A DEEP STEPPED THERMOHALINE STRUCTURE DEEP IN THE MEDITERRANEAN

by

O.M. Johannessen*
and
O.S. Lee**

ABSTRACT

A deep stepped thermohaline structure has been observed in the Tyrrhenian Sea below the Levantine water salinity maximum. The layers are remarkably homogeneous starting with a thickness of 10 m - 20 m at 600 m and thereafter increasing dramatically to 200 m thickness at 1200 m depth. The thickness of the interfaces between the layers is a few metres or less with typical changes of 0.05°C - 1°C and -0.02‰ for temperature and salinity respectively decreasing with depth. The identity of the layers is sustained over a horizontal distance of at least 75 n.mi and at a point for a time interval of more than a year.

Stepped structure is also reported in the Sardinian Channel, however, the steps are less regular and the maximum thickness of the layers is about 40 m. The layers are not continuous from one station to the next which indicates that horizontal coherence is less than 10 n.mi - 15 n.mi.

*SACLANT ASW Research Centre, La Spezia, Italy.

**Naval Undersea Research Development Centre, San Diego, California, U.S.A.

INTRODUCTION

Some recent continuous temperature, salinity and speed of sound profiles (STDV) carried out by the USNS SP LEE of the Naval Undersea Research and Development Centre, San Diego, have established a striking stepped structure in the profiles of temperature, salinity and speed of sound below the salinity maximum of the Levantine water in the Tyrrhenian Sea. Stepped structures of smaller dimensions in the Sardinian Channel and the western part of the entrance of the Strait of Sicily have also been observed. Also included in this study are STD stations in the Tyrrhenian Sea carried out respectively by the R/V MARIA PAOLINA of SACLANTCEN [Stockhausen, unpublished data, 1972], the USNS LUNCH of US Naval Oceanographic Office [Farquhar, unpublished data, 1972] and US CHAIN, Woods Hole Oceanographic Institution [Katz, unpublished data, 1968].

The stepped structure reported here is similar to that reported by Tait and Howe (1968), Howe and Tait (1970) and Tait and Howe (1971) west of Gibraltar but some important characteristics of the two sets of data differ. The stepped structure west of Gibraltar has a maximum layer thickness of 40 m, and the thicknesses decrease with depth, whereas the layers in the Tyrrhenian Sea increase with depth to a maximum value of 200 m.

The primary purpose of this note is to report that stepped structure has been observed in the Tyrrhenian Sea and that the high gradient steps are separated by nearly homogeneous layers that are much larger both vertically and horizontally than heretofore reported in the literature.

Other requirements did not permit a systematic study of the deep stepped-structure in the Tyrrhenian Sea; however during a westward passage through the Sardinian Channel one of the aims was to investigate if stepped structure could be found under the Levantine outflow in analogy with the Tait and Howe observations under the Mediterranean water intrusion into the north-east Atlantic.

OBSERVATION

The STDV (Bissett and Berman model 9040) casts from USNS LEE were carried out in the Tyrrhenian Sea during the first two weeks of October and in the Sardinian Channel in mid December 1970. Due to a failure in the digital recording system only analogue records were obtained. Figures 1 and 2 show respectively one station from the deep part of the Tyrrhenian Sea and one from the Sardinian Channel; an enlargement of part of the profiles is given in Fig. 3. (The profiles are very carefully retraced from the analogue records). The location of these two stations and other stations used in this paper are shown in Fig. 4.

Two prominent features of the stepped structure in the Tyrrhenian Sea are that the thickness of the layers increases rather dramatically with depth, and that the layers are nearly homogeneous except for a small increase in temperature within the layers due to the adiabatic heating. Layer thicknesses vary from 10 m - 20 m at about 600 m depth, increasing nearly exponentially to 200 m thickness at the 1500 m level and thereafter decreasing somewhat. Some 15 layers are present in each profile. Plotted on Fig. 1 is a Nansen cast from 2 March 1962, some 30 n.mi west of A4D3, [Miller et al (1970)], which suggests that no significant changes have occurred in the deep water during the last decade.

The interfaces between the layers were a few metres thick, in some cases near a metre or less, as well as we can estimate. However, the resolution of the analogue record is not fine enough to allow any detailed study of the structure of the interfaces, nor to get an accurate measurement of their thicknesses. The changes across the interfaces were about $0.05^{\circ}C - 0.1^{\circ}C$, 0.02‰ respectively for temperature and salinity and 0.2 m/s for the speed of sound, decreasing with depth.

The stepped structure in the Sardinian Channel is not as regular, and the layers are not as homogeneous as in the Tyrrhenian Sea.

Again the thickness of the layers increases with depth, but only up to about 40 m maximum thickness. Figure 5 is a comparative plot of the layer thicknesses versus depth for the two stations and shows that the distributions are essentially the same. Thicknesses of the interfaces in the Sardinian station are similar to those in the Tyrrhenian but the magnitude of the changes across them is about half as large. It can be seen from Fig. 5 that the layered structure is present over a larger depth interval for the Tyrrhenian station compared with the Sardinian Channel station.

The positions of STDV stations in the Ionian Sea from the USNS LEE cruise have been plotted in Fig. 4; however, none of these stations showed deep stepped structure. All the stations on Fig. 4 have been coded in order to display where the deep stepped-structure has been discovered so far.

SPACE AND TIME COHERENCE

The bar graph for station A4D3 [Fig. 5] shows a persistent (but not monotonic) trend toward increasing thickness of the homogeneous layers with depth before a decrease starts at about 1200 m. These data are based on one of the stations in a zone deeper than 1800 fathoms in the Tyrrhenian basis [see Fig. 6 for detailed topography and station locations]. Even a casual examination of all the Tyrrhenian Sea profiles (USNS LEE), A4D3 - A4U - A1D2 - A1D, confirms that the bar graph [Fig. 5] is typical of the four stations located in the deepest portion of the basin. The layer thicknesses in the four separate stations in Fig. 7 are strikingly similar; the dashed lines show, in fact, the correspondence of one station with another. This suggests that the layers are coherent over the horizontal distance of some 75 n.mi that separates the stations.

Figure 7 indicates that the interfaces show vertical displacement over the 10 days observation period, most probably caused by the internal waves. A downward slope toward the north is also indicated.

A further verification of the horizontal coherence of the layers is shown in the T-S diagram [Fig. 8], for which the T-S values have been read at the mid-depth of each of the different layers to the nearest 0.01°C in temperature and 0.01‰ in salinity. Apart from station A4U, which shows a systematic lower salinity of 0.03‰, nearly the same T-S characteristics were obtained for the other layers, with a maximum difference of 0.02°C and 0.01‰ for layers 2-7.

The reason for the lower salinity for station A4U may be due to the probe being hoisted for that record, or simply that an intermittent shift might have occurred. The latter possibility is considered significant because an analysis of all the STDV records taken in different parts of the Mediterranean during the USNS SP LEE cruise (Anderson and Lovett, 1971) indicated that a shift in the frequency of the salinity signal did occur later in the cruise and caused an error of about 0.03‰ in salinity. Although an intermittent shift in the salinity frequency could have occurred, the frequencies generated for the salinity, temperature and speed of sound are independent and therefore the latter two measurements are not subject to the same error.

Station A2D (75 n.mi west of the station pair A1D/A1D2), the "LYNCH" station* (75 n.mi east of A1D/A1D2), and the "CHAIN" station* CH (western part of the Tyrrhenian Sea) give some insight into the east-west horizontal coherence of the layers, although it should be mentioned that station L 2 was obtained 16 months later than the A2D station, and the CH station more than 2 years earlier. None of these stations showed the strong stepped-structure, as in the other Tyrrhenian stations. Further, an indication of some smaller layers was found only at stations A2D and L 2 where there was some similarity to the smaller scale layers in the Sardinian Channel.

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* Using a Bisset and Berman 9040 STVD.

** Using a Bisset and Berman, Hutex 9040.

The temperature profiles from the Sardinian Channel [Fig. 4] are plotted serially [Fig. 9] from east to west; some of the stations (469-474) are omitted because they extended to less than 500 m. Only the temperature profiles are shown, because the salinity and speed of sound reflect the same variation as seen in the temperature structure. The two stations A2D and L 2 from the Tyrrhenian Sea, which had similar characteristics to the Sardinian Channel stations, are also shown for comparison. Station 468 (located in the deep water south-east of Pantelleria in the Strait of Sicily) shows no sign of deep stepped structure. The water below 200 m is the Levantine water, constant in salinity and nearly constant in temperature. The stepped-structure is present in all the deep water stations west of the sill, apart from stations 479 and 481. However, it is not possible to identify the same layers from one station to the next, which shows that horizontal coherence is not present over the station interval of 10 n.mi - 15 n.mi.

Stations 2B and 2A in the Tyrrhenian Sea (separated by 3.7 n.mi) were carried out by R/V MARIA PAOLINA G.* in December 1970 (2B) and early March 1972 (2A). The LYNCH station L 2 in the same position as 2A and only two days earlier and the CHAIN station CH 82 located some 25 n.mi west of the other stations, provide some insight into the life time of the stepped-structure. Unfortunately the salinity sensor on the MARIA PAOLINA STDV was malfunctioning and cable limitation caused only shallow dips to be carried out; also the analogue traces were on a different scale than the LEE and LYNCH casts. Stations 2A and 2B have, therefore, been converted by hand to the same scales as the other records.

The CHAIN stations† were digitally plotted profiles, each data point representing an average value over a depth interval of 2 m.

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*Bisset and Berman, Hytex Model 9006.

†Kindly provided by Dr E. Katz, Woods Hole Oceanographic Institution.

Figure 10 shows the salinity and potential temperature profiles from the CH 82 station. Several layers are present; however, because of a contracted vertical scale compared with the other analogue records, the smaller scale layers just below the salinity maximum are not seen clearly. The temperature profile has therefore been converted by hand to the same scale as the other profiles. Figure 11 is a comparison of temperature profiles extending over an area of 15 n.mi (north-south) by 30 n.mi (east-west) during a period of almost four years. Figure 11 implies that the life time of the thicker layers (layers 4-7) are at least 16 months (comparing stations A4D3 and L 1. Although the deep layers are present in CH 82, the profile does not exhibit the obvious stepped structure as do the others, and we cannot draw the conclusion that the larger layers are the same as the others (suggested by the dashed line). Stations A4D3 and 2B, 14 months apart, show similar structures even for the small layers starting to occur below 600 m, but stations L 1 and 2A (only $2\frac{1}{2}$ months apart) exhibit poor similarity for the smaller layers. In fact, the thinner layers (thicknesses up to 40 m), for example layers 1 and 2, disappeared during the $2\frac{1}{2}$ month period.

Another interesting feature is the deepening of the thicker layers with time (indicated by a dashed line in Fig. 11) which amounted to about 100 m over 16 months or 0.2 m/day when comparing stations A4D3 and 2A. However, in view of the observed shorter-time depth-variations (20 m - 30 m for the interfaces of the layers in Fig. 7, and between station L 1 and 2A in Fig. 10) it is believed that a shorter period phenomena such as internal waves causes part of the apparent (Nyquist folded) long-term depth variation of 100 m.

Also, a significant weakening* of the gradient across the interfaces occurred between the winter stations L 1 and 2A only two days later. One asks whether the weakening of the gradient across the interfaces indicates that the layered system is becoming unstable as studied theoretically by Huppert (1971).

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*Assuming that the observed interface (sheet) thickness is not biased by rapid lowering rates of the probes contributing to time-lag-induced apparent thicknesses.

VERTICAL STABILITY

The hydrostatic stability can (in the absence of shear flow) be represented by the Vaisala-Brunt frequency, Eckart (1960) and Roden (1970) by Eq. 1.

$$N^2 = -g\left[\frac{1}{\rho}\frac{\partial\rho}{\partial z} + \frac{g}{C^2}\right] \qquad \text{[Eq. 1]}$$

$$N^2 \begin{matrix} > \\ = \\ < \end{matrix} 0 \quad \begin{matrix} \text{Stable} \\ \text{Indifferent} \\ \text{Instable} \end{matrix}$$

where ρ is the in-situ density, g the gravity, C the local speed of sound calculated using Wilson (1962) and Z is negative downward. Since the stepped-structure is very regular, at least in terms of the STDV resolution [probably much finer microstructure is present in the layers and across them, which special microstructure probes such as used by Gregg and Cox (1971) and Woods and Wiley (1972) could probably establish], only "significant" points have been digitized from station A4D3 resulting in somewhat simplified temperature and salinity profiles. Figure 12 shows the digitized profiles together with the Vaisala profile which indicates that the density profile is slightly stable within the layers, but that across some of the interfaces above 900 m instability occurs. Below 900 m, the stability across the interfaces is higher than in the layers, respectively 1-2 c/h compared with 0.5 c/h. This will theoretically allow higher frequency internal waves to be trapped on the interfaces, as also suggested by Cox, Osborne, and Nagata (1971), with the possibility of causing mixing and a change of the detailed structure of the interface.

DISCUSSION

It has been established that in the Tyrrhenian Sea all the available stations at locations deeper than 1800 fathoms (3300 m) had the pronounced deep stepped-structure and that the horizontal extent of 7 of the layers was at least 75 n.mi. The ratio of layer thickness to horizontal extent (in the north-south direction) varies between 1/3000 to 1/1000 for 50 m to 150 m thick layers. The other stations to the west and east of the deep Tyrrhenian basin do not show the pronounced deep-layering, although thinner layers were present.

This leads us to speculate on some correlation between the occurrence of the deep layering and the station location in the deepest part of the Tyrrhenian Sea. The physical reason might be that circulation is weaker over the deepest part, allowing the layers to be formed rather than destroyed by advection and current shear as previously suggested by Tait and Howe (1970). Possibly the weaker layering and poor horizontal layer coherence in the Sardinian Channel, where certainly the circulation is stronger and more complex than over the deep water in the Tyrrhenian Sea, indicates that the velocity field is a strong factor in the formation of layers and contributes to determining the horizontal extent and life time of the layers.

The recent result of Tait and Howe (1971) showed that stepped-structure was present over an area of at least 4000 sq. n.mi in deep water 250 n.mi - 300 n.mi west of Gibraltar. Layers could be traced over a horizontal distance of 30 n.mi, or less than half the horizontal coherence distance found for our stations in the Tyrrhenian Sea. Tait and Howe also recorded some 20 layers between 1200 m - 1800 m below the maximum salinity of the Mediterranean intrusion; the layer thicknesses, the interface thicknesses, and the magnitudes of thicknesses in temperature, salinity and density all decreased significantly with increasing depth, contrary to the structure in Tyrrhenian Sea. The maximum layer thickness found west of Gibraltar was about 20 m - 30 m, compared with 200 m in the Tyrrhenian Sea.

Indications of a life time of more than 16 months exist for the thicker layers in the Tyrrhenian Sea, whereas the disappearance of some of the smaller-scale layers suggests a life time of some months for these thinner layers. To properly study the life time and dynamics of the layered system, one should lock-on an instrumented vehicle to one particular layer as suggested by Stommel and Federov (1967), which vehicle could then freely take part in the motion of the layer and observe its oceanographical variations.

Our suggestions for the layer life times are based on rather spotty observations, both in time and space, and since we have no definitive information about the circulation of the area, we cannot conclude what degree of variation is caused by changes in convection or advection. Therefore the suggested life times must be accepted with some reservations.

Stommel and Federov (1967) have calculated the life time of layers by using the formula $T = h^2/2K$, where h is the layer thickness and K is the turbulent eddy coefficient. Tait and Howe (1968) using this formula calculated a life time of six days for their 20 m thick layer ($K = 5\ cm^2\ s^{-1}$). Using the same value for K we calculated life times of 6 days - 4 months - 15 months for layers with thicknesses of 20-100-200 m respectively, a result at least of the same order of magnitude as our observations.

Turner (1967) suggested that the layered system observed west of Gibraltar by Tait and Howe might be caused by the "salt fingering" mechanism, a double-diffusive process investigated both theoretically and with laboratory experiments by for example Stern (1960, 1968), Turner and Stommel (1964), Turner (1965, 1967, 1968), Federov (1970), and Huppert (1971). Certainly the oceanographical condition in the Tyrrhenian with hot saline water overlying cold fresher water, and with low vertical stability between the layers caused by the nearly compensating effect of temperature and salinity on density, is favourable for saltfingering.

One direct proof of saltfingering in the ocean could be photographic or other optical techniques in combination with STDV measurement.

The stations in the Ionian Sea [Fig. 4] made by the USNS LEE showed no layering, although the oceanographical conditions with respect to saltfingering are about the same as in the Tyrrhenian Sea. If saltfingering is in fact the mechanism causing the layered structures we have seen, this reinforces the supposition that the controlling factor for saltfingering is the intensity of the circulation and the vertical shear. If saltfingering is <u>not</u> causing the layered structure one could suggest several other mechanisms such as:

(1) The overflow of the Levantine water through the Strait of Sicily, followed by mixing with the intermediate water of the western Mediterranean followed by slow advection and sinking in the Tyrrhenian Sea and Sardinian Channel.

(2) Local deep winter convection in the northern part of the Tyrrhenian Sea in a small area followed by the collapsing of the uniform water column thereby forming intruding layers, as recently demonstrated by the MEDOC Group (1969) in the Gulf of Lyon off the French coast.

(3) Layered structure caused by breaking internal waves as demonstrated in a numerical experiment by Orlanski and Bryan (1969).

We are continuing our study of the layered system in the Mediterranean and plan to carry out experiments which hopefully will give more insight into the mechanisms of the generation, horizontal extent and life time of the layers.

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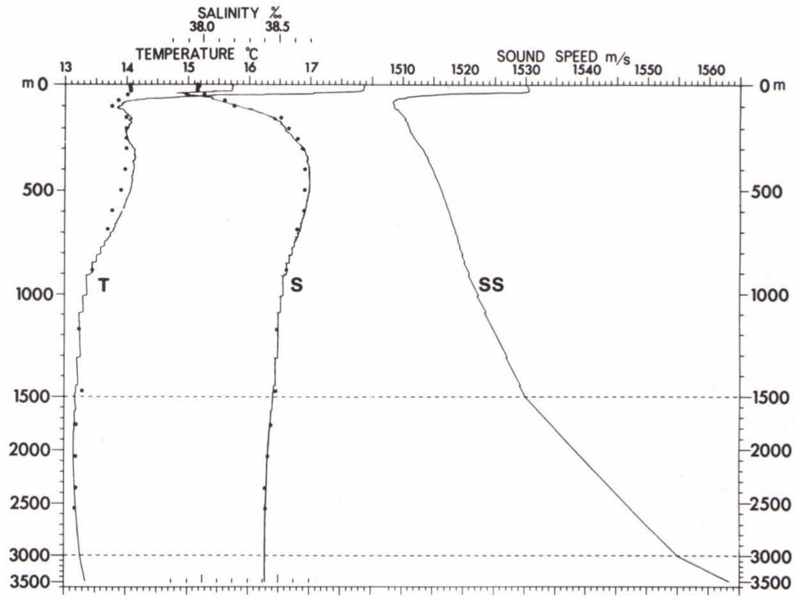


FIG. 1

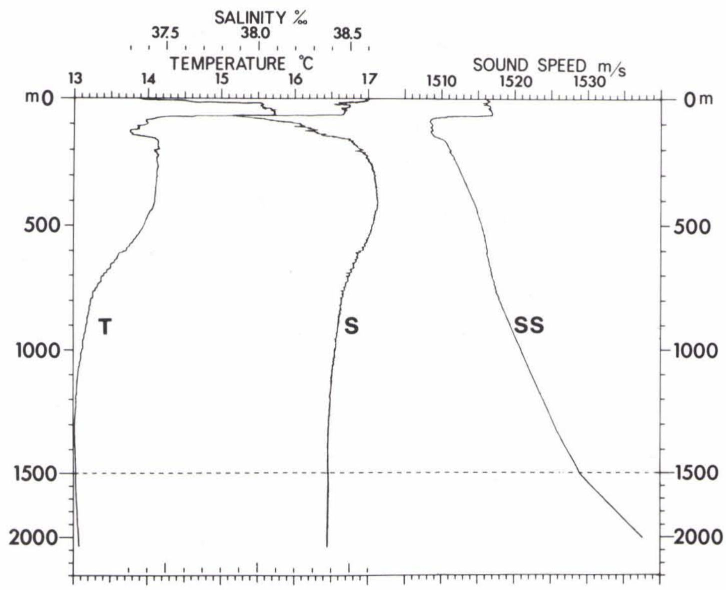


FIG. 2

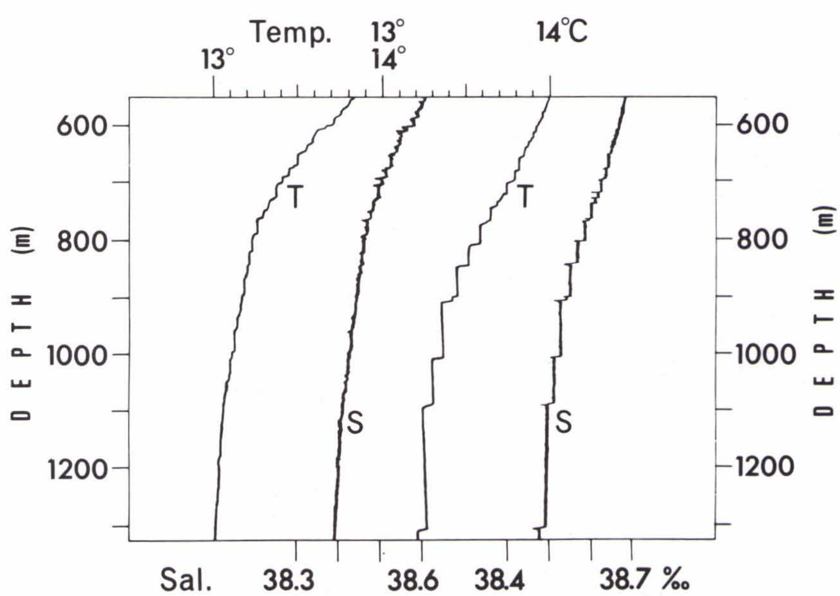


FIG. 3

STEPPED STRUCTURE UNDER SALINITY MAXIMUM OF LEVANTINE WATER

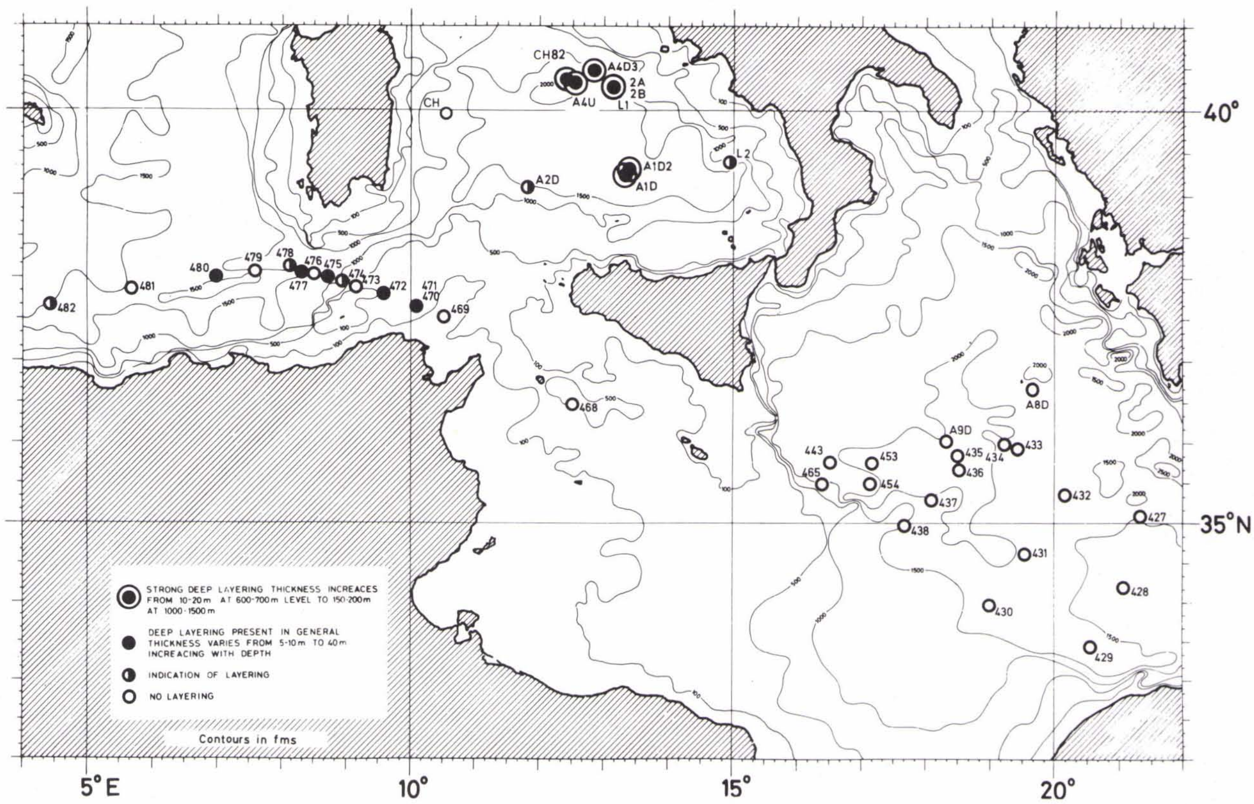


FIG. 4

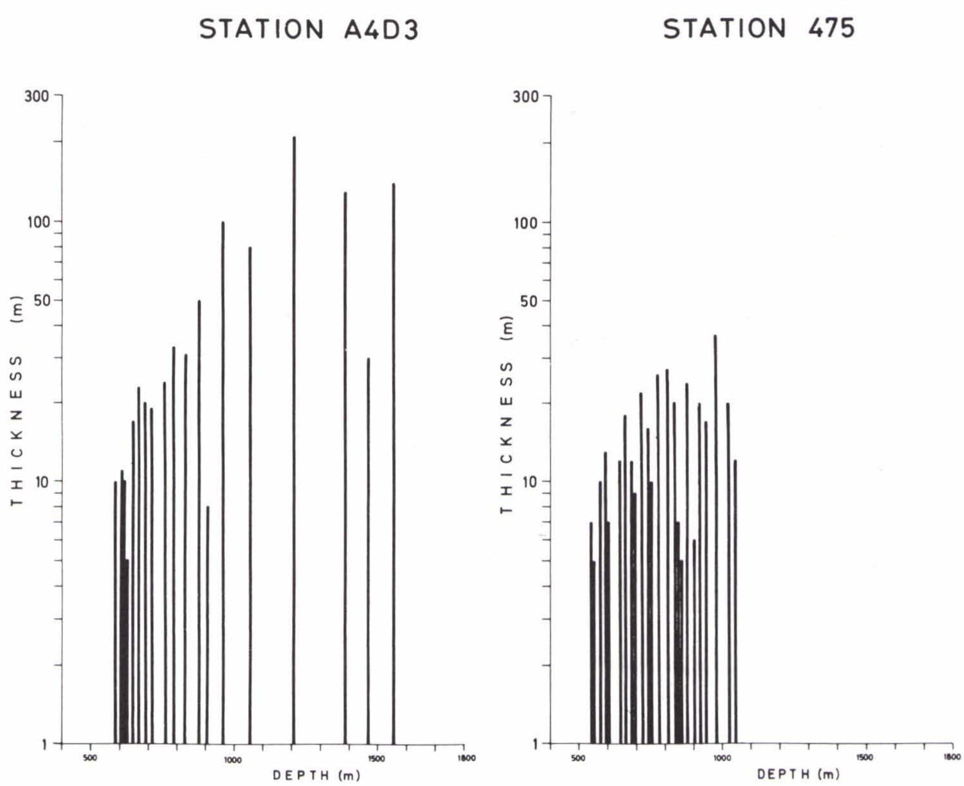
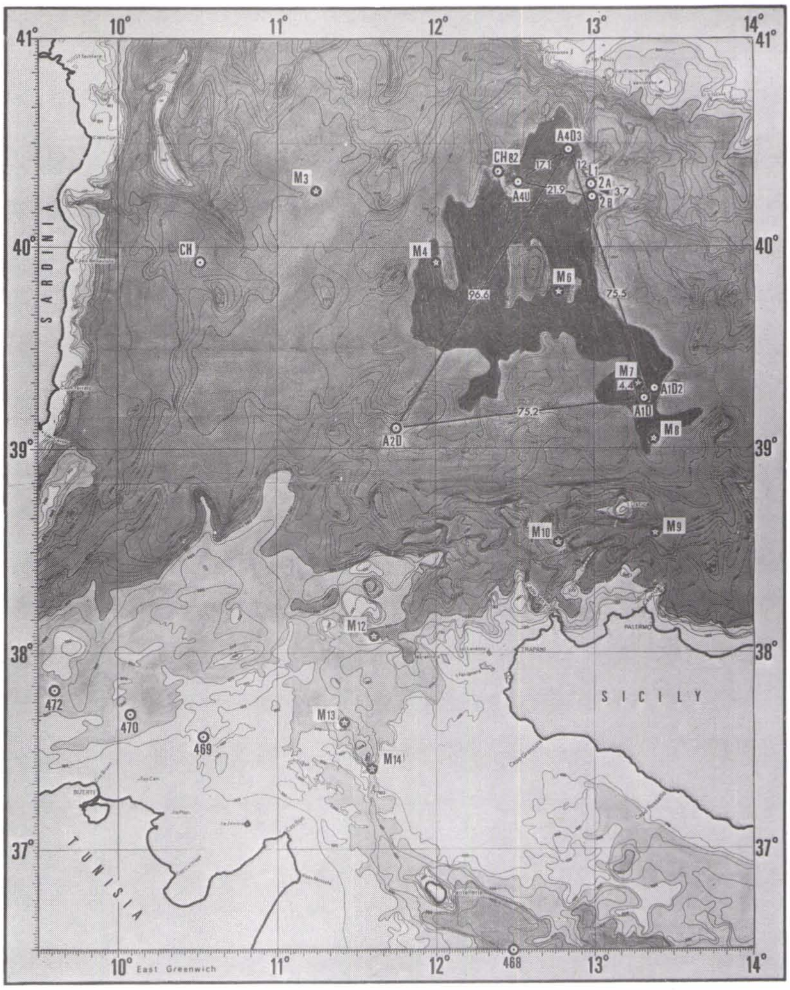


FIG. 5


10°
11°
12°
13°
14°
41°
40°
39°
38°
37°
SARDINIA
SICILY
TUNISIA
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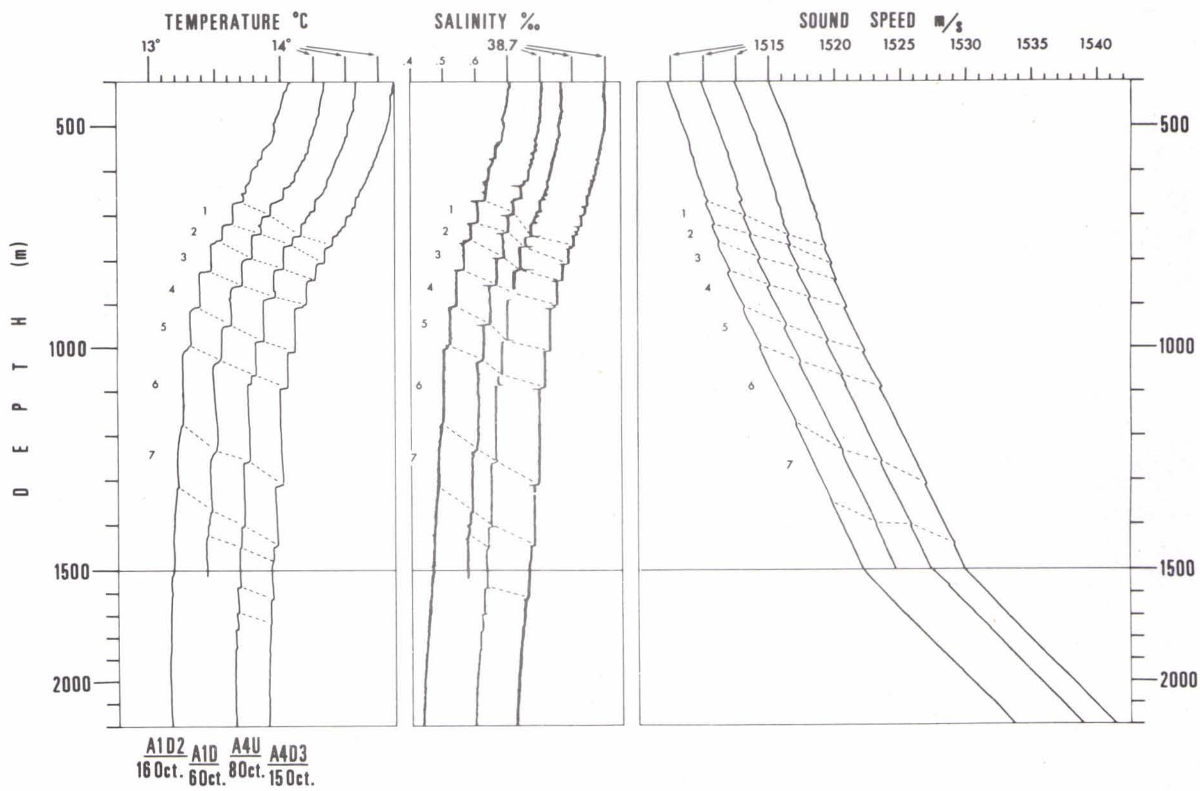
CH82
A4U
2A
2B
M3
M4
CH
M6
M7
A1D2
A1D
M8
A2D
M9
M10
M12
M13
M14
472
470
469
468
17.1
21.9
12.1
3.7
96.6
75.5
75.2
4.4
10° East Greenwich

FIG. 6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14°
SALINITY ‰
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SOUND SPEED m/s
1515
1520
1525
1530
1535
1540
DEPTH (m)
500
1000
1500
2000
1
2
3
4
5
6
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15 Oct.

FIG. 7

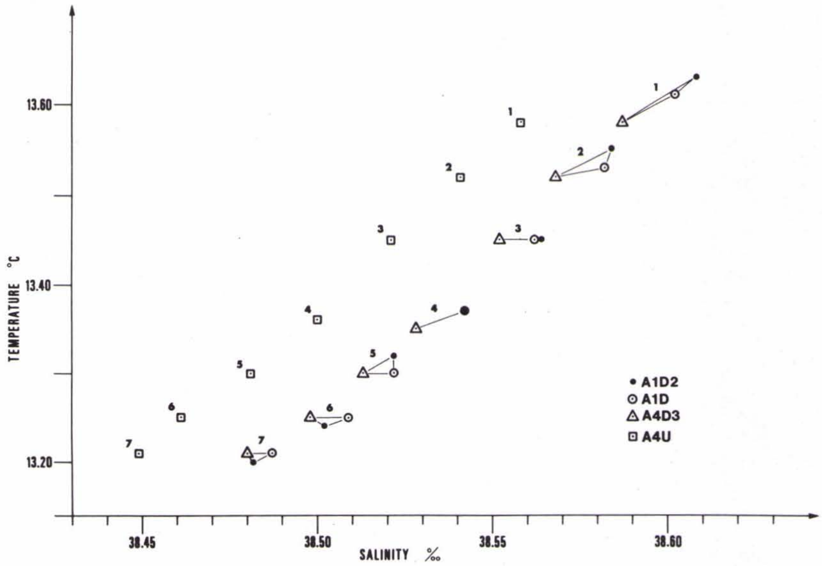


FIG. 8

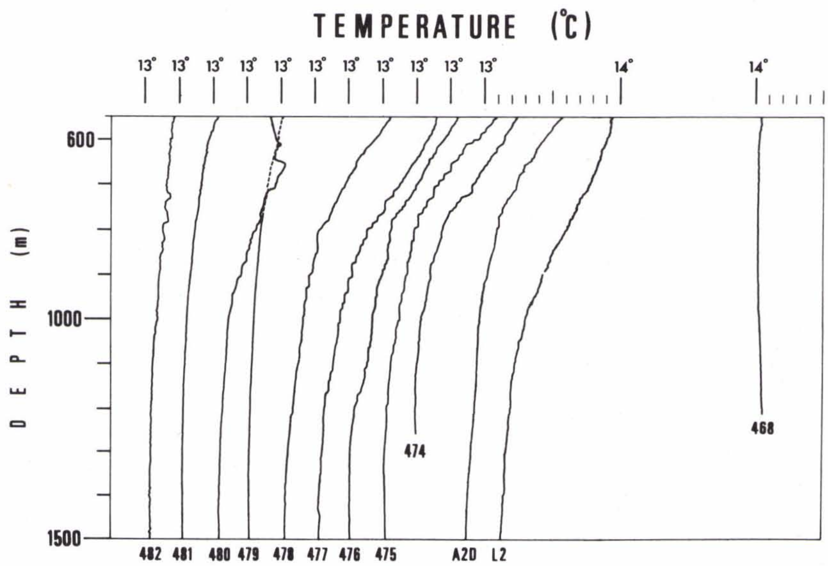


FIG. 9

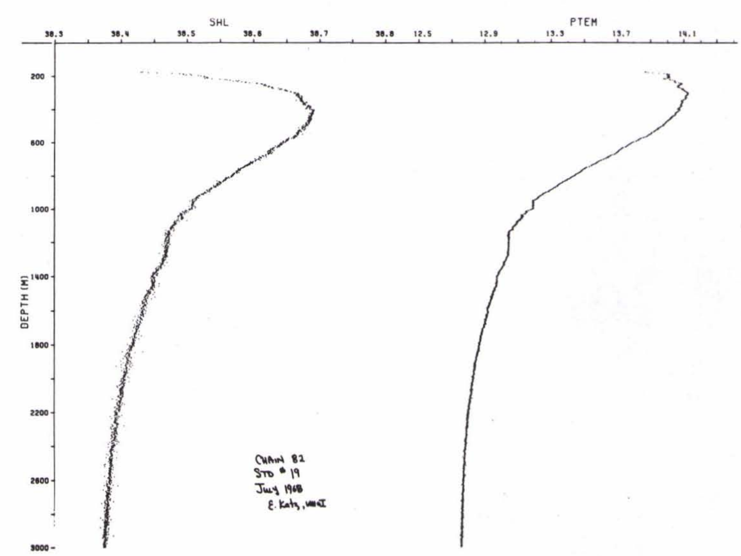


FIG. 10

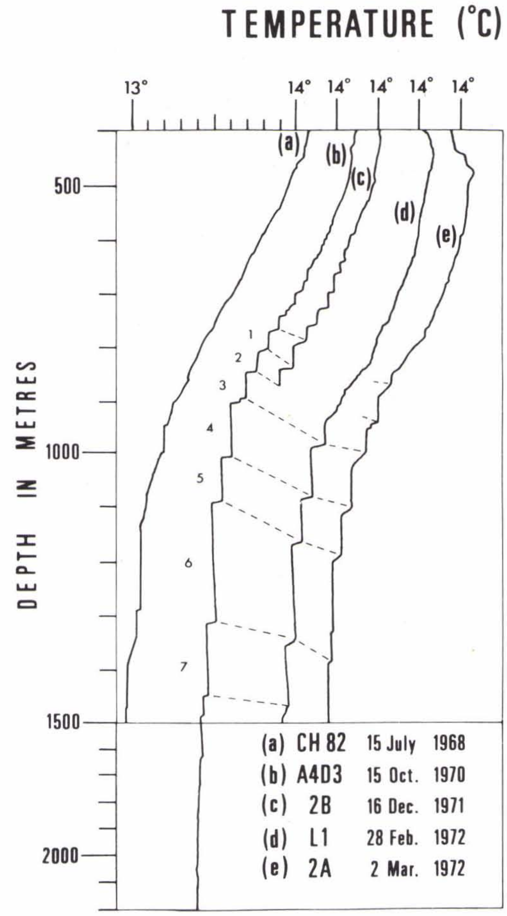
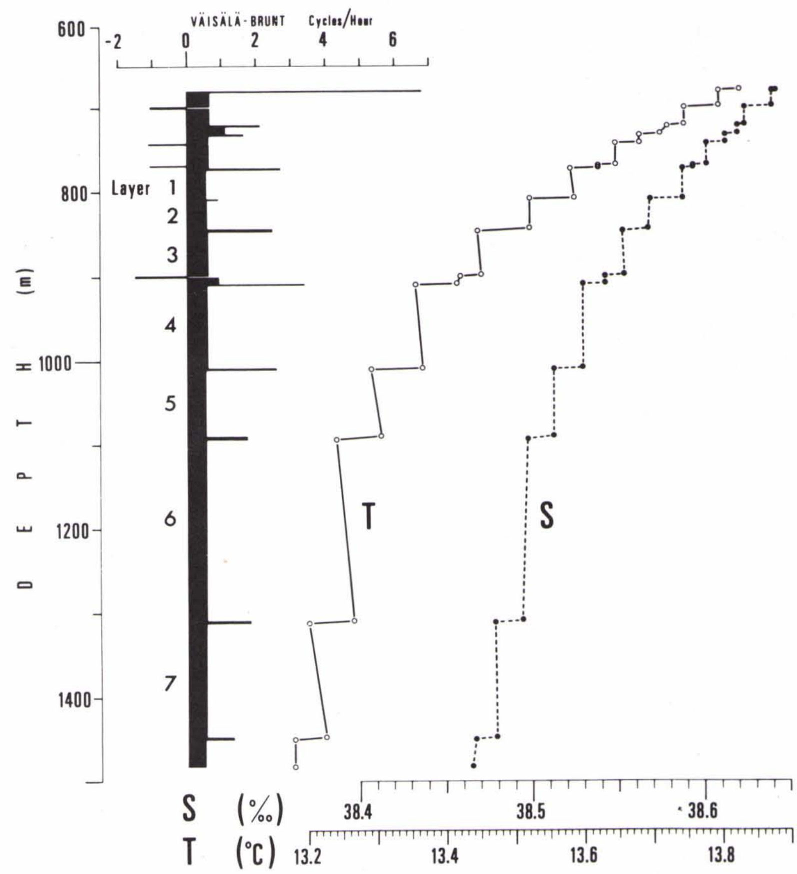

TEMPERATURE (°C)
13°
14° 14° 14° 14° 14°
DEPTH IN METRES
500
1000
1500
2000
(a)
(b)
(c)
(d)
(e)
(a) CH 82 15 July 1968
(b) A4D3 15 Oct. 1970
(c) 2B 16 Dec. 1971
(d) L1 28 Feb. 1972
(e) 2A 2 Mar. 1972

FIG. 11

FIG. 12


VÄISÄLÄ - BRUNT Cycles/Hour
-2 0 2 4 6
600
800
1000
1200
1400
DEPTH (m)
Layer 1
2
3
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5
6
7
T
S
S (‰) 38.4 38.5 38.6
T (°C) 13.2 13.4 13.6 13.8