THE STRUCTURE OF FRONTS IN THE SEASONAL THERMOCLINE

by

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INTRODUCTION

Some years ago, when the first continuous profiling temperature-salinity-depth probes came available it was discovered that the thermocline had a layered structure. The thickness of these layers was a few metres and individual layers could be traced for some kilometres to tens of kilometres. The layers were separated by much thinner interfaces, typified by temperature, salinity, density and velocity gradients significantly stronger than are found in the adjacent layers.

In a recent paper [Ref. 1] we have described the results of detailed measurements of the interfaces between layers (we call the interfaces "sheets" since they are effectively vortex sheets) and we have proposed a model for the diffusion of these interfaces by intermittent billow turbulence. In that paper we pointed out that the patches of turbulence which occur in the thermocline (occupying a few percent of the volume at any instant; the remainder of the flow being laminar) do not achieve a vertical heat transport through the thermocline in the classic implied by the use of eddy diffusivity, but that their sole achievement was to "fray the edges of the layers". In order to understand the mechanism of heat transport through the thermocline it was necessary to understand how layers were formed. This need provided the motivation for the investigation of fronts to be described in my paper. The idea underlying the search for fronts in the thermocline was that at a front two quite dissimilar water masses lie in close proximity and that nature, by some at that stage unknown process, might cause the water of the two water masses to intrude one into the other. Such intrusion would, we imagined, take the form of layers of the kind we knew to be common in the thermocline.

Experimental Method

The method used in our investigation of fronts off Malta has been described in a paper by Woods and Watson [Ref. 2]. It may be summarized briefly as follows.

Firstly we fly over the selected area, searching for the surface outcrop of a front, which shows up on the airborne radiation thermometer (ART) as a sharp step in the sea surface temperature. This surface outcrop may have been displaced some kilometres from the underlying frontal surface by wind action, so the aircraft report may only tell us the general area in which to search for a front.

Next the boat drops a trial pattern of XBTs to discover the location of the internal frontal surface, its orientation and slope. Then the boat drops a pattern of XBTs along a series of sections designed to pass parallel and orthogonal to the mean orientation of the front. Finally the boat makes a series of STD or microstructure soundings at chosen locations in the front.

The aim of using XBTs is to achieve a rapid survey of the broad features of the frontal structure before embarking on the very slow process of STD or microstructure measurements. We avoid making the latter measurements in unsurveyed water since they are of little value except when studied in the context of the frontal structure as a whole.

The isotherm sections drawn up from the XBT measurements are related to simple descriptive models of fronts, usually either an inclined plane or a wavy inclined plane. When the orientations of the sections turn out not to have been (as we had planned) parallel and orthogonal to the front we find that it is necessary to use a computer to assist in the fitting process.

Geostrophic Balance

The classic analysis of a front in the ocean [see, for example, Ref. 3] shows it as an inclined plane separating two uniform water masses without convergence (and hence no frontogenesis) but with geostrophic balance, expressed in terms of Margules's equation

$$\tan \alpha = \frac{2f \Delta U}{g \Delta \rho} .$$

As described by Ref. 2 we have been able to confirm that the fronts we studied off Malta do obey Margules's equation to the limit of our experimental accuracy, so we conclude that the fronts are in essentially geostrophic balance and that they may therefore be compared with similar fronts in the atmosphere.

Nevertheless, we shall show that the ageostrophic effects of fronts, studies theoretically by, for example, Hoskins [Ref. 4] are as important to the dynamics of thermocline fronts as they are for fronts in the atmosphere. Hoskins finds that it is impossible to describe the formation of fronts (frontogenisis) and their vertical circulation without considering these ageostrophic effects. It is the latter aspect (vertical motion) that I wish to discuss in this paper, since I now believe that the vertical transport through the thermocline is achieved to a significant extent by vertical advection (upwelling and downwelling) along the sloping surfaces of fronts. These up and downwelling motions are an inevitable consequence of the processes of frontogenesis and are therefore likely to be a universal feature of fronts in the ocean. The vertical motions are expected to appear in sections through fronts as tongues of deep water displaced upwards along the frontal surface and tongues of relatively shallow water displaced downwards. In the simplest theoretical model of a front the displacements of these tongues of up- and downwelling water would be similar; the vertical circulation would be symmetrical. But when we examine our sections through fronts in the seasonal thermocline off Malta we find that usually either the upward tongue has a much greater displacement that the downward tongue, or vice versa. The relative strengths of the up- and downwelling tongues appear to be different within a few kilometres on the same front at the same time. Why is this? Are there any other structural features of the fronts that also lead to fluctuations over the same sort of distance?

Waves of the Fronts

The solution to these questions appears to be provided by waves on the fronts. Our ART surveys of the sea surface temperature in the vicinity of fronts reveal waves on the fronts with wavelengths of the order of 10 km and peak-to-peak amplitudes of about half the wavelength. The corresponding horizontal sections below the sea surface derived from XBT measurements do not have the same resolution as the ART measurements, but they are consistent with the conclusion that the waves are simple displacements of the front as a whole, as shown schematically in Fig. 1.

Model of Up- and Downwelling on Wavy Fronts

The similarity between the wavelengths of the frontal waves and of the variation in up- and downwelling along the front leads to the hypothesis that the two phenomena are associated. Waves on atmospheric fronts lead to similar variation in the vertical motions and a simple consideration of the distribution of convergences in such waves leads us to expect enhanced downwelling at the wave crest (where the front waves towards the denser water mass) and enhanced upwelling at the wave trough, as shown in Fig. 2.

Experimental Evidence for the Model

In order to test our model of vertical circulation on wavy fronts we made a series of orthogonal XBT sections. Two examples are shown in Figs. 3 and 4. In Fig. 3 the section orthogonal to the front shows a strong upwelling lobe which is particularly prominent at about 16°C; this lobe is intersected by the section parallel to the front, where we see that it is some three kilometres wide (at 16°C) and about 6 metres thick. There is some indication of a second upwelling lobe at approximately 10 km to the left of the main one; perhaps it does not show up so clearly because the section is not perfectly aligned with the mean orientation of the front. In the second example [Fig. 4], there are two sections aligned at right angles to the front, and we clearly see the two upwelling lobes running along the direction of these sections. These lobes are cut by the third section which is aligned parallel with the front's mean orientation. In fact, the two examples presented in Figs. 3 and 4 were obtained on successive days in the same area and it is quite probable, when we allow for the weak mean southward drift that we observed in this area during our measurements, that the same features were being observed on the two days. If this is the case, then the lobes may be considered rather slowly changing features of the fronts. If one were to follow a water particle as it moves along parallel to the frontal surface we would see it follow a switchback motion as it rose up and down in successive upward and downward lobes. If the water particle is mixed into the surrounding water by a turbulence event when it is displaced vertically from its mean level, then a vertical transfer of mass will have resulted and hence a vertical heat transport. Thus the up- and downwelling on wavy fronts (which achieve far greater vertical displacements than do non-wavy fronts) produces a vertical heat flux by vertical advection plus local mixing.

The lobes, which have thicknesses of a few metres, widths of a few kilometres and lengths of ten or more kilometres are examples of thermocline layers.

ACKNOWLEDGEMENTS

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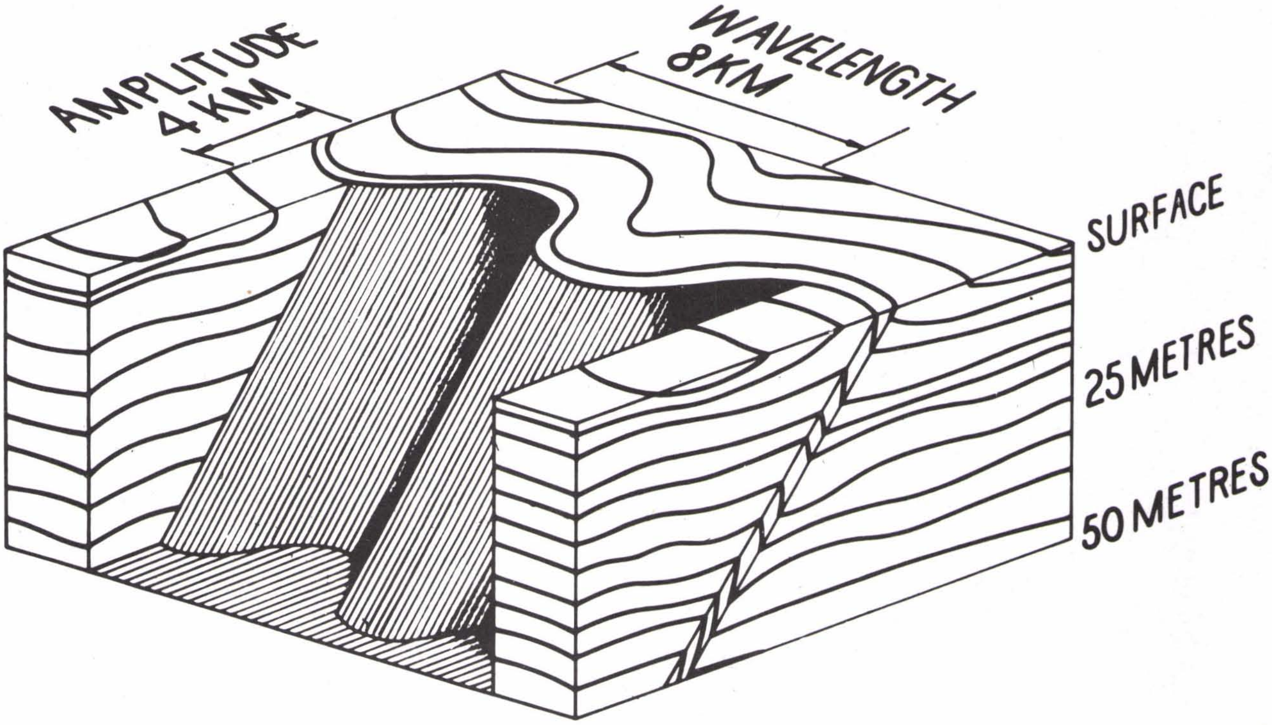
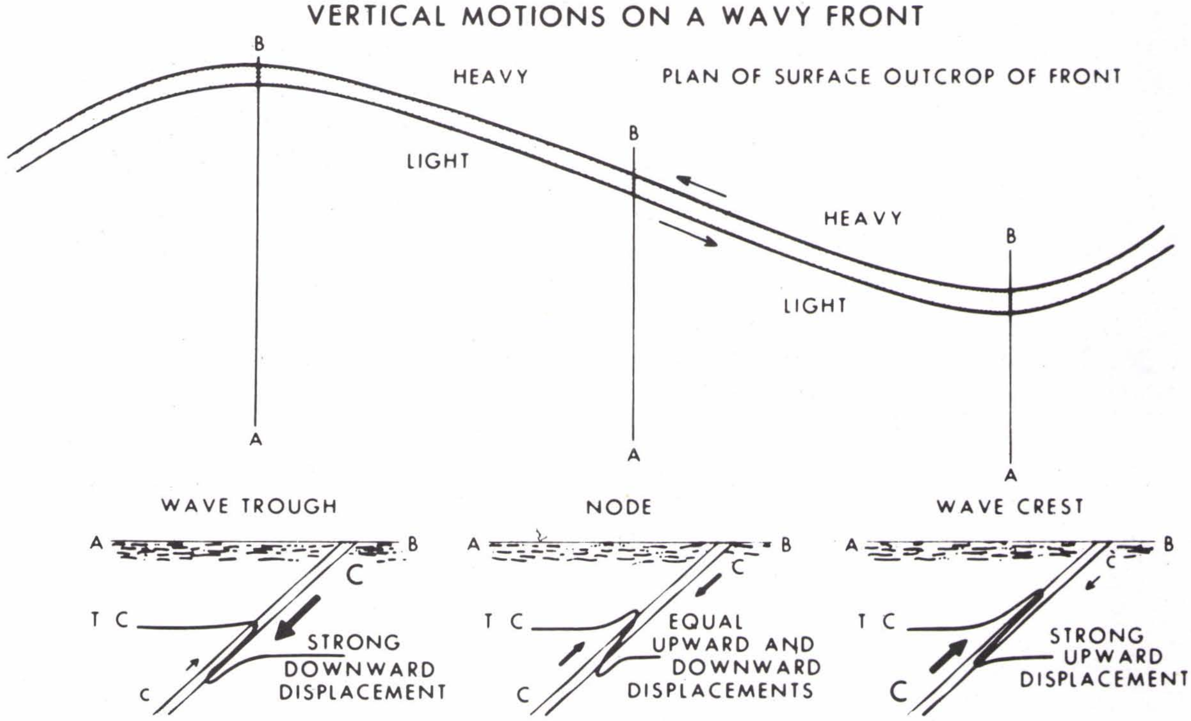


WAVES ON A FRONT IN THE THERMOCLINE

FIG. 1

VERTICAL MOTIONS ON A WAVY FRONT



VERTICAL SECTIONS THROUGH FRONT

FIG. 2

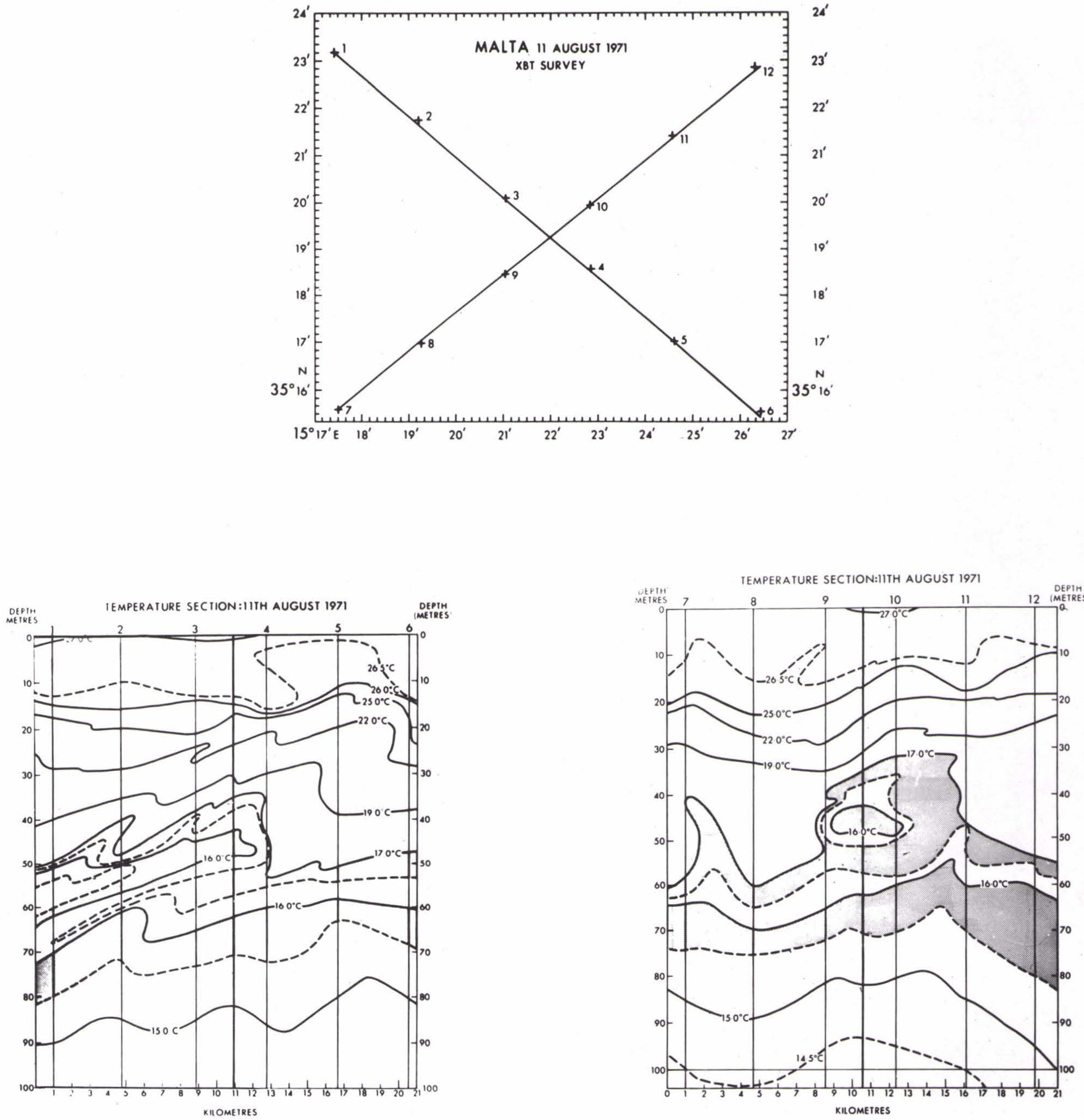
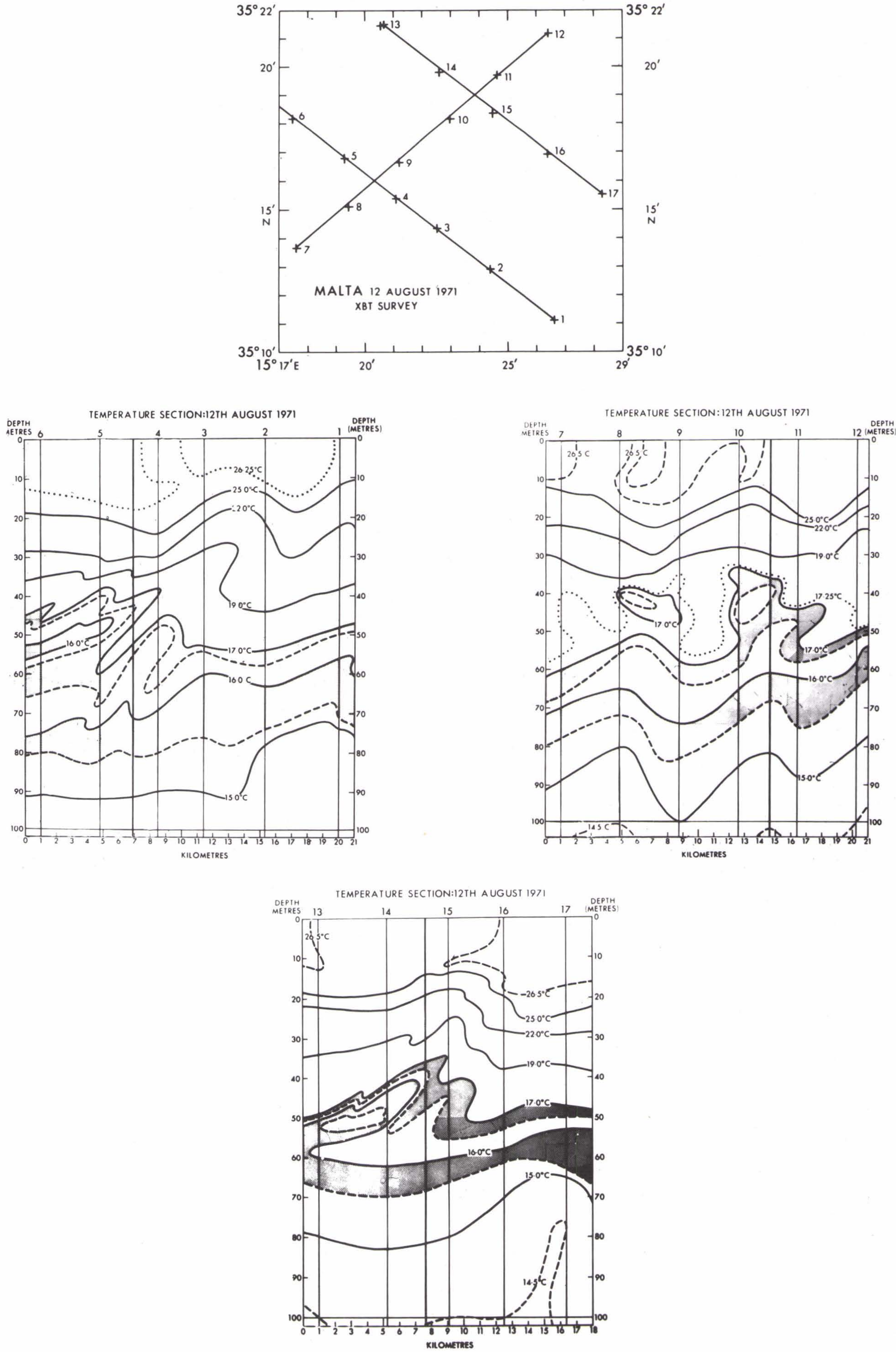

MALTA 11 AUGUST 1971
XBT SURVEY
TEMPERATURE SECTION:11TH AUGUST 1971
TEMPERATURE SECTION:11TH AUGUST 1971
DEPTH METRES
KILOMETRES
KILOMETRES

FIG. 3



MALTA 12 AUGUST 1971
XBT SURVEY
35° 22′
20′
15′
N
35° 10′
15° 17′E
25′
29′
TEMPERATURE SECTION:12TH AUGUST 1971
DEPTH METRES
DEPTH (METRES)
KILOMETRES
26.25°C
25.0°C
22.0°C
19.0°C
17.0°C
16.0°C
15.0°C
26.5°C
17.25°C
14.5°C

FIG. 4