INTERNAL OCEANOGRAPHIC MICROSTRUCTURE PHENOMENA

by

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ABSTRACT

This paper is concerned with the nature and causes of both fine structure and microstructure in the ocean. Following an account of the acoustic/oceanographic background to subject, the characteristics of fine structure are described in terms of temperature and salinity profiles from the N.E. Atlantic. The three main causal mechanisms, horizontal advection, shear instability and double diffusion are discussed and their relative importance to fine scale phenomena is assessed. Microstructure observations from high resolution free fall instruments are used to illustrate the main features of the true microscale. These data provide evidence for the presence of both shear instability and double diffusive mechanisms. An examination of the relationship between the fine and micro scales leads to the conclusion that within an otherwise "quiet" ocean intensive vertical mixing occurs sporadically in specific areas characterized by the presence of an appreciable fine structure.

INTRODUCTION

It is now well established that the oceans are not smoothly stratified. When we look at the fine-scale structure, i.e. at the scale structure with vertical wave number of $K < 1.0$ cycle/metre which is the range covered by the standard STD, we find numerous inversions in temperature salinity and also mixed layers separated by interfaces where the gradients are relatively sharp. At higher wave numbers, $K > 1.0$ cycle/m, which is defined as the microstructure range, the new generation of instruments currently under development have revealed that this situation continues right down to the diffusive cutoff scales* of the order of a few centimetres. The situation is illustrated in Fig. 1.

In reviewing the field of microstructure, it is particularly appropriate at this meeting to acknowledge the early role played by acousticians. The existence in the ocean of a finer structure than the classical two-layer picture first became apparent during World War II when the scintillation of sound waves observed during sonar experiments was attributed to the presence of small isotropic scatterers. Although evidence of fine thermal stratification was known from BT's, acousticians preferred to study the temperature fluctuations horizontally rather than vertically, in the same direction as the propagation. Extensive work of this nature between say the late 1940's and early 1960's gave rise to an ocean model composed of small random thermal scatterers that were statistically spheroidal. Although this concept of thermal patches of dimension ~1 m was, perhaps still is, acceptable to acousticians it is far from realistic from the oceanographic point of view.

Now what were the oceanographers doing during this period? It so happened that during the time when the acousticians were working with high-resolution equipment, which identified the effects of small-scale features, oceanographers were concerned with large-scale low-frequency oceanic structures and movements as revealed by Nansen bottles. The dialogue between acoustics and oceanography appeared to be at a low ebb**. This was not the fault of the oceanographers: they had no instrumentation available for fine structure profiling in the ocean.

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* The division as defined above between fine structure and microstructure corresponds approximately to a wave number $K_B = \frac{1}{2\pi}\left(\frac{N^3}{\epsilon}\right)^{\frac{1}{2}}$ which represents the scale of the largest eddies that can be considered isotropic. The diffusive cut-off scales for velocity and temperature are given respectively by $K_v = \frac{1}{2\pi}\left(\frac{\epsilon}{\nu^3}\right)^{\frac{1}{4}}$ and $K_T = \frac{1}{2\pi}\left(\frac{\epsilon}{\nu K_T^2}\right)^{\frac{1}{4}}$.

** Paradoxically, as was pointed out by Bethell 1972 , when oceanographers did become interested in fine structure it seemed as though acousticians began to loose interest, e.g., the 1950-70 Review of Underwater Acoustics by Berman Guthrie 1972 where the section on thermal microstructure contains references dated no later than 1963.

1. FINE-SCALE STRUCTURE

Intensive oceanographic interest in fine structure measured vertically stems from the development of STD systems in USA and Europe in the early 1960's. It is worth remembering that the STD was developed as a modern replacement for the traditional Nansen cast, over which it had obvious advantages, but its full value did not become apparent until it began to be used at sea, when the degree of fine structure observed came as a distinct surprise. Clearly here was a phenomenon of great interest and well worth studying.

At Liverpool University we were fortunate in acquiring in 1965 one of the earlier STD's, the Hytec 9006. In the summer of 1966 my colleagues and I made the first STD observations of the Mediterranean outflow in the NE Atlantic. In spite of hints from the earlier work of Cooper [1967] in this area with closely-spaced water bottles the degree of fine structure found was unexpected.

Figure 2 shows a plot of the original analogue record for a station about 100 miles west of Lisbon. I have three reasons for showing this:

1. It has historical value and the data have not been published.

2. It is typical of the T & S profiles found not only in this area but also wherever we have the intrusion of a discordant water mass of different origin.

3. I can use it to illustrate several points concerning fine structure.

Our main concern is with the section of the record from 300 m to 1500 m corresponding to the depth scale on the right. The horizontal scales span 5° (15° to 10°) and 2‰ (36.5‰ to 34.5‰) for T & S respectively. On the largest structure scale we have the main feature of the high S & T bulge of the Mediterranean water separated above and below from the Atlantic water by two boundary zones where the mean vertical gradients are relatively large and of opposite sign. The main salinity maximum is apparent at the usual depth for this region of 1200 m, but we also have another secondary maximum at about 800 m which is particularly apparent on the T trace (right). The Mediterranean water is thus divided here into two main water types, the upper being warmer and therefore of lower density. This upper water, which has been the subject of a long term investigation at Liverpool University, has also been discussed by Siedler [1968], Madelain [1970], Zenk [1970 & 1975], and Howe and Abdullah [1974]. It is considered to be Mediterranean water that has been subjected to a different mixing history from that of the main stream of Mediterranean outflow.

If we now look at the smaller-scale effects we find apparently random temperature inversions occurring throughout the column, from a few tens of metres in thickness down to the STD cutoff scale at about 2 m. The presence of thermal structure below this in the true microstructure range is apparent from the S trace, which at the smallest scale reflects conductivity rather than salinity. On the medium scale every T change has an associated S change and the two invariably combine to produce a stable relatively-smooth density profile. This is most easily seen on a T/S diagram. I have labelled various key points on both traces in Fig. 2 and the corresponding T/S plot is given in Fig. 3. The inversion layers tend to run parallel to the isopycnals but show a general downward progression with each successive point, implying that the stratification is statically stable.

Since 1966 the medium-scale structure associated with the Mediterranean outflow has been studied by Tait and Howe [1968, 1971], Pingree [1969, 1971], Zenk [1970, 1975], Katz [1970] and many others over a wide area from Finisterre to Madeira and out as far as the Azores. Going even further afield, Ichye and Sudo [1971] have detected the Mediterranean water in the Caribbean and the Gulf of Mexico.

Figure 4 shows a processed record, again from the Mediterranean outflow area, due to Pingree [1970]. The position is 160 miles SW of Finisterre. The fine structure features are similar and shown also are the calculated profiles for potential density σ_θ and specific volume anomaly δ. The apparent instability in the lower part of the σ_θ profile is due to a compressibility effect. In this region of large negative temperature gradient, $\frac{d\sigma_\theta}{dz}$ does not reflect the true stability of the water column, and one must take the increasing compressibility of the cooler water into account. Pingree shows that under these conditions the stability is better related to the δ gradient but the more conventional approach is now to estimate stability in terms of the Väisälä frequency, N, given by $N^2 = \frac{g}{\rho}\frac{\partial\rho}{\partial z} - \frac{g^2}{c^2}$, where $\frac{\partial\rho}{\partial z}$ is the in-situ density gradient. Results from other similar oceanic areas, i.e. similar in the sense of the presence of different water masses e.g. Gregg and Cox [1972] in the Pacific; Gilmour [1972], in the Mediterranean; Hamon [1967] in the Indian Ocean have given the same general picture regarding the fine structure. Two main general conclusions can be drawn from this work.

1. The ratio between the horizontal and vertical scales for inversions seems to be of the order of 10^3. This general relationship appears to apply over a wide range of scales and also the other types of stratification such as the step structures associated with the thermocline described by Cooper and Stommel [1968].

2. The temperature and salinity changes are highly correlated and density compensating, leading to a stable density profile.

2. CAUSES OF FINE-SCALE STRUCTURE

The above observations, together with the fact that the fluctuations are aligned with constant-density surfaces, suggest that the structures are formed by the lateral interleaving of different water types, i.e. by horizontal advection. It was, I think, Phillips who stated recently that "it is almost certain that not all the fine structure found in the ocean can be ascribed to a single mechanism".

The three most likely mechanisms involved in the medium-scale structure are:

1. Advective processes.
2. Wave-induced shear instability; Billow turbulence.
3. Double diffusion.

All have been extensively discussed in the literature. The most comprehensive quantitative experiments on double diffusion (i.e. diffusion processes related to the different molecular diffusivities of heat and salt), particularly on the phenomenon known as salt fingering, are those of Turner and his associates at Cambridge, e.g. Turner and Stommel [1964], Turner [1967, 1968], Stern and Turner [1969], Shirtcliffe and Turner [1970], Huppert and Turner [1972], Linden [1973].

Many attempts have been made to apply the theoretical results to the ocean, seeing in the oceanographic data a reflection of the phenomena produced in the laboratory. K.N. Federov has been particularly active in this respect: Federov [1970] applied the double-diffusion theory applicable to the heating of a salt gradient from below to Zenk's observations of the Mediterranean water and was criticized for so doing by Huppert and Turner [1972] who point out the dangers of applying small-scale microstructure laboratory experiments to the larger medium-scale oceanographic case.

The second cause of fine structure: turbulence created by shear instability or the breaking of internal waves, billow turbulence, has been discussed by many, particularly by Woods and Wiley [1972], demonstrated in the laboratory by Thorpe [1969], and in the ocean thermocline off Malta by Woods [1968]. On an STD record one can easily find S-shaped profiles and mixed layers characteristic of billow turbulence, but these predominate at the higher wave numbers at scales of 1 m or less, which cannot be resolved with respect to density. At larger scales, S-shaped profiles are invariably statically stable and clearly are not billows. Both these mechanisms — double diffusion and billow turbulence — which really belong to the true microstructure scale involve some degree of vertical mixing. When we look at the medium-scale structure there is nothing to suggest that the numerous irregularities in the profiles are direct expressions of the vertical mixing. The features are well stratified, density-compensating and aligned along isopycnal surface, all of which points to horizontal advection. This view seems to have gained universal acceptance. Stommel and Federov [1967] produced simple models to illustrate how the interleaving could arise and Stern [1969], showed that a horizontal variation in T & S could give rise to layered convection.

Although it is easy to see how, for example, the extensive mixing in the Strait of Gibraltar and along the continental shelf and slopes of the Spanish and Portuguese coasts could provide a ready source of different water types, there still remain some problems to be resolved e.g., the life time of an inversion layer of thickness ΔZ is given by

$$T = \frac{(\Delta Z)^2}{8\ K_z} .$$

If we accept that $K_z \sim 1\ \mathrm{cm^2/s}$ the current value required by most thermocline models and also the value estimated by Munk [1966] for the deep ocean, then for, say, a 20 m thick inversion, T works out at about 6 days. Yet we still find pronounced medium-scale structure 500 miles away from the source of mixing where the travel time must be at least several months. We therefore conclude that either the interleaving must be a continuing process that is active away from the source, or the value for K_z must be much smaller. To attempt to answer this question we need to look at the interchange taking place at the interfaces, i.e. we need to examine the microstructure.

However, before I move on to discuss the microscale, there is one important aspect of fine-scale stratification that must be mentioned as it is a possible manifestation of double diffusion. In the boundary zones of larger-scale water masses there is often a tendency toward the formation of step layers. Sometimes we find a spectacular series of steps, as shown in Fig. 5, which in this case are associated with the lower boundary layer of the Mediterranean water.

I first observed this structure in 1966. This picture dates from a later cruise in 1969 [Tait and Howe (1970)]. Similar observations have been made by Johannessen and Lee [1974] and by Molcard [1975] in the Tyrrhenian Sea, by Neshyba [1969] in the Arctic Ocean, and Lambert [1975] in the W. Atlantic. The steps here average about 20 m in thickness for the mixed layer and 7 m for the interface. The mean T & S interface increments are as shown. Higher-resolution traces in Figs. 6 and 7 give the profile in more detail.

We have shown that these layers can extend for up to 30 miles and over this distance the mean T of a mixed layer varies by only a few hundreds of a Celsius degree. The system is stable; the steps are density compensating, with T exerting sufficient control to maintain stability.

Elliott has shown that the life time of a step layer is given by $\frac{(\Delta z)^2}{80\ K_z}$, i.e. one tenth that of an inversion layer (this is assuming that a layer once formed is allowed to diffuse away). My observations have shown no significant change in the system over two to three weeks. Molcard [1975] has recently produced impressive evidence that the Tyrrhenian Sea layer system has a life-time that must be reckoned in terms of years. One can only conclude from this that steady-state conditions prevail and that the interfaces are maintained by convection within the mixed layer.

All this is in accordance with double-diffusion theory, in particular the salt-finger case that is applicable here. Turner has demonstrated how a series of convecting layers can be established by salt fingering. If salt fingering is going to occur in the ocean then it is at interfaces such as this where we are most likely to find it and recently Williams [1974], using an optical technique, and Magnell [1975] using a towed sensor, have demonstrated the existence of salt fingers both in the Mediterranean outflow region and also in the Tyrrhenian sea steps. The salt-finger theory, when combined with the oceanographic data, enables us to calculate the heat and salt flux through the steps and arrive at values of about 1 cm^2/s for Ks and about 0.6 cm^2/s for Kt. However, theory and observation are not quite in accordance regarding the depth dimensions of the layers but the answer to this may again be in the microstructure of the interfaces. Recent work with high resolution probes has shown the interfaces to possess their own step structure, which is more in line with the theoretical scale predictions.

3. MICROSCALE PHENOMENA

The STD systems left us with much data but few answers and it was felt that the key to the whole vertical mixing process would be in the microstructure range from 1 m to 1 cm. We needed to examine the microscale density structure for evidence of shear instabilities and of double-diffusive effects and to determine the relative roles of these two mixing processes in the ocean. The study of the fine-scale structures had given the impression of a lamina as opposed to a turbulent ocean. Some degree of turbulence must however be associated with local mixing at interfaces and boundaries.

In an attempt to gain insight into the physical processes taking place at the interface areas, users of standard STD systems pushed the resolution to the limit. Dissatisfaction with what could be achieved led to the development of what I have already referred to as the new generation instruments — the true microstructure recorders — which began to appear around 1970 and are still being developed.

Two types of instruments evolved: the free-fall self-recording type, as described by Gregg and Cox [1971], and the more traditional suspended type, such as the Niel Brown CTD. Both these instruments are capable of resolving centimetre-scale fluctuations.

Measurements with the Cox free-fall probe have been extensively discussed by Osborne and Cox [1972], Gregg and Cox [1972], Gregg, Cox and Hacker [1974], and Gregg [1975]. I have time to review only the most important aspects of this work, starting with Osborne and Cox [1972], who in a key paper laid down some basic ideas, that have had a considerable influence on subsequent work. Taking as their model a laterally-homogeneous ocean and assuming steady-state conditions they derived an expression relating the turbulent heat flow to the microscale temperature fluctuations.

They showed that the ratio of the temperature gradient variance to the square of the mean gradient is related to the actual rate of diffusion of heat relative to that which would occur due to molecular diffusion along the mean gradients. By this means they arrived at an expression for K_z:

$$K_z = k \cdot \frac{(\nabla\theta')^2}{(\nabla\bar{\theta})^2} = k \cdot C$$

where $\theta_z = \theta'_z + \bar{\theta}_z$.

The ratio $\frac{(\nabla\theta')^2}{(\nabla\bar{\theta})^2}$, which subsequently became known as the Cox number, C, in an expression of the degree of microstructure present. We thus have a means of estimating K_z from the microstructure measurements. In evaluating K_z in this manner one must assume that the temperature gradient variance measured is representative of the oceanic area in which one is working and also that there is no net lateral transport of temperature fluctuations into the region. The validity of these assumptions is still in question and a wide range of K_z values have been obtained using this technique.

The Gregg and Cox MSR (microstructure recorder) measured the temperature gradient directly as well as the temperature and conductivity profiles. In a subsequent paper, Gregg and Cox [1972] discuss a single profile taken with this instrument in the San Diego trough (Fig. 8).

The T & S points are averaged over 20 cm: it is not a full resolution record. What is striking here is the general similarity between this picture and the fine-scale Mediterranean outflow records. We have a similar situation in the presence of two water types, in this case the lower-salinity northern water and the more saline water from the south. The stability is expressed here in terms of the square of the Väisälä frequency averaged over 84 cm on the left and 5 m on the right. On the smaller scale some instabilities involving about 8% of the profile are indicated associated with the features marked AD & E, but otherwise the stable structures can be assigned to the lateral advective process.

The T/S diagram in Fig. 9 could well be a NE Atlantic T/S diagram, except for the different scale. The instability at A is obvious while those at D & E appear as loops in the T/S trace.

The high-resolution profile enables us to look at these regions in detail: e.g. Fig. 10 shows the region around feature A in Fig. 8 at a resolution of 0.36 cm. The N^2 profile is given at resolution of 2.9 cm and 84 cm.

Some degree of small-scale overturn resulting from shear instability is suggested by the high level of activity associated with the density inversion, but the picture is inconclusive. More definite evidence of billow turbulence is shown in Fig. 11. Here we have the gradient profile on the left and the temperature on the right showing a characteristic 1 m scale overturn. Gregg and Cox conclude that about 1% to 2% of any record in the area have signatures suggestive of local overturning.

On the other hand, examination at high resolution of the larger stable inversions showed that the interfaces could be resolved into several sharp steps strongly suggestive of layering produced by double-diffusive phenomena. An example is shown in Fig. 12.

Some of these are very sharp (< 2 cm in thickness). Heat flux calculations showed general agreement with measured fluxes from the laboratory experiments on double diffusion. The authors thus find evidence in the microstructure for both processes: shear instability and double diffusion. They finally apply the Osborne and Cox equation to different parts of the record and obtain values of $K_z \sim \frac{1}{2} - 1$ cm^2/s for the most active regions and 0.02 cm^2/s for the relatively "quiet" sections.

Subsequent to this work in the San Diego trough, the next observations reported were from a contrasting site, hopefully typical of mid-ocean conditions, in the centre of the sub-tropical gyre in the North Pacific [Gregg, Cox, and Hacker (1973)]. The discussion in this paper centres on the gradient spectra. Back in 1968 Roden [1968] had described STD profiles in terms of wave number spectra and this theme was taken up by several other investigators. The problem was complicated by the need to remove the overall trend in the records before spectral analysis, and results obtained were much influenced by the type of filter used. With gradient spectra this difficulty largely disappears and we have the added advantage of dealing directly with the gradient variance, which, as we have seen, is a direct expression of the microstructure.

Compared with previous near-shore records, the mid-ocean data show a distinct lack of features on the medium scale. Activity was also generally low on the microscale. A section of one record (Fig. 13) did however show a step structure of the salt fingering type.

Figure 14 shows the measured T gradient, which reveals the structure of the interfaces (high gradient) region and the mixed layers. The wing thermistor, which describes a helical path as the instrument rotates during descent, covers a distance ten time greater than that of the nose probe. In spite of this low angle of attack (6°) little additional structure is seen, which implies that the structures are horizontal. Unfortunately the detection of centimetre-scale salt fingers is beyond the cutoff of the wing probe.

4. MICROSTRUCTURE SPECTRA

Figure 15 shows a composite gradient spectra built up from STD records for the low wave numbers ($K = 2 \times 10^{-3} - 2 \times 10^{-1}$ cycle/m), from the gross temperature data for $1 \times 10^{-2} - 6$ cycle/m from the gradient measurements for 1×10^{-1} to 6×10^{1} cycle/m. The spectra divide into two groups, shallow and deep, covering the range 200 to 2000 m. Although the variance spectrum levels vary appreciably by a factor of 100 from shallow water to deep, the ratio of the variances to the squares of the mean gradients shows a range of less than two. This means that the normalized microstructure levels are uniformly low. The Cox number is about 2, which yields a vertical thermal diffusion coefficient of $K_z = 3 \times 10^{-3}$ cm²/s i.e. little above the molecular value.

This is in marked contrast to the situation near shore, where we had a value of 3.7×10^{-1}. In spite of the fact that the mean temperature gradient at the Pacific site is twice that in the San Diego trough, the spectral levels are lower at all wave numbers and by a factor of more than 50 in the microstructure range. All this points to the conclusion that the velocity shears, which generate the microstructure, must be much weaker at the mid-ocean site.

In a recent paper, Gregg [1975] discusses two profiles from stations about 10 km SW of Cabo San Lucas in the California current (Fig. 16). Although separated by only a few kilometres, these stations present quite different structures: one is similar to the mid-gyre records with an irregular "steppy" appearance and a low Cox number, while the other, which shows much activity on both medium and microstructure scales, has a large average Cox number. The first type is considered to represent the background condition of the ocean in which the levels of vertical turbulence are quite low and the principal dissipation occurs by small-scale instabilities at the step structures. The second type, characterized by the presence of appreciable medium-scale structure (due to multiple interleaving of different water types) has regions of intense microstructure activity, associated with the intrusion interfaces, which is considered to result from shear and double-diffusive effects. The San Diego trough records belong to this class.

The high microstructure levels associated with temperature inversions indicate that they are major factors in the dissipation of temperature and salinity fluctuations. While inversions occur on many vertical scales, the observations suggest that it is the ones from several metres to a few tens of metres that produce the particularly high levels of microstructure. The oceanic regions with high dissipation rates can therefore be identified from standard STD profiles. Some of these regions are reasonably well known already but much can still be learnt from STD work.

The microstructure observations have done much to identify some of the small-scale mixing processes and have given some estimates of vertical heat fluxes, rate of energy dissipation, etc. What is required for the future is associated measurements of current shear in order to determine the Richardson number on the microscale. Instruments for this purpose are being developed: Simpson [1972], Osborne [1974]. This will lead to more reliable estimates of the energy dissipation rate, ϵ, a factor of great importance in ocean physics.

All the evidence to date points toward high rates of energy exchange occurring in sporadic bursts in specific regions in an otherwise quiet ocean. The key to the active areas lies in the juxtaposition of different water masses where the presence of an appreciable fine-scale structure is a likely indicator of regions of increased acoustic variability.

REFERENCES

BETHELL, J.P. The fine structure of the ocean, SACLANTCEN TM-184. La Spezia, Italy, SACLANT ASW Research Centre, 1972. [AD 753 445].

COOPER, L.H.N. Stratification in the deep ocean. Science Progress 55, 1967: 73-90.

COOPER, J.W. and STOMMEL, H. Regularly-spaced steps in the main thermocline near Bermuda. Jnl of Geophysical Research 73, 1968: 5849-54.

GILMOUR, A.E. Temperature stratification in the western Mediterranean Sea. Deep Sea Research 19, 1972: 341-353.

GREGG, M.C. and COX, C.S. Measurements of the oceanic microstructure of temperature and electrical conductivity. Deep Sea Research 18, 1971: 925-934.

GREGG, M.C. and COX, C.S. The vertical microstructure of temperature and salinity. Deep Sea Research 19, 1972: 355-376.

GREGG, M.C. The microstructure of the ocean. Scientific American 228 (2), 1973: 65-77.

GREGG, M.C., COX, C.S. and HACKER, P.W. Vertical microstructure measurements in the central North Pacific. Jnl of Physical Oceanography 3, 1973: 458-469.

GREGG, M.C. Microstructure and intrusion in the California Current. Jnl of Physical Oceanography 5, 1975: 253-278.

HAMON, B.V. Medium-scale temperature and salinity structure in the upper 1500 m in the Indian Ocean. Deep Sea Research 14, 1967: 169-181.

HOWE, M.R. and TAIT, R.I. Further observations of the thermohaline stratification in the deep ocean. Deep Sea Research 17, 1970: 963-972.

HOWE, M.R., ABDULLAH, M.I. and DEETAE, S. An interpretation of the double T-S maxima in the Mediterranean outflow using chemical tracers. Jnl of Marine Research 32, 1974: 377-386.

HUPPERT, H.E. and TURNER. J.S. Double-diffusive convection and its implication for the temperature and salinity structure of the ocean and Lake Vanda. Jnl of Physical Oceanography 2, 1972: 456-461.

ICHIYE, T. and SUDO, H. Saline deep water in the Caribbean Sea and in the Gulf of Mexico, Ref 71-16-T. College Station, Texas, Texas A & M University, 1971.

JOHANNESSEN, O.M. and LEE, O.S. Thermohaline staircase structure in the Tyrrhenian Sea. Deep Sea Research 21, 1974: 629-639.

KATZ, E.J. Diffusion of the core of Mediterranean water above the Mid-Atlantic Ridge crest. Deep Sea Research 16, 1970: 275-295.

LAMBERT, R.B. Graduate School of Oceanography, Univ. of Rhode Island, Kingston, R.I. Private communication.

LINDEN, P.F. On the structure of salt fingers. Deep Sea Research 20, 1973: 325-340.

MADELAIN, F. Influence de la topographie du fond sur l'écoulement Mediterranéen entre le détroit de Gibraltar et le Cap Saint-Vincent. Cahiers Oceanographiques 22, 1970: 43-62.

MaGNELL, B.A., EG & G Inc. Environmental Consultants Div., Waltham, Mass. 02154. Private communication.

MOLCARD, R. and WILLIAMS, A.J. Deep stepped structure in the Tyrrhenian Sea. Mémoires Société Royale des Sciences de Liège 6 (7), 1975: 191-210.

MUNK, W. Abyssal recipes. Deep Sea Research 13, 1966: 707-730.

NEAL, V.T., NESHYBA, S. and DENNER, W. Thermal stratification in the Arctic Ocean. Science 166, 1969: 373-374.

OSBORNE, T.R. and COX, C.S. Oceanic fine structure. Geophysical Fluid Dynamics 3, 1972: 321-345.

OSBORNE, T.R. Vertical profiling of velocity microstructure. Jnl of Physical Oceanography 4, 1974: 109-115.

PINGREE, R.D. Small-scale structure of temperature and salinity near St Cavall. Deep Sea Research 16, 1969: 275-295.

PINGREE, R.D. In situ measurements of salinity, conductivity and temperature. Deep Sea Research 17, 1970: 603-610.

PINGREE, R.D. Analysis of the temperature and salinity structure in the region of Mediterranean influence in the N.E. Atlantic. Deep Sea Research 18, 1971: 841-844.

STERN, M.E. and TURNER, J.S. Salt fingers and convecting layers. Deep Sea Research 16, 1969: 497-511.

SIEDLER, G. Die Haufigkeitsverteilung von Wasserarten in Ausstromgebiet von Meeresstrassen. Kieler Meeresforschungen 24, 1968: 59-65.

SIMPSON, J.H. A free-fall probe for the measurement of velocity microstructure. Deep Sea Research 19, 1972: 331-336.

TAIT, R.I. and HOWE, M.R. Some observations of thermohaline stratification in the deep ocean. Deep Sea Research 15, 1968: 275-280.

TAIT, R.I. and HOWE, M.R. Thermohaline staircase. Nature 231 (5299), 1971: 178-179.

THORPE, S.A. Experiments on the stability of stratified shear flows. Jnl of Fluid Mechanics 39, 1969: 25-28.

TURNER, J.S. and STOMMEL, H. A new case of convection in the presence of combined vertical salinity and temperature gradients. Proceedings National Academy of Science (U.S.) 52, 1964: 49-53.

TURNER, J.S. Salt fingers across a density interface. Deep Sea Research 14, 1967: 599-611.

TURNER, J.S. The influence of molecular diffusivity of turbulent entrainment across a density interface. Jnl of Fluid Mechanics 33, 1968: 639-656.

SHIRTCLIFFE, T.G.L. and TURNER, J.S. Observations of the cell structure of salt fingers. Jnl of Fluid Mechanics 41, 1970: 707-719.

WILLIAMS, A.J. Salt fingers observed in the Mediterranean outflow. Science 185, 1974: 941-943.

WOODS, J.D. Wave-induced shear instability in the summer thermocline. Jnl of Fluid Mechanics 32, 1968: 791-800.

WOODS, J.D. and WILEY, R.L. Billow turbulence and ocean microstructure. Deep Sea Research 19, 1972: 87-121.

ZENK, W. On the temperature and salinity structure of the Mediterranean water in the northeast Atlantic. Deep Sea Research 17, 1970: 627-631.

ZENK, W. On the Mediterranean outflow west of Gibraltar. METEOR Forschungsergebnisse Reihe A, 16, 1975: 23-34.

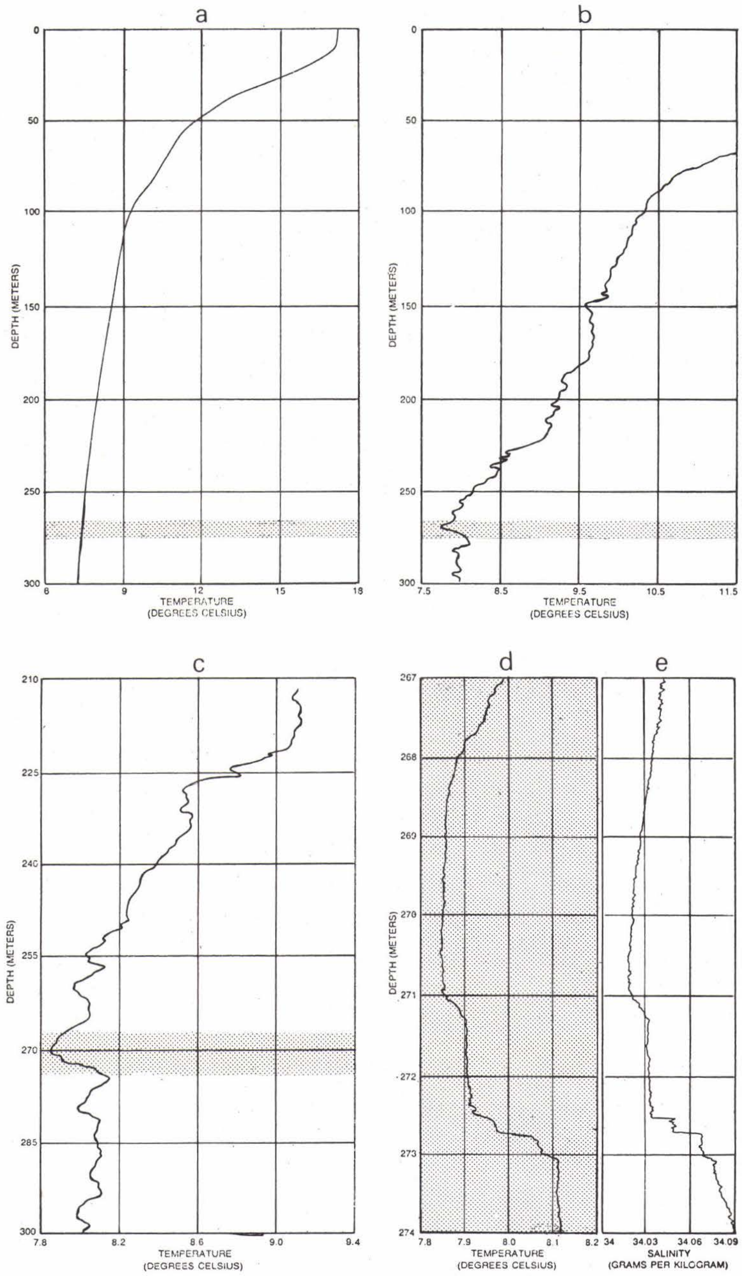


FIG. 1 TEMPERATURE PROFILES (GREGG 1973)

a. TEMPERATURE PROFILE FROM NANSEN CAST
b. STD RECORD OF THE SAME PROFILE
c. HIGHER RESOLUTION TRACE
d. CENTIMETRE SCALE RESOLUTION

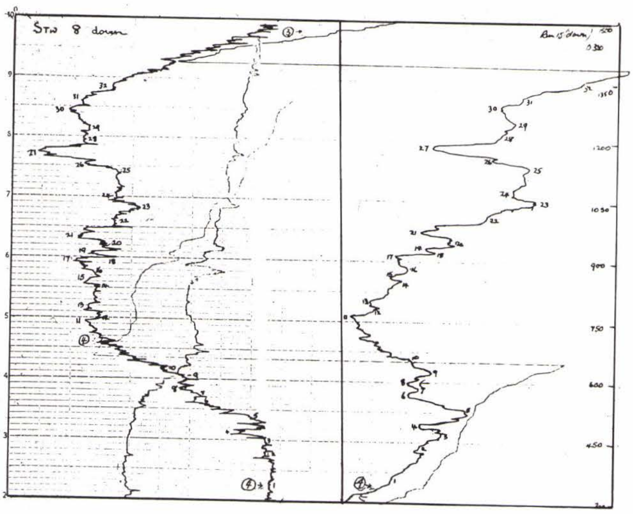


FIG. 2
STD RECORD. DISCOVERY 1966 STA. 8

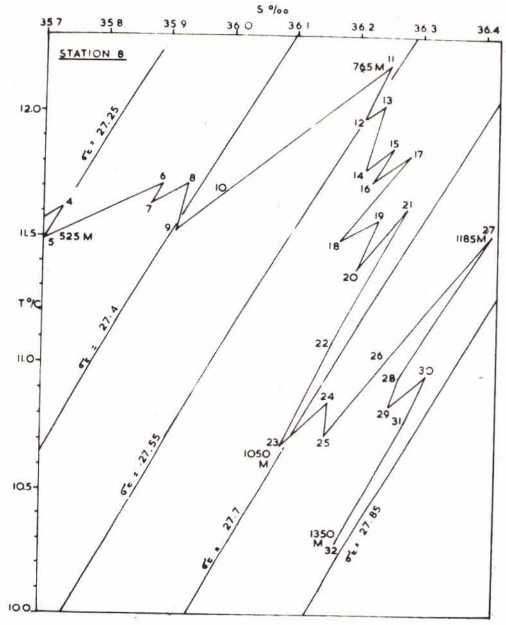
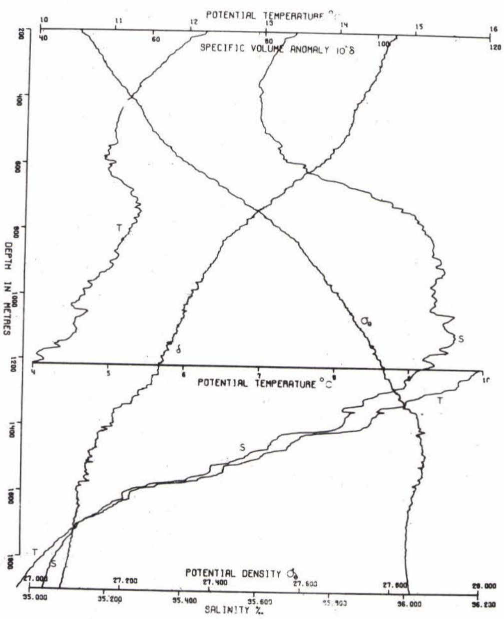


FIG. 3
T/S DIAGRAM. DISCOVERY 1966 STA. 8



The temperature and salinity profiles together with [illegible] potential density and specific volume anomaly profiles obtained using the T/S [illegible] 200 to 1900 m.

FIG. 4
PROFILES OF T, S, σ_0 & δ (PINGREE, 1970)

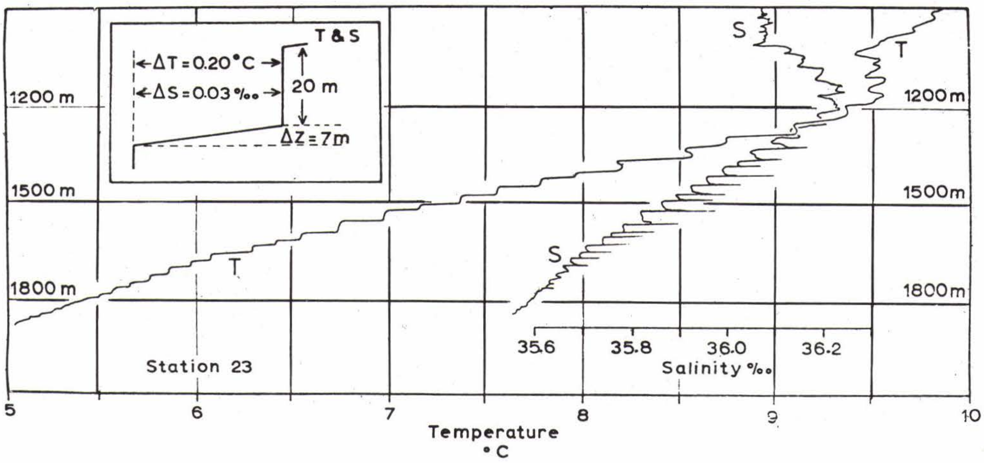


FIG. 5 THERMOHALINE STAIRCASE (TAIT & HOWE, 1970)

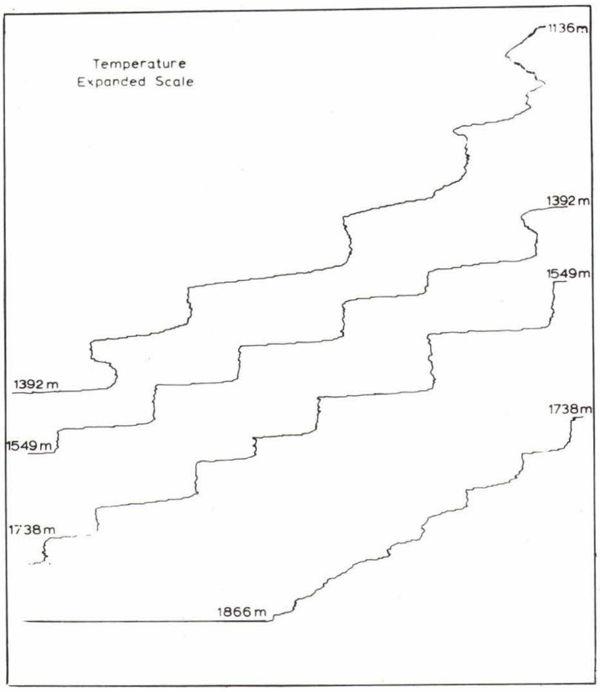


FIG. 6
EXPANDED SCALE RECORD STA. 23

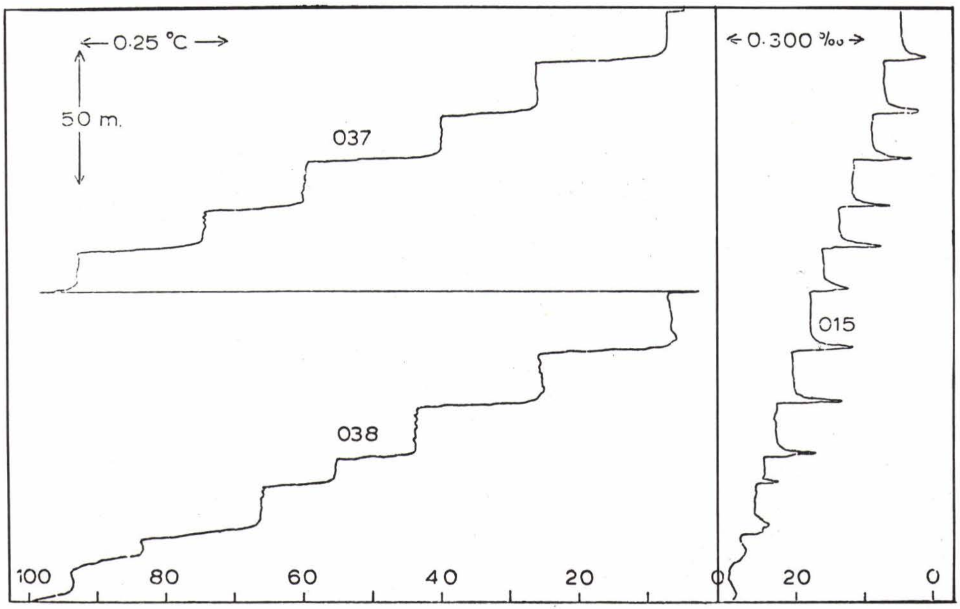


FIG. 7 EXPANDED SCALE RECORD STA. 28

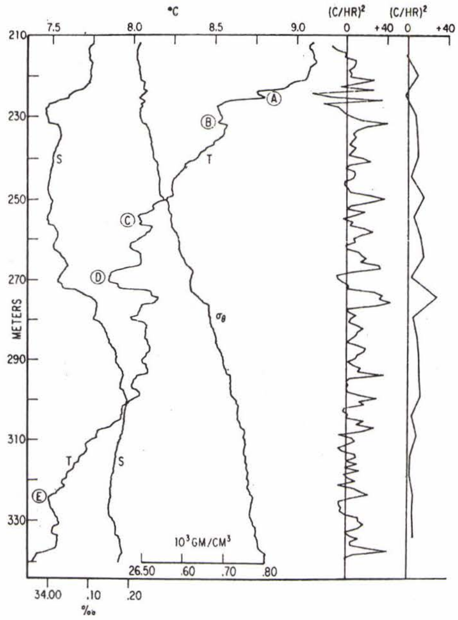
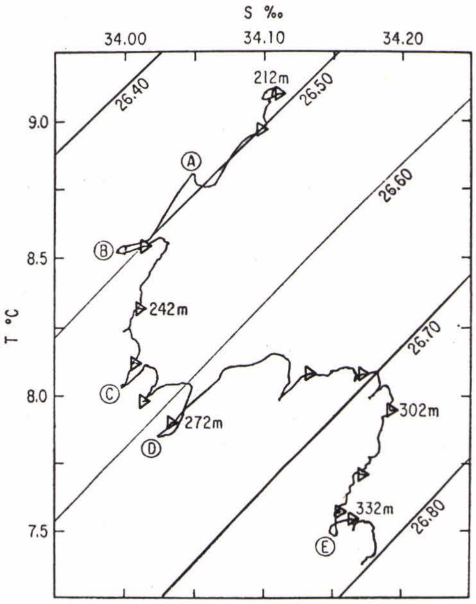


FIG. 8
MSR RECORD (GREGG & COX, 1972)

FIG. 9
T/S DIAGRAM (GREGG & COX, 1972)



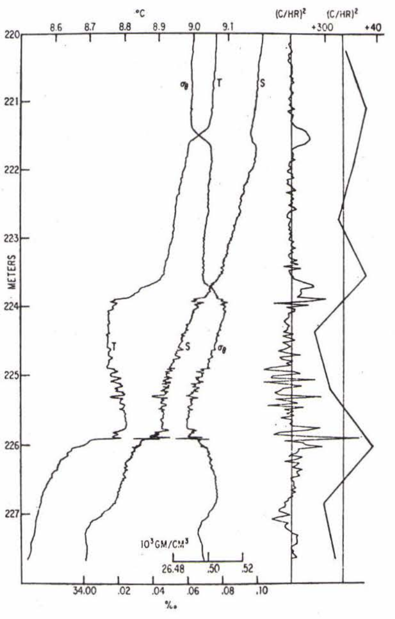


FIG. 10
MSR TRACE AT HIGH RESOLUTION (GREGG & COX, 1972)

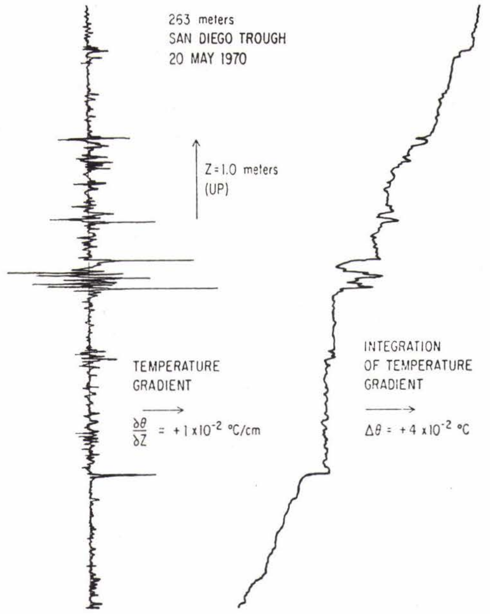


FIG. 11
HIGH RESOLUTION TEMPERATURE & TEMPERATURE GRADIENT PROFILE (GREGG & COX, 1972)

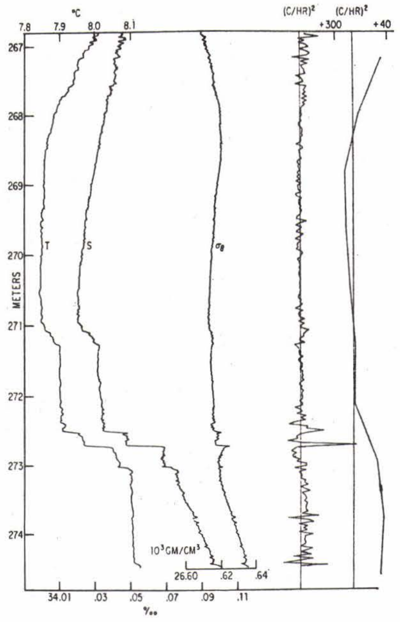


FIG. 12
MSR RESOLUTION OF INVERSION INTERFACE (GREGG & COX, 1972)

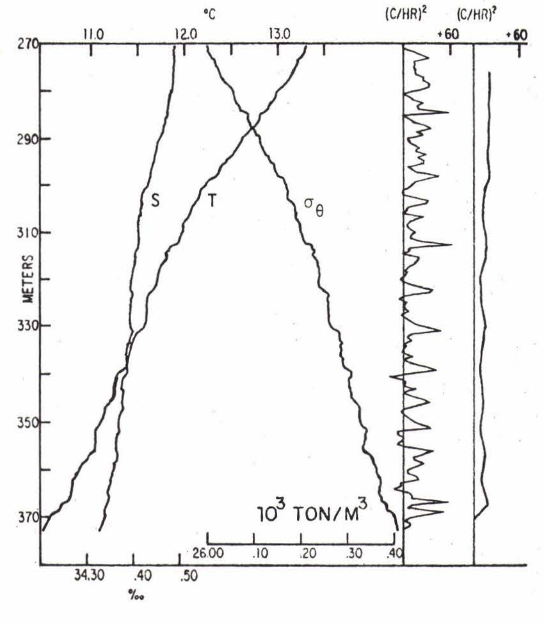


FIG. 13
MID-OCEAN STATION (GREGG, COX & HACKER, 1973)

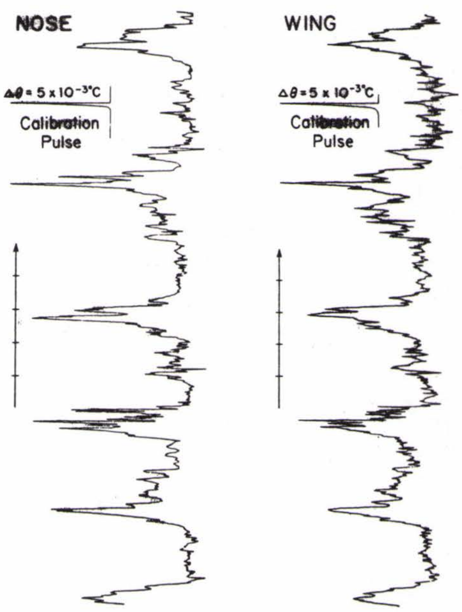


FIG. 14
TEMPERATURE GRADIENT PROFILES FOR STEP-LIKE STRUCTURES (GREGG, COX & HACKER, 1973)

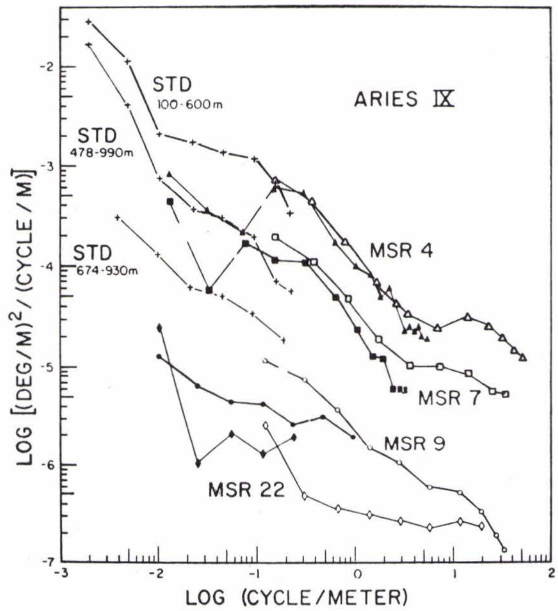


FIG. 15
GRADIENT SPECTRA – GREGG, COX & HACKER, 1973

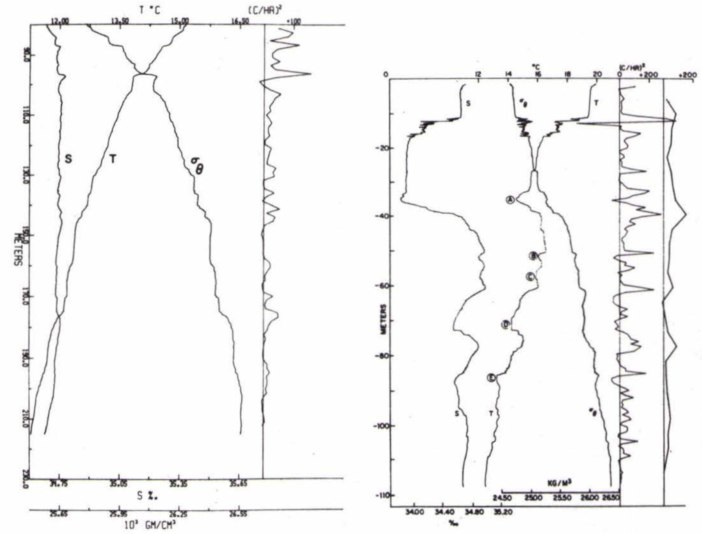


FIG. 16
MSR RECORDS SHOWING THE TWO GENERAL TYPES OF PROFILE