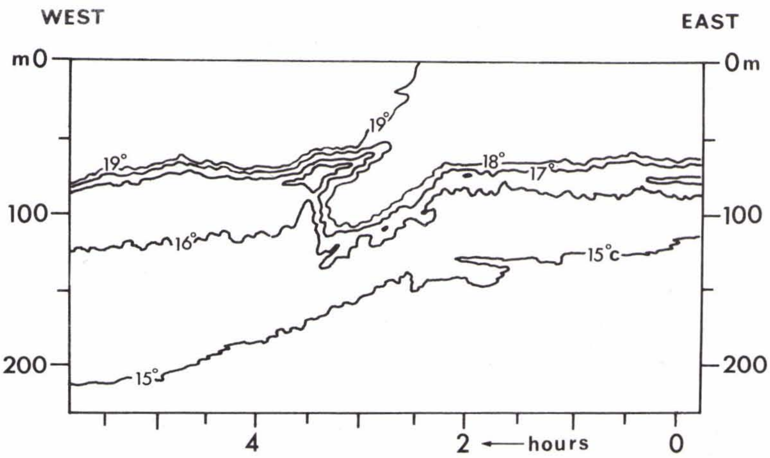


FIG. 17

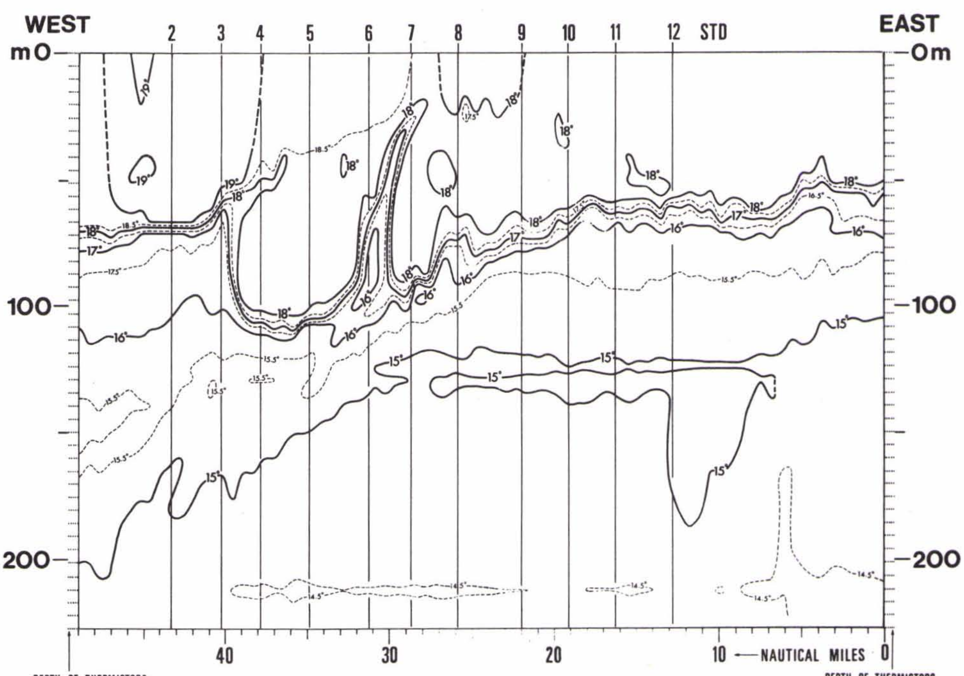


FIG. 18

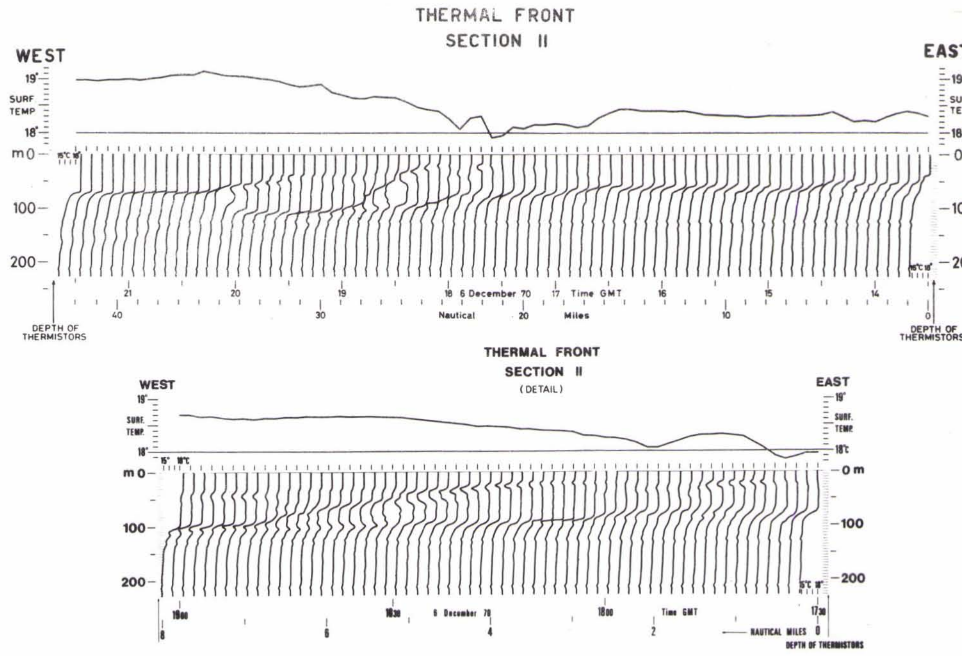


FIG. 19

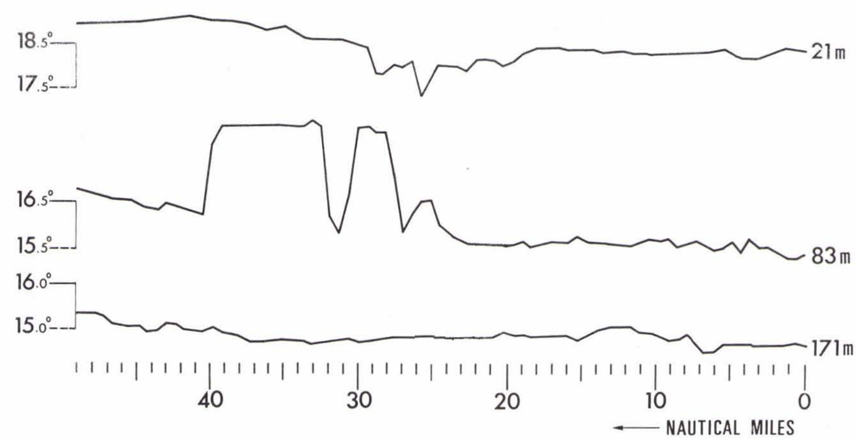


FIG. 20

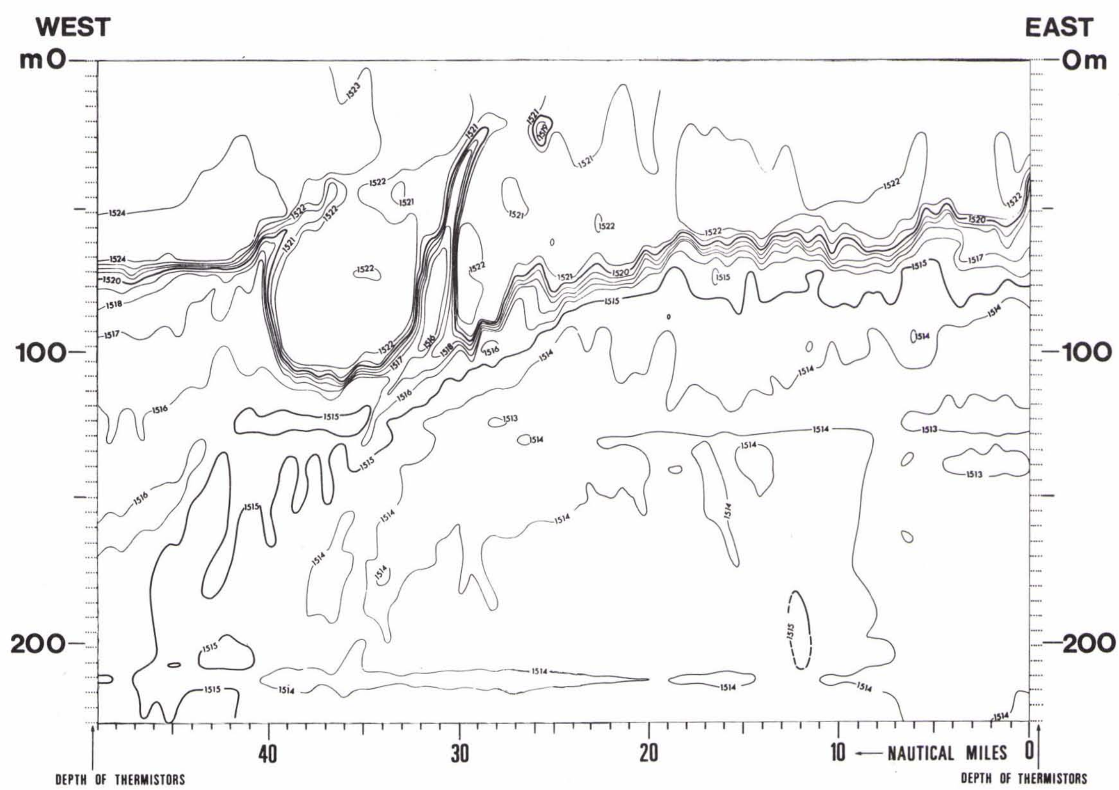


FIG. 21

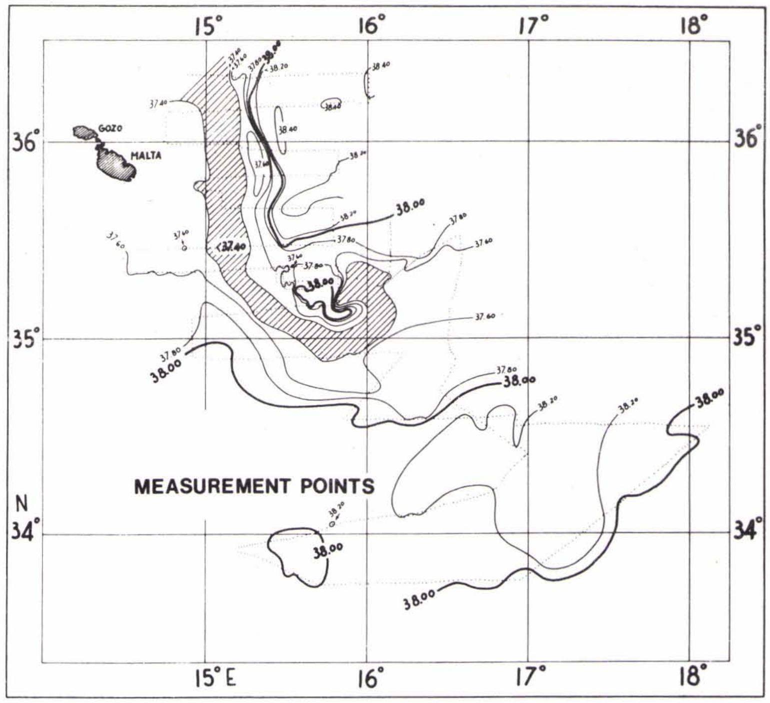


FIG. 22

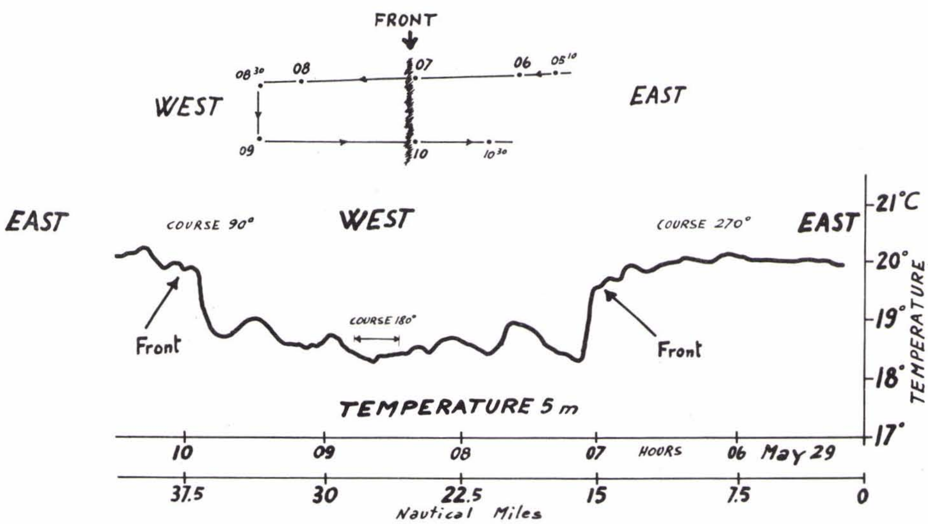


FIG. 23

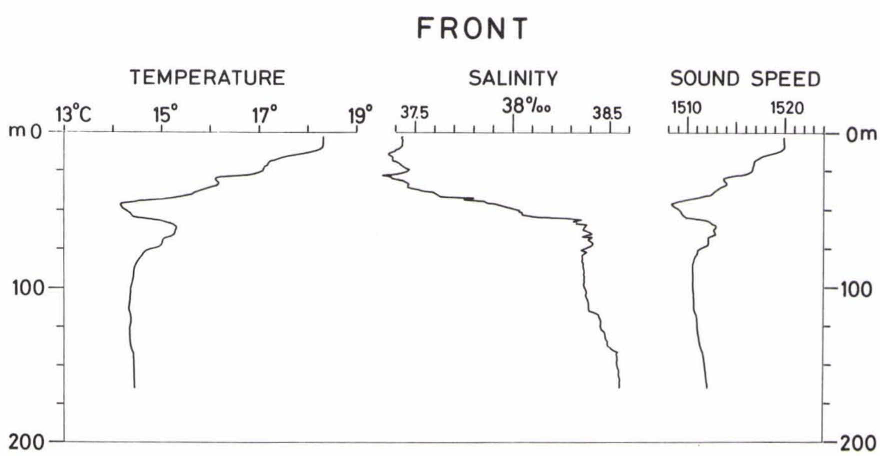


FIG. 24