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Some observations of thermo-haline stratification in the deep ocean

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Abstract—In the course of a series of S.T.D. probe observations of the temperature and salinity profiles of the Mediterranean water intrusion in the Northeast Atlantic, a remarkable series of deep layers was noted at two stations roughly mid-way between Cape St. Vincent and Madeira. The layers were formed at a depth of 1280–1500 m, i.e. immediately below the Mediterranean water, and were characterised by discrete temperature and salinity steps of the order of 0·25°C and 0·044‰ respectively and of thickness from 15 to 30 m. Up to nine layers were observed down to 1500 m (the maximum depth of measurement) and there may well have been more below this level.

The stratification was shown to be of low inherent stability, i.e. density changes across the layer boundaries due to temperature steps were almost compensated by corresponding changes in salinity. It is suggested that the layer formation is due to " salt fingering " occurring in the ocean.

INTRODUCTION

IN JULY and August, 1966 the Oceanography Department of the University of Liverpool was carrying out a combined physical and chemical programme in the Northeast Atlantic in R.R.S. *Discovery* and in the course of this work a series of hydrographic stations at 60-mile intervals was worked along a line running out from the approaches to the Strait of Gibraltar towards Madeira. The instrument used for the hydrographic casts was a Hytech 9006 salinity–temperature–depth (S.T.D.) probe. This equipment is capable of an absolute accuracy comparable with the best reversing water-bottle techniques (HOWE and TAIT, 1966) and has the great advantage of giving a continuous profile of both temperature and salinity and therefore a record of the detailed structure of the profiles. Typically, changes in temperature can be read to 0·01°C and in salinity (with some reservations) to 0·005‰.

At two of the stations (Nos. 14 and 15) on the traverse out towards Madeira, a layered structure was observed at a depth between 1280 and 1500 m, i.e. immediately below the Mediterranean water intrusion. The layers were characterised by discrete steps of the order of from 0·17 to 0·35°C in temperature, from 0·02 to 0·055‰ in salinity and of thickness (of depth of individual layer) between 15 and 30 m.

DESCRIPTION OF THE LAYERS

The relevant sections of the S.T.D. traces for the two stations are shown in Figs. 1 and 2. It was found impractical to photograph directly the actual records but the small amount of retouching necessary to distinguish the temperature and salinity traces has been kept to a minimum. The depth scale is presented inverted with increasing depth upwards and the salinity trace is of necessity displaced in depth

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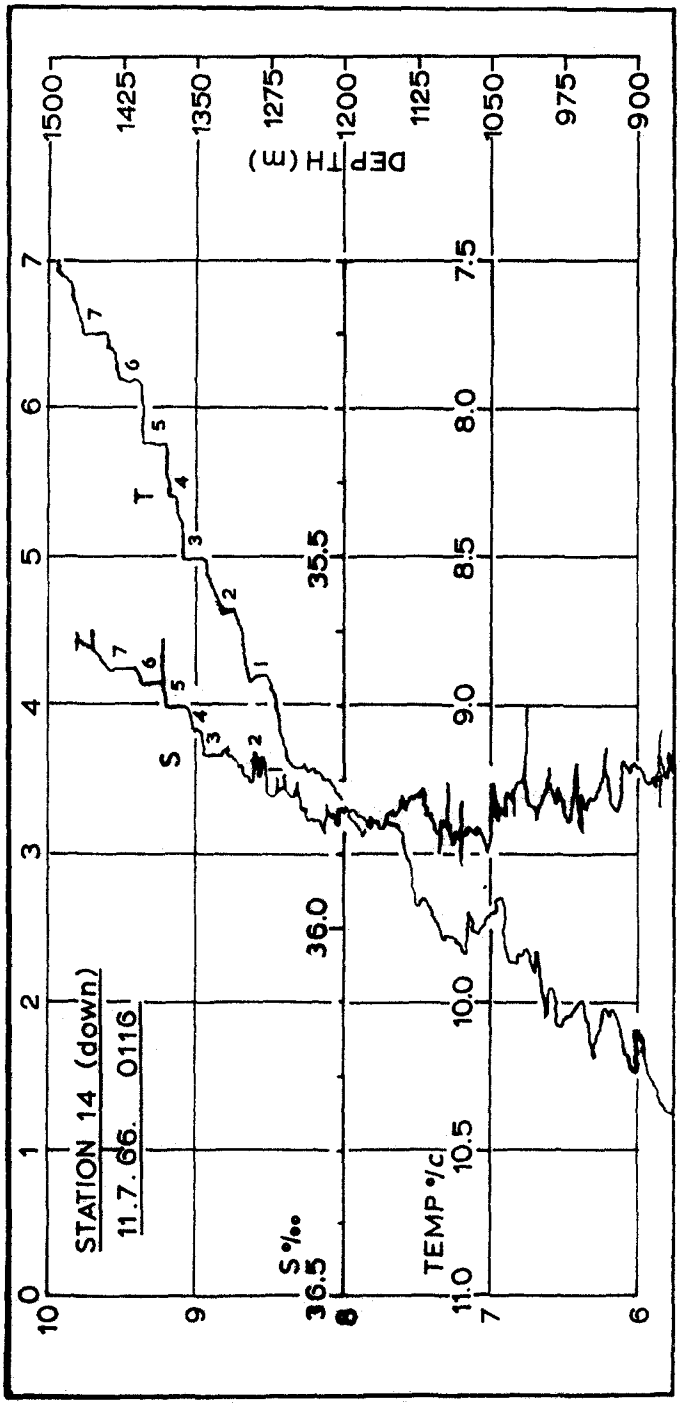

Fig. 1. S.T.D. record, Sta. 14 (34° 35·5'N, 12° 19'W).

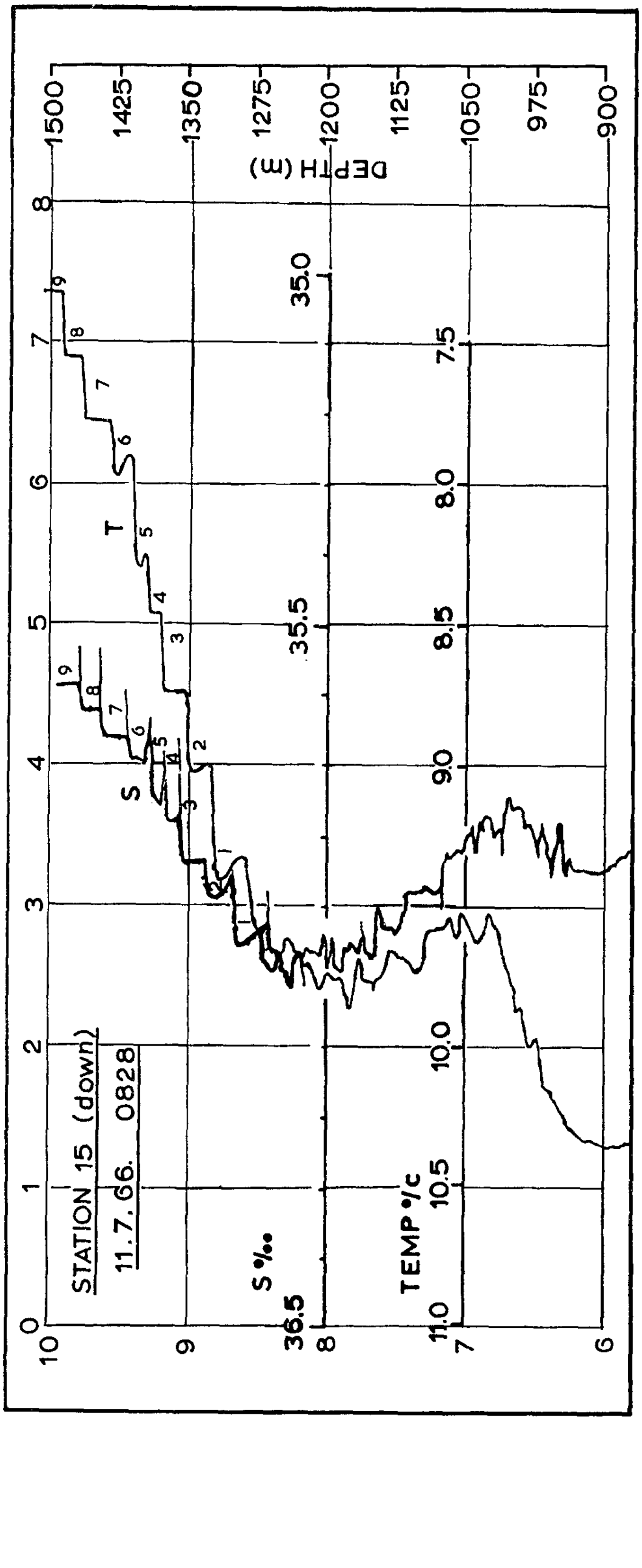

Fig. 2. S.T.D. record, Sta. 15 (34° 21′N, 13° 30′W).

relative to the temperature trace to enable the two pens on the recorder to cross over. The spikes evident on the salinity trace are instrumental and can be ignored, but they are an indication of a large temperature gradient occurring at the interface between one layer and the next. The record for Sta. 14 (Fig. 1) shows the temperature decreasing with increasing depth and tending to form a series of discrete steps, particularly in the section around 1350 m. The salinity trace is seen emerging from the high salinity bulge of the Mediterranean water and showing corresponding step functions.

At Sta. 15 (Fig. 2) the layering was more pronounced. The S.T.D. trace shows a well-defined stratification which develops immediately below the Mediterranean water at 1275 m and is still evident at 1500 m with the probability of more layers below. Within several of the layers the structure is almost isothermal and isohaline and in these cases the temperature gradients across the interfaces between the layers are relatively large, of the order of 0·2°C/m.

The records for both stations illustrate the complex micro-structure of the Mediterranean water itself. At nearly all of the 22 stations worked in the area numerous temperature inversions of the order of 0·1°C on an average were found and these were invariably accompanied by corresponding salinity changes to give an overall stable structure. In general this random layering effect is most pronounced above the Mediterranean water but it usually persists with reduced amplitude through and below the intrusion giving rise to the deeper inversions shown in both records. This could be described as the normal state of affairs, but it was apparent that at Stas. 14 and 15 there was strong evidence for an additional mechanism at work giving rise to sharp T and S gradients with well mixed layers in between.

DENSITY STRUCTURE

In Fig. 3 the relevant parameters for the 9 layers of Sta. 15 are presented as a single step function in terms of the mean change in temperature (ΔT) and salinity (ΔS) across the interface and the average layer thickness (ΔZ). The standard deviations for ΔT, ΔS and ΔZ are 0·06°C, 0·014‰ and 7 m respectively. With

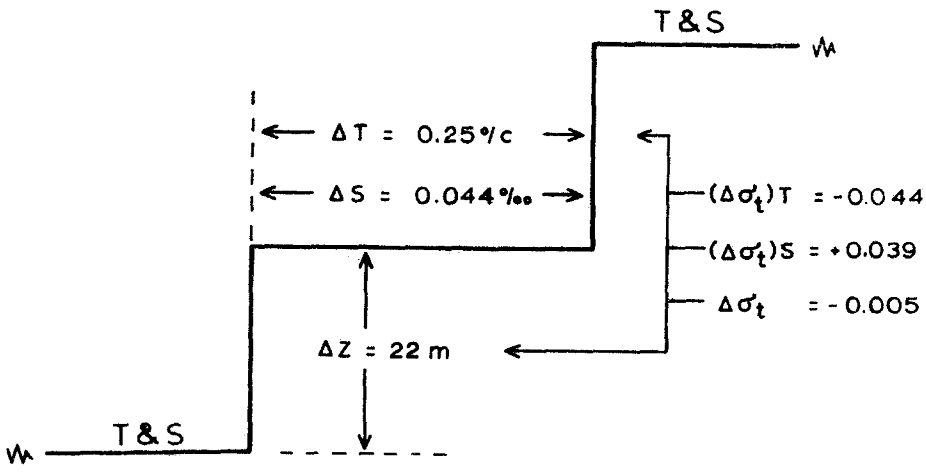

Fig. 3. Average layer parameters at Sta. 15.

regard to the mean density change $\Delta\sigma_t$, across the interface, the situation is clearly one of opposing density gradients. The temperature step of 0·25°C gives a density increase across the interface of 0·044 expressed in terms of σ_t, whereas the salinity step gives a decrease in σ_t of 0·039. These figures are given in the diagram as $\Delta(\sigma_t)\,T$ (implying a density change due to temperature alone) and $\Delta(\sigma_t)\,S$, the negative sign indicating an increase of density with depth. Thus for the average layer of Fig. 3 the negative component (due to temperature) is the greater giving an increase in density of 0·005 in σ_t and therefore a stable layer system.

This situation of opposing density gradients due to temperature and salinity must, of course, apply everywhere beneath the Mediterranean water intrusion. However, it does appear from the measurements that the overall density gradient at the depth of the layering zone is somewhat lower than the mean gradient at comparable depths at other stations where layering does not occur. A typical value for $(1/\rho).\ (\partial\sigma_t/\partial z)$ at other stations is $32 \times 10^{-5}\ \mathrm{m}^{-1}$, whereas at Sta. 15 the gradient is about $22 \times 10^{-5}\ \mathrm{m}^{-1}$. Thus it would appear that the stratification is probably associated with a lower than normal order of stability rather than higher, as one might at first suppose.

DISCUSSION

Unfortunately the cruise schedule did not permit any detailed study to be made of the stratification at Stas. 14 and 15. There are therefore many unknown factors, so many in fact that it is perhaps premature to discuss the results at all and any conclusions drawn can only be tentative at this stage. However, during a subsequent cruise in R.R.S. *John Murray* layering was again found in the same area and more extensive measurements were made which will be reported in due course. A preliminary examination of some 50 S.T.D. records for both cruises has revealed that over a wide area many stations show signs of embryonic layering at the appropriate depth. At Sta. Cavall in the Bay of Biscay, COOPER (1967) has reported abrupt changes in temperature and salinity occurring beneath the Mediterranean water. These measurements were made with reversing water-bottles, but without the continuous trace facility of an S.T.D. probe it is impossible to say whether the changes observed were true step functions or the more usual inversion layers characteristic of the Mediterranean water mass.

From the Liverpool data alone it is concluded that the formation of stratified layers as exemplified at Stas. 14 and 15, is not of uncommon occurrence : the mechanism tending to form the layers is always present and given the right conditions layers will form. The criterion governing the formation of the system must depend on some relation between the vertical gradients of temperature and salinity and the current shear at the appropriate depth. It has been proposed (TURNER, 1967) that the layers here described are an indication of a " salt fingering " effect occurring in the open ocean. The phenomenon of salt fingering which has been described by STERN (1960) and TURNER and STOMMEL (1964) is familiar as a laboratory experiment wherein a layer of warm salty water is placed above a cooler fresher layer and transport of heat and salt takes place across the interface in the form of convective fountains or " salt fingers." These long narrow convective cells which move alternately up and down are maintained because of the great difference between the molecular diffusivity of heat ($K_T = 1{\cdot}5 \times 10^{-3}\ \mathrm{cm}^2\ \mathrm{sec}^{-1}$) and salt ($K_s = 1{\cdot}3 \times 10^{-5}\ \mathrm{cm}^2\ \mathrm{sec}^{-1}$).

The situation of warm salty water overlying a cooler less salt water mass is precisely what we have beneath the Mediterranean water in the Northeast Atlantic and there seems to be no reason why, given favourable conditions, convection of the salt-finger type should not occur. Accepting then the principle that the vertical diffusion processes may be at least in part molecular, the unstable buoyancy flux due to salt would initially produce a well-mixed convection layer whose front would advance into the temperature gradient. The velocity of the front would decrease with time and when it approached the salt fingering velocity (about 0·02 cm sec^{-1}) one would expect the advance of the front to stop and another layer to form. The picture we have, is therefore of a series of layers with salt fingering occurring across the boundaries of the layers and convection driven by the unstable buoyancy flux due to salt giving rise to well-mixed layers in between.

In a series of laboratory experiments on salt fingering, TURNER (1967) has demonstrated the possibility of layer formation by this process. Using the measured values from the laboratory experiments for the flux of both heat and salt and extrapolating these values back to the oceanic case of Fig. 3, it is possible to calculate the vertical transport coefficients for salt (K_s) and heat (K_T) across the interface. These values are of the order of 5 cm^2 sec^{-1} and 2 cm^2 sec^{-1} respectively, which seems not unreasonable. The dynamics of layers in general have been discussed by STOMMEL and FEDOROV (1967) who show that the lifetime of even small laminae may be appreciable. The lifetime T of a layer may be calculated from the equation $T = (\Delta Z)^2/(2K)$ where K is the appropriate diffusion coefficient. Applying this to Fig. 3 gives a lifetime of 6 days (for $K_s = 5$ cm^2 sec^{-1}) without replenishment from the layer above.

Clearly further experiments are required to test the salt finger hypothesis. In particular the interfaces between layers need to be examined with much greater resolution, together with current profiles in order to evaluate the Richardson number. The experimental difficulties are considerable but if it can be definitely established that salt fingering is taking place then we must acknowledge that molecular processes play a more significant role in oceanic phenomena than is normally supposed. It is probable that molecular diffusion is also concerned in the production of inversion layers through the world oceans. The large temperature and salinity gradients produced by the Mediterranean water in the Northeast Atlantic highlight these effects thus providing an ideal field laboratory for the study of oceanic micro-structure.

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