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# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



# THESIS

DENSITY STRUCTURE ASSOCIATED  
WITH SALT FINGERS

by

Suk In Lee

September 1983

Thesis Advisor:

T. R. Osborn

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(continuation of abstract)

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The observed small scale temperature and velocity data were examined to find signatures which might be due to salt fingers. Then the CTD data from the depth of these signatures were examined to verify whether the mean water properties were suitable for fingering to have occurred. The regions corresponding to six observed patches of potential fingers were located on the T-S plot. All occurred where salinity and temperature decrease with depth. This result supports their identification as fingers.

The results suggest that one group of the salt fingers had a horizontal extent of at least 300m and a vertical extend of less than 1m.



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Density Structure Associated with Salt Fingers

by

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Submitted in partial fulfillment of the  
requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

from the

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ABSTRACT

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## I. INTRODUCTION AND OBJECTIVE

### A. SALT FINGERING SIGNATURE

There is increasing evidence that salt fingers are an important mechanism for cross-isopycnal transport in the ocean. There is a large body of laboratory data available, but very little information from oceanic measurements. The laboratory experiments show that salt fingering convection arises from a local instability when both the temperature and the salinity decrease with depth, i.e., at a region with relatively warm, salt water in upper layer and cool, fresh water in lower layer. The salinity gradient reduces the density stratification that is due to the temperature gradient. Experiments have shown that the vigor of the fingering convection depends on the relative contributions of the temperature and salinity gradients to the density gradient.

An important parameter for the salt finger is the density ratio  $R \equiv \alpha \Delta T / \beta \Delta S$ , where  $\alpha \Delta T$  is the density change due to the temperature changes and  $\beta \Delta S$  is the density change due to the salinity changes. Schmitt (1979) showed that the growth rate of salt fingers is larger, with e-folding times as short as one Brunt-Väisälä period, in regions where the value of  $R$  approaches 1, while the growth rate falls off for values of  $R$  in the range from 2 to 3.





Huppert and Manins (1973) showed that the fingers can exist for values of  $R$  as large as 700. It is important to determine the range of values for  $R$  in which salt fingers are found in the ocean.

Small scale temperature and velocity measurements and CTD data were collected from the USS DOLPHIN (Figure 1) near San Diego at  $32^{\circ}46.1'N$ ,  $117^{\circ}34.2'W$  (Figure 2) on April 22, 1982. The small scale temperature and velocity measurements show signatures in the temperature gradient data that suggest both salt fingering and turbulence. In Figure 3, we can see two distinctive signatures. One is a turbulence signature that shows the temperature gradient fluctuations with large (measureable) velocity shear fluctuations. The other one is interpreted as a salt fingering signature in that it has the temperature gradient fluctuations without velocity shear fluctuations. Such data have not been observed in the past with vertically profiling instruments, lending further credence to the explanation of salt fingering convection, since salt fingers are aligned vertically and would be missed by a vertical falling profiler.

The major objective of this thesis is to examine some of the small scale temperature and velocity data in detail, to find the signatures which might be due to salt fingers, and then to examine the temperature and salinity fields to see if they were suitable for fingering to have occurred.



## B. CTD DATA PROCESSING

To study the large scale temperature and salinity fields, the measurements of the temperature and electrical conductivity obtained with Neil Brown Instruments Systems (NBIS) CTD probes mounted on the submarine must be converted to temperature and salinity.

There are several constraints in dealing with the CTD data. First there are many bad data points in the electrical conductivity data which show up as bad points in the calculated salinity. These bad values are due to biological fouling of the electrical conductivity sensor and to an unknown problem in the digitizing system of the CTD. The digitizer problem also affects the temperature channel and, hence, contaminates the salinity through the temperature signal as well as through the electrical conductivity values. The best approach for correcting CTD data for sensor response is to filter both the temperature and conductivity data so that there is no mismatch in the response of the two sensors. We can't use this approach for the preliminary analysis because of the noise spikes which must be removed before any filtering process and because we do not have sufficient information about the sensors' response functions. We want to develop a simple processing system to guide the preliminary analysis in order to decide on how much effort should be spent on the CTD data.



The second objective of this thesis is to determine a simple processing scheme for the CTD data to enable us to determine the relative contributions of salinity and temperature to the local density stratification. The resulting processing scheme will be used to support the salt fingering studies outlined in the first objective.





## II. DESCRIPTION OF THE INSTRUMENTATION AND DATA PROCESSING

The NBIS CTD and the turbulence package were mounted on a tripod 4.2m above the bow of the USS DOLPHIN (Figure 1). The details of the data acquisition and the data processing procedures are described in this section. NBIS CTD transducers and one acoustic current meter were located 1/2m below the turbulence package. The turbulence package, built at University of British Columbia, was mounted on top of the tripod. While there are other instruments on the DOLPHIN, in this thesis we examine only the data from the CTD and the turbulence package.

### A. CTD

The CTD system mounted on the submarine is a modification of the usual commercial model manufactured by the Neil Brown Instruments Systems. The system contains the usual electrical conductivity sensor, platinum resistance thermometer, and fast thermistor. These sensors are augmented with a three component acoustic current meter to measure the velocity of the submarine. In addition, the system records the data from the fast thermistor separately from the platinum resistance thermometer. Some of the commercial systems combine the signals from the two temperature sensors into one signal.



The conductivity sensor is a 3cm long tube with a square cross section 4.95mm along each side (Figure 4). The wall thickness of the material is .48mm. There are four electrodes, two to carry the current and two to sense the voltage. The sensor has been discussed in detail by Gregg et. al. (1982). The fast thermistor is a Thermometrics FP07, the same type of thermistor that is used in the turbulence package.

The digitization interval for the data points is .038 seconds. The data are written onto magnetic tape with 28 consecutive samples of every data channel forming a tape block. Timing information is included in the tape header information for each block. The timer of the NBIS system was manually synchronized to the master clock which generated the timing information recorded by the turbulence package. Because each block represents 1.064 seconds in time, and because the computing is easiest when handling complete tape blocks, it is "natural" to average the data by blocks on the tape. Hence the data are referred to by two names in the laboratory, "scan data" are individual readings, and "block data" are the averaged values derived by averaging over the tape blocks. It would have been much more convenient for many reasons if the CTD data were sampled or blocked on the tape in units that converted simply to integral units of seconds. The major problem is the sample interval of .038 seconds.



The NBIS CTD data are converted to engineering units using the nominal calibration values which are shown in Appendix A. The fast thermistor data must then be linearized to correct for the electronic circuit. The third order polynomial correction formula is also given in Appendix A. These coefficients are calculated from calibration data furnished by NBIS.

The salinity is calculated from the formulas of Lewis and Perkin (1981). The density is calculated from the formulas of Millera and Poisson (1981). Before starting this project, some preliminary calculations had been done using block data for conductivity and the slow temperature. This work showed a considerable amount of "spiking" on the salinity plots due to the sensor mismatch. An often used technique to reduce this spiking is to add a bit of the temperature gradient to the temperature data to "speed up" the temperature sensor. This approach was tried with some success, but it was decided that a much more appropriate approach would be to use the fast thermistor data. Thus the linerization scheme for the fast thermistor data was developed. The problem then became one of determining how much to enhance the fast thermistor data by adding in some of the temperature gradient.

This thesis focuses on a subset of the data (Figure 5), specifically the data collected on 22 April 1982 between 30m and 45m depth. The temperature and salinity profiles





are shown in Figures 6 and 7. The upper layer is relatively well mixed in salinity compared to the temperature. There is a salinity decrease around 36m depth suggesting the possibility of doubly diffusive convection.

The submarine (Figure 5) descended from the surface to a depth of 37.5m, rose to a depth of 34.5m, and then descended again. The linearized fast thermistor data and the conductivity data are used on a scan-by-scan basis to calculate the salinity, and the fast thermistor data and the salinity are used on a scan-by-scan basis to calculate the density. There are spikes in the calculated salinities (Figure 7) due to the sensor mismatch of the fast thermistor and conductivity.

The first attempt to reduce the spiking was to add a small amount of the temperature gradient to the fast temperature to generate an enhanced temperature. The enhanced temperature is calculated before the salinity and density are calculated and then used to those calculations instead of the fast temperature. The enhanced temperature is calculated from the formula:

$$ET(j) = T(j) + \delta (T(j) - T(j-1))$$

where  $T(j)$  is the  $j$ th value of the fast temperature,  $ET(j)$  is the  $j$ th value of the enhanced temperature, and  $\delta$  is an adjustable parameter that is changed to get the best results





as judged by a detailed visual examination of the profiles. The judgement is subjective.

The resulting salinity profiles were calculated with different values of  $\delta$ . For the scan data plots the most appropriate value of  $\delta$  was found to be about 1. Samples of the results with  $\delta=1$  are shown in Figures 8 and 9 for the same portions of the profile seen in Figure 7. A different portion of the temperature and salinity profile is shown in Figures 10 and 11 with  $\delta=0$ , and Figures 12 and 13 show the enhanced temperature and salinity profile with  $\delta=1$ . While the use of the enhanced temperature reduces salinity spiking in some regions, especially where the temperature gradient is relatively small, it does not reduce the salinity spiking in all regions. Thus the enhanced temperature does not reduce the salinity spiking in general. The important result is that no value of  $\delta$  is appropriate all the time in this data set. Therefore, the linearized fast temperature, with no enhancement, is used henceforth for calculating salinity in this thesis.

## B. TURBULENCE PACKAGE

The turbulence package is an adaptation of the turbulence measurement technology developed for freefall vehicles to the horizontal measurements with the submarines. The system is described by Osborn, Lueck and Gargett (1981). It measures the downstream variations of the vertical velocity



fluctuation ( $\partial w / \partial x$ ), the downstream variations of the lateral velocity fluctuation ( $\partial v / \partial x$ ), the temperature, the temperature gradient, and the three perpendicular components of acceleration. The calibration of the turbulence package is described in a manuscript report (Osborn and Lueck, 1983).

The velocity shear probes response to small scale velocity fluctuations at the size scales over which the dissipation of mechanical energy occurs in the ocean (.01 to 0.5m). If the water is of uniform temperature, there are no associated fluctuations in the temperature gradient. If there is even a small mean gradient, small scale temperature gradient fluctuations about the mean value are seen. This observation has been developed into a "rule of thumb" that two-sided temperature gradient fluctuations are a sign of small scale turbulence (Crawford and Osborn, 1978). The submarine measurements show small scale temperature gradient fluctuations with the associated velocity shear fluctuations (Figure 3). However, the submarine data also contain many regions where there are small scale temperature gradient fluctuations with no velocity shear fluctuations above the noise level of the system (Figure 3). The work of Gargett and Schmitt (1982) leads one to associate these signatures with salt fingering (Turner, 1973). The next step is to examine the mean temperature and salinity field associated with the specific turbulence package data signatures.



### III. DATA ANALYSIS

In this section, we use the CTD data in the form of temperature-salinity plots (T-S plots) to examine the relative contributions of salinity and temperature to the local density stratification. For the small scale temperature and velocity data, the locations of suspected regions of salt fingering convection are transferred to the T-S profile to verify whether the mean fields are suitable for fingering to have occurred. Finally, we examine both data sets to determine the range of values for R, the occurrence of salt-finger-like signatures, and their correspondence.

The T-S diagram is a plot of salinity against temperature. The depth is an implicit variable; i.e., a parameter of a particular T-S curve. This type of plot can show density changes if lines of constant density are plotted also. The constant density line is determined by connecting several points which have the same density but different values of temperature and salinity. In this thesis 16 values of temperature and salinity were used to determine the lines of constant density. In Figure 14, the solid lines represent the line of constant density;  $R=1$ . If a portion of the T-S relation for a water mass is parallel to the lines of constant density then  $R=1$  for that portion of the water mass. The  $R=2$  line was drawn by making a line with a slope of  $1/2$  of





$R=1$  line and an  $R=n$  line has  $1/n$  of the slope of the  $R=1$  line. The constant density line is drawn for four values of  $\sigma_t$  ( $(\rho-1) \cdot 1000$ , where  $\rho$  is density); 25.1, 25.06, 25.02, 24.98.

In Figure 3, we can see the two different types of temperature gradient fluctuations signatures, one is not associated with velocity shear fluctuations and the other one has velocity shear fluctuations. Spectra of the temperature gradient in the upper patch shows it to be band-limited like the spectra of salt finger signatures in Gargett and Schmitt (1982). The temperature differential plot of the CTD allows us to locate the same features on the T-S plot (Figure 15). We can then locate the correct spot on the T-S relation with absolute assurance. Figure 15 shows the two regions seen in Figure 3; the upper one can be identified with a value of  $R$  that is less than 2 in the upper portion and about 2 in the lower portion. The other region can be identified as a turbulent patch which is below the salinity minimum so salt fingering can not occur. This evidence leads us to conclude that the upper patch is probably due to salt fingers.

If we transfer times and depths from the turbulent plots, we do not get perfect agreement between Figure 3 and Figure 15 on the vertical extent of the lower patch. The region in the temperature profile from the CTD in Figure 15 is not the



same thickness as in Figure 3 because of the horizontal variations of the turbulent patch.

Several salt finger regions might be expected from the T-S plot of CTD data where the value of R generally ranges from 1 to 2. The expected salt finger regions are #a, #b, #c, #d, #e and #f, and they are shown in Figure 16. For these regions the value of R is about 2, except region #e where R is less than 2. The region #c had three samplings since the submarine first descended, ascended and descended again.

It was already mentioned that the salt fingers can occur where relatively warm, salty water lies above cool, fresh water. We can identify several regions which have the temperature gradient fluctuations without large velocity shear fluctuations as regions #1 through #6 in Figure 17. Region #2 and the first part of region #3 show a temperature increase with time, but, as we can see in Figure 5, those two regions are the ascending portion of the submarine track. Thus, these two regions actually have the temperature decreasing with depth. Based on our previous study of Figure 3, these six regions are identified as probably having salt fingers. Variations in regions #2 and #4 are not as intense as in regions #1, #5 and #6. Region #6 has the strongest temperature gradient.

The salt finger regions are located on the T-S diagram in Figure 18 in order to determine the value of R in the T-S



profile. Region #1 has a R value of 2 to 3 in the upper portion, 3 to 4 in the middle portion, and greater than 4 at the lower portion (which is believed to be the same portion as the first descending portion of region #c in the CTD data). Region #1 has a 43.7m horizontal scale and a 0.9m vertical scale (see Figure 20). Region #2 has the value of R=3 in the upper portion and R>4 in the lower portion and is the ascending segment from the depth of 35.9m to 35.6m (which is believed to be the same segment as the ascending segment of region #c in the CTD data). Region #2 has a 7.4m horizontal scale and a 0.3m vertical scale (see Figure 20). Region #3 has the value of R=3 and this is the top area of the loop of the submarine track. The highest temperature point of region #3 is the top of the loop of the submarine track, since the shallowest depth has the highest temperature. In region #4, R>4, which is believed to be the same region as the second descending portion of region #c in the CTD data. Region #4 has a 32.5m horizontal scale and a 0.9m vertical scale (see Figure 20). The temperature of the lower portion of regions #1, #2 and #4 is 13.7°C; hence, we expect that they are in the same patch. In region #5, R=2 in the upper portion and R=2 to 3 in the lower portion. Region #6 has the largest fluctuations in T-S diagram; in it, R=1 to 2 in the upper portion, R=2 in the middle portion (which has the largest temperature gradient fluctuations), and R=3 to 4 in the lower portion of region #6.





The relationship between the regions (which are from CTD data indicated by #a - #f and the small scale sensors indicated by #1 - #6) is shown in Figure 19. As can be seen, region #1 is related to regions #a and #b. The lower portion of region #1 consists of the first descending portion of region #c in the CTD data. Regions #2 and #4 consist of the ascending and descending parts of region #c in the CTD data. The latter portion of regions #1, #2 and #4 has no clear signature in the small scale temperature gradient data.

Region #3 was not expected to show strong salt fingering from the T-S diagram of CTD data because R is about 3, but the signatures in region #3 are quite obvious in the temperature gradient data in Figure 17. Region #5 is relatively well matched with #d and the signature in region #5 is quite clear in the temperature gradient data and R is about 2 in T-S diagram of the CTD data. Region #6 is related to regions #e and #f, and the middle portion of region #6 has the largest fluctuations in the turbulence patch, and also in region #e, R is 1 to 2. Generally, the salt finger signatures from the small scale temperature gradient data are well matched with the expected regions of the T-S diagram of CTD data. In region #3, which is clear in small scale temperature gradient data, the fingers are quite prominent in spite of the lower growth rate where R is about 3. Thus temperature gradient signatures, suitable for fingering to





have occurred, are found with values of the density ratio from the range of rapid growth,  $R=1$  to  $2$ , to values of  $R$  greater than  $4$ .



#### IV. CONCLUSIONS

The following conclusions have been reached on the basis of the work discussed in this thesis:

1) The fast temperature and the conductivity data are suitable for preliminary analysis of the CTD data. No simple algorithm for the enhancement of the temperature (by adding some of the gradient) reduces the salinity spiking problem in general.

2) The small scale temperature and velocity measurements show regions of salt fingers and turbulence patches. Salt fingers appear as temperature gradient fluctuations without velocity shear fluctuations.

3) Six salt finger features were found in the small scale temperature gradient data within the depth range of 31m to 41m. They occurred over a wide range of  $R$ , ranging from  $R=1$  to 2 (where growth is fastest) to values of  $R>4$ .

4) The salt finger region identified as #c on the T-S plot, which is believed to be the same portion of the ocean as regions #1, #2 and #4 in the small scale data, had a horizontal extent of at least 300m and a vertical extent of less than 1m.





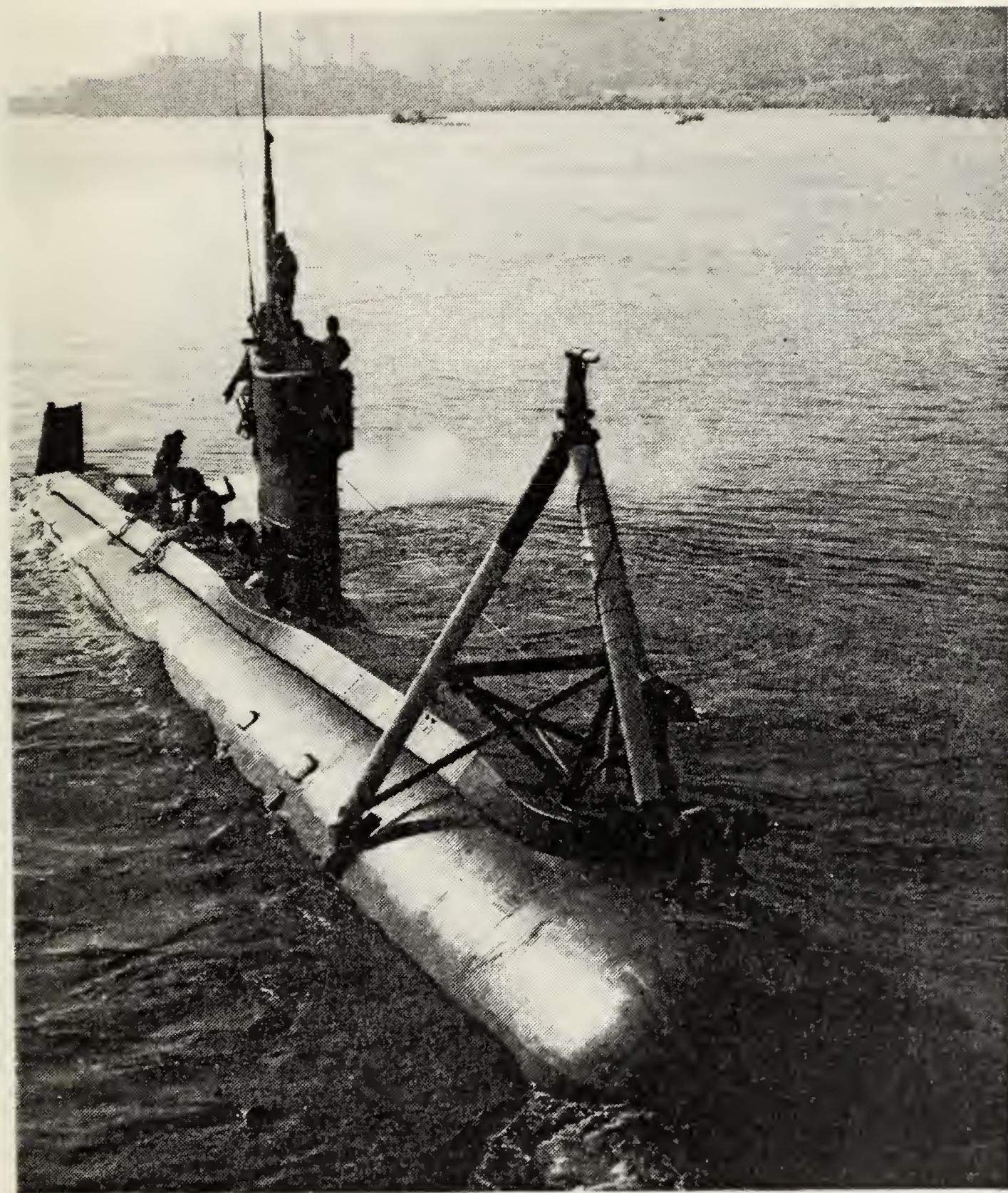


Figure 1. Photograph of Instruments. The turbulence package was mounted on top the tripod 4.2m above the deck of the USS DOLPHIN. The NBIS CTD transducers and one acoustic current meter were located 0.5m below the turbulent package.





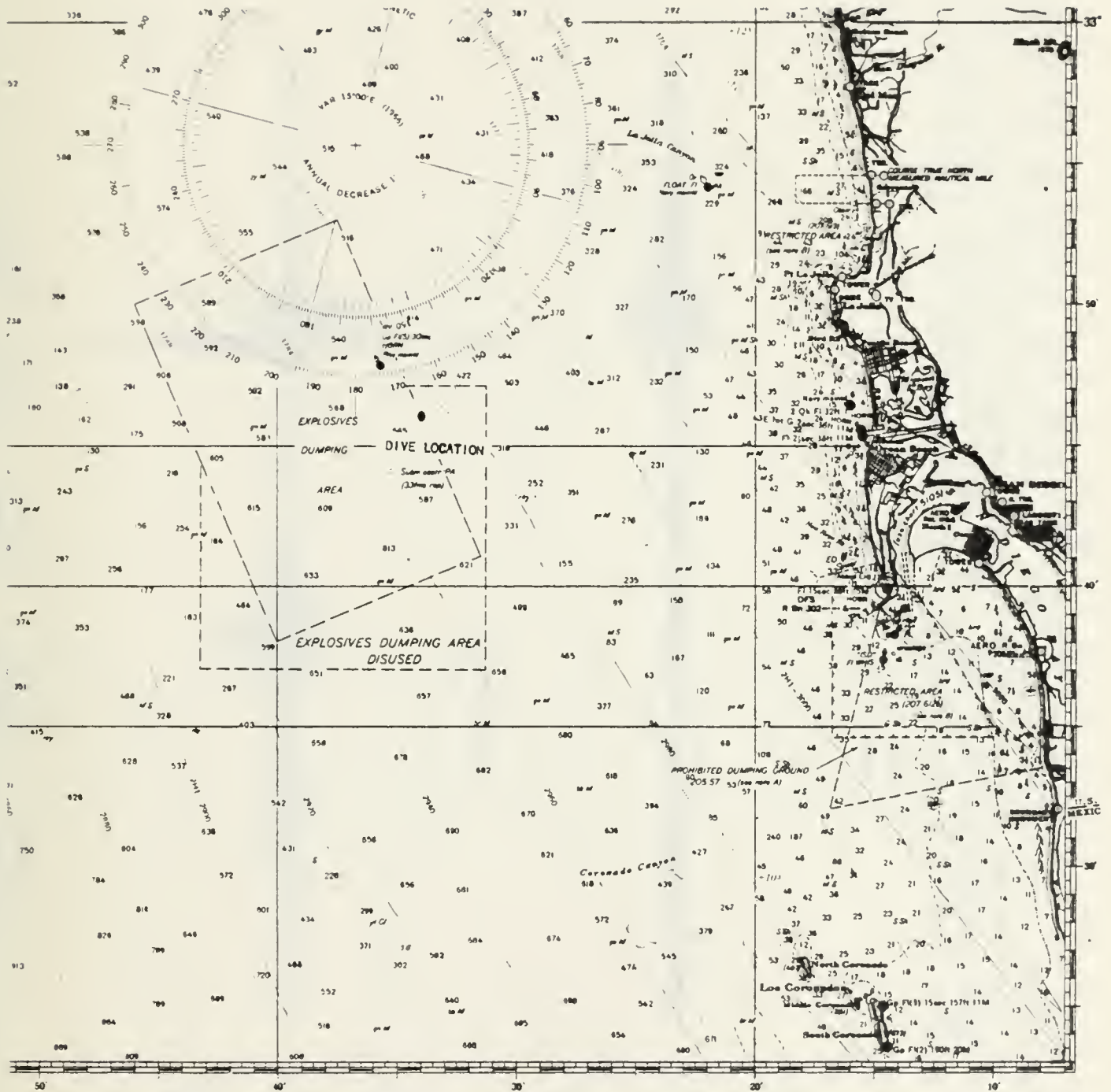


Figure 2. Dive Location. The data were collected at 15 miles west ( $32^{\circ} 46.1'N$ ,  $117^{\circ} 32.2'W$ ) near San Diego on April 22, 1982 by the USS DOLPHIN.



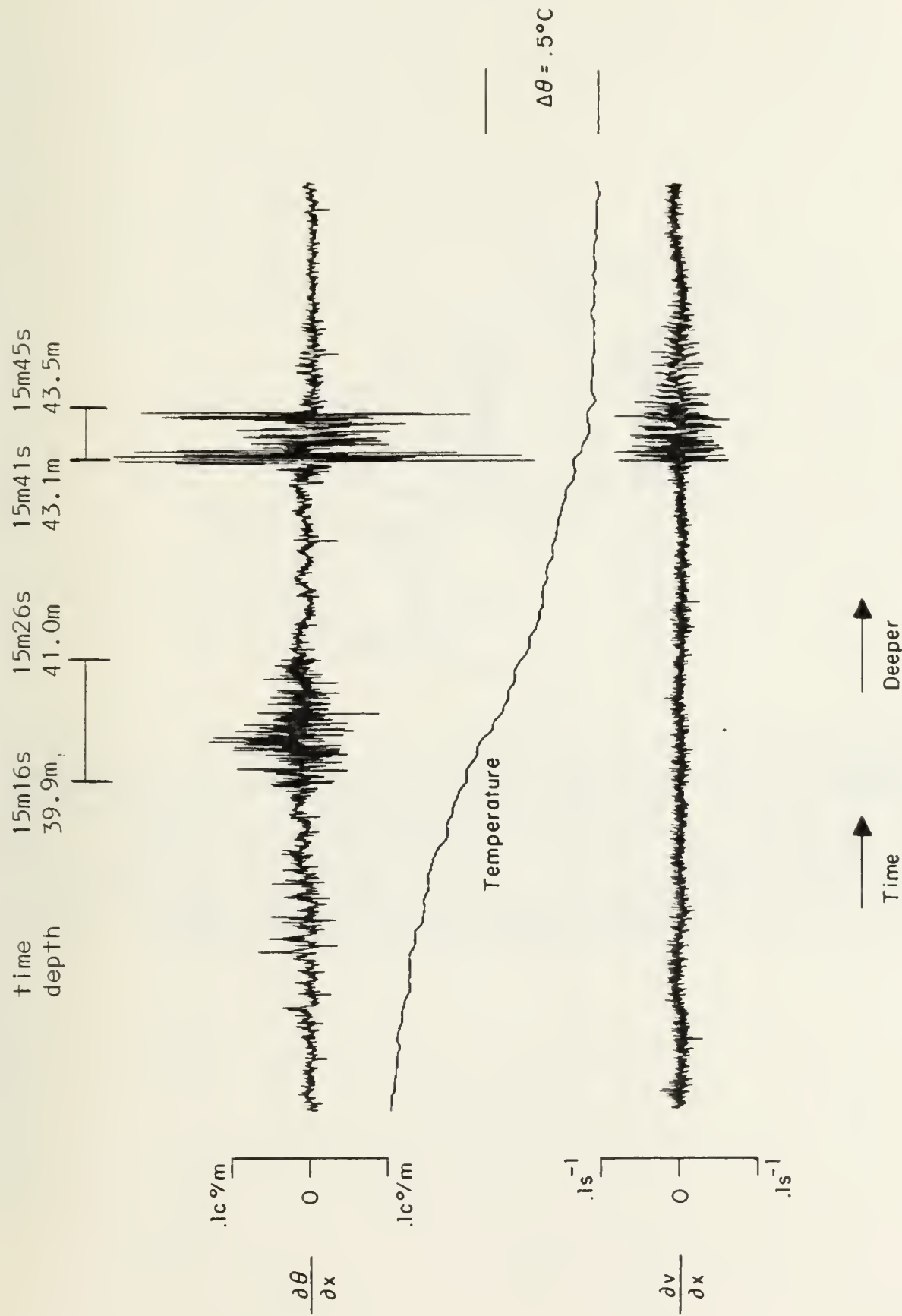


Figure 3. Analog Traces of the Small Scale Temperature and Velocity Data Between 30m to 50m. These data show the two different distinctive signatures. One is a salt finger signature which has temperature gradient fluctuations without velocity shear fluctuations. The other signature is from a turbulent patch which has the temperature gradient fluctuations associated with the velocity shear fluctuations.



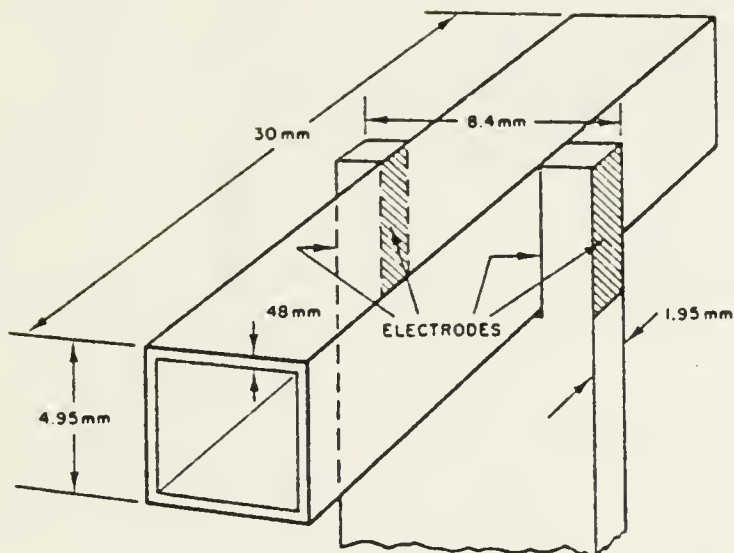


Figure 4. Schematic Illustration of Conductivity Sensor. Schematic illustration of the geometry of the conductivity sensor, which is the standard for use with NBIS CTD system. Two of the four electrodes are shown and could be either the current or voltage pair. (From Gregg & Schedvin, "Dynamic Response Calibration of the Neil Brown Conductivity Cell", Journal of Physical Oceanography, Vol. 12, 1982)



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 FROM SCAN NUMBER 100884 TO 136752

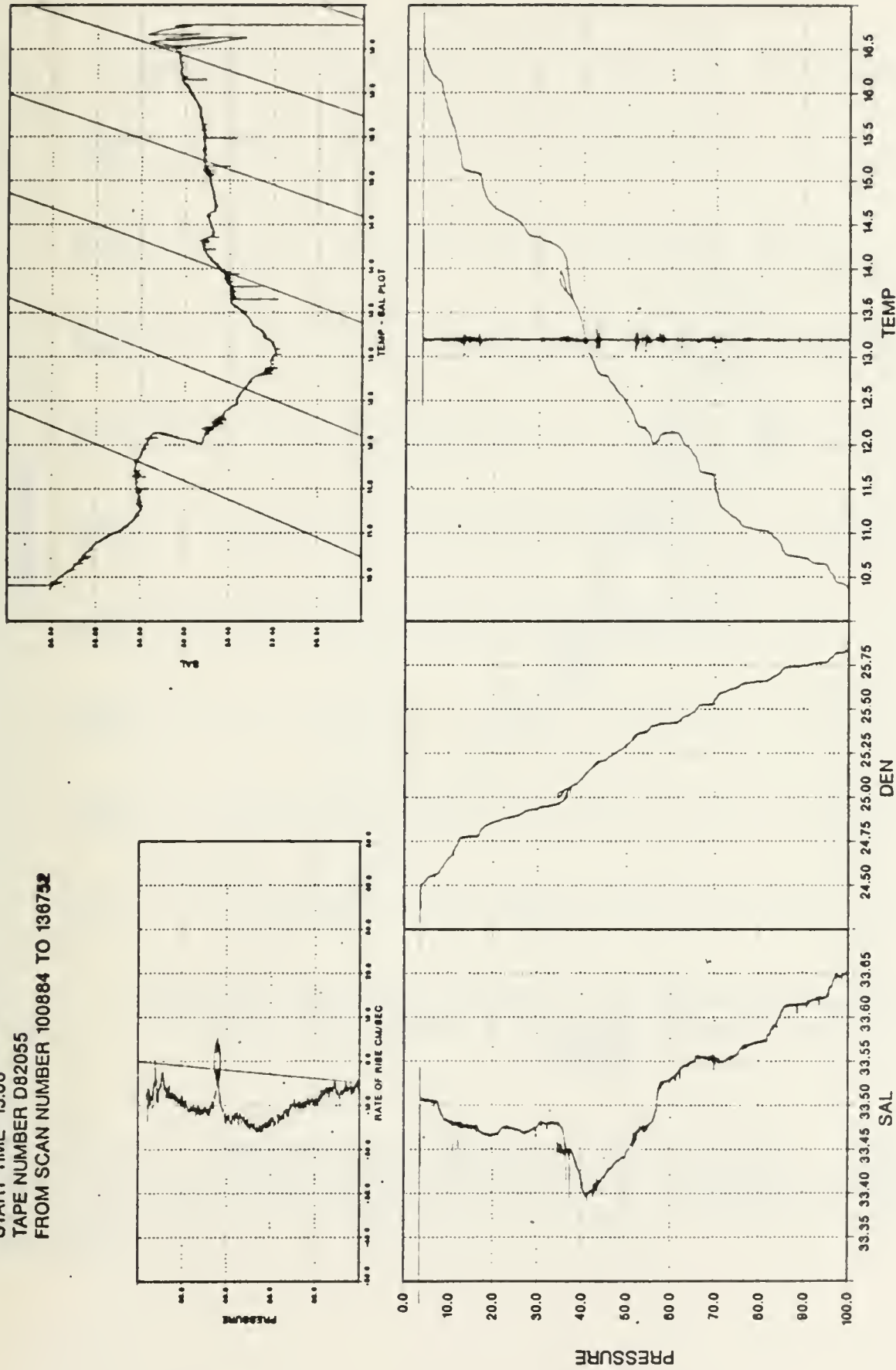


Figure 5. CTD Data (Surface to 100m). This thesis focuses on the data between 30m and 45m depth. The graph on the upper left side shows the vertical speed vs depth plots, the pressure (in decibars) indicates the ascending/descending motion of submarine.





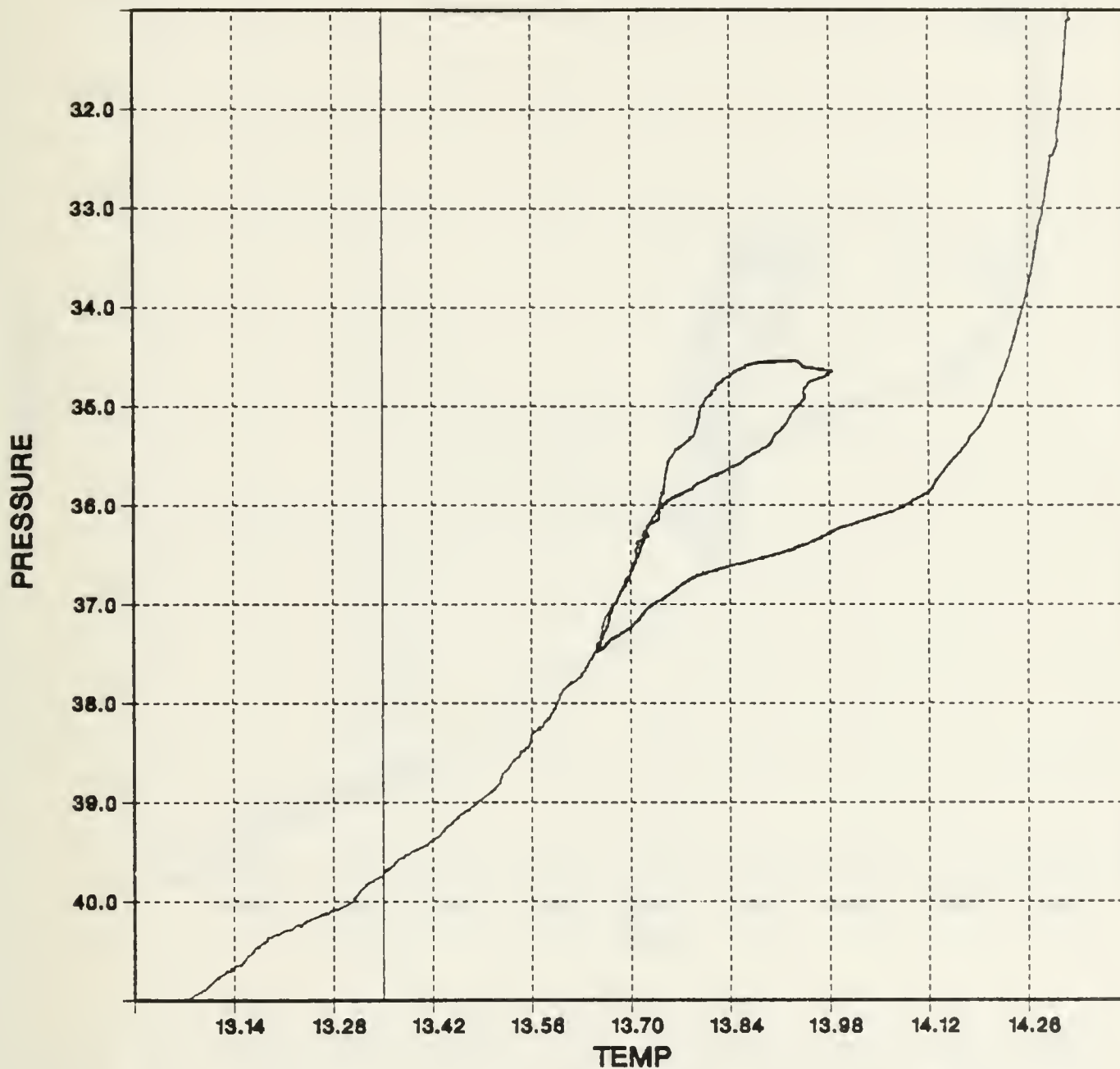


Figure 6. Temperature Profiles (31m to 41m). Temperature profile at the depth of 31m to 41m. Pressure units are decibars which are approximately equal to depth units in meters.



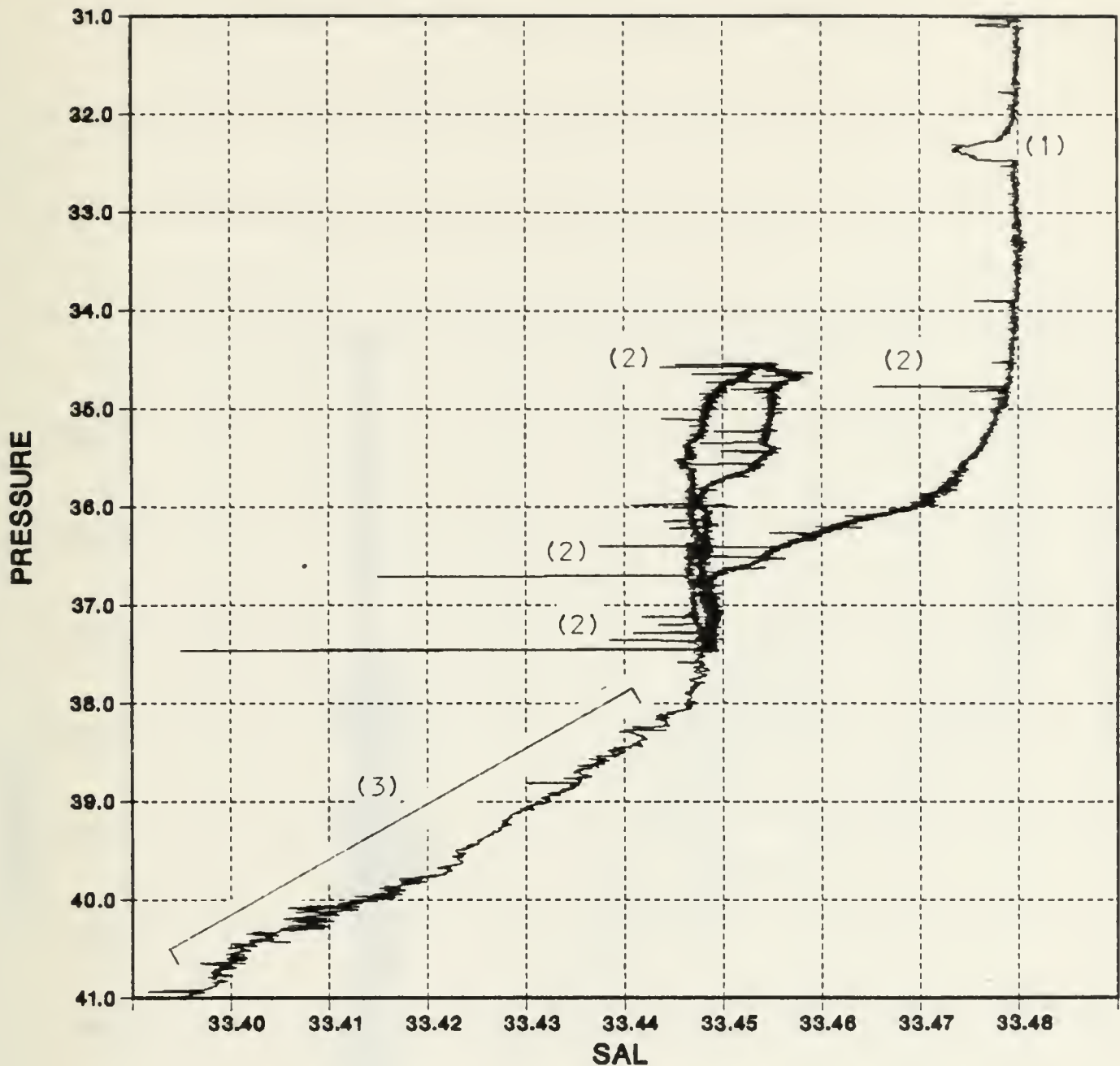


Figure 7. Salinity Profile (31m to 41m). Salinity profile at the depth of 31m to 41m. The upper layer is well mixed compared to the temperature. The salinity decreases with depth below 35m suggesting the possibility of double diffusive convection. Region (1) shows abrupt salinity change associated with the slight temperature change in Figure 6. Region (2) shows noise due to digitizer errors or biological fouling. We see salinity spiking in region (3).



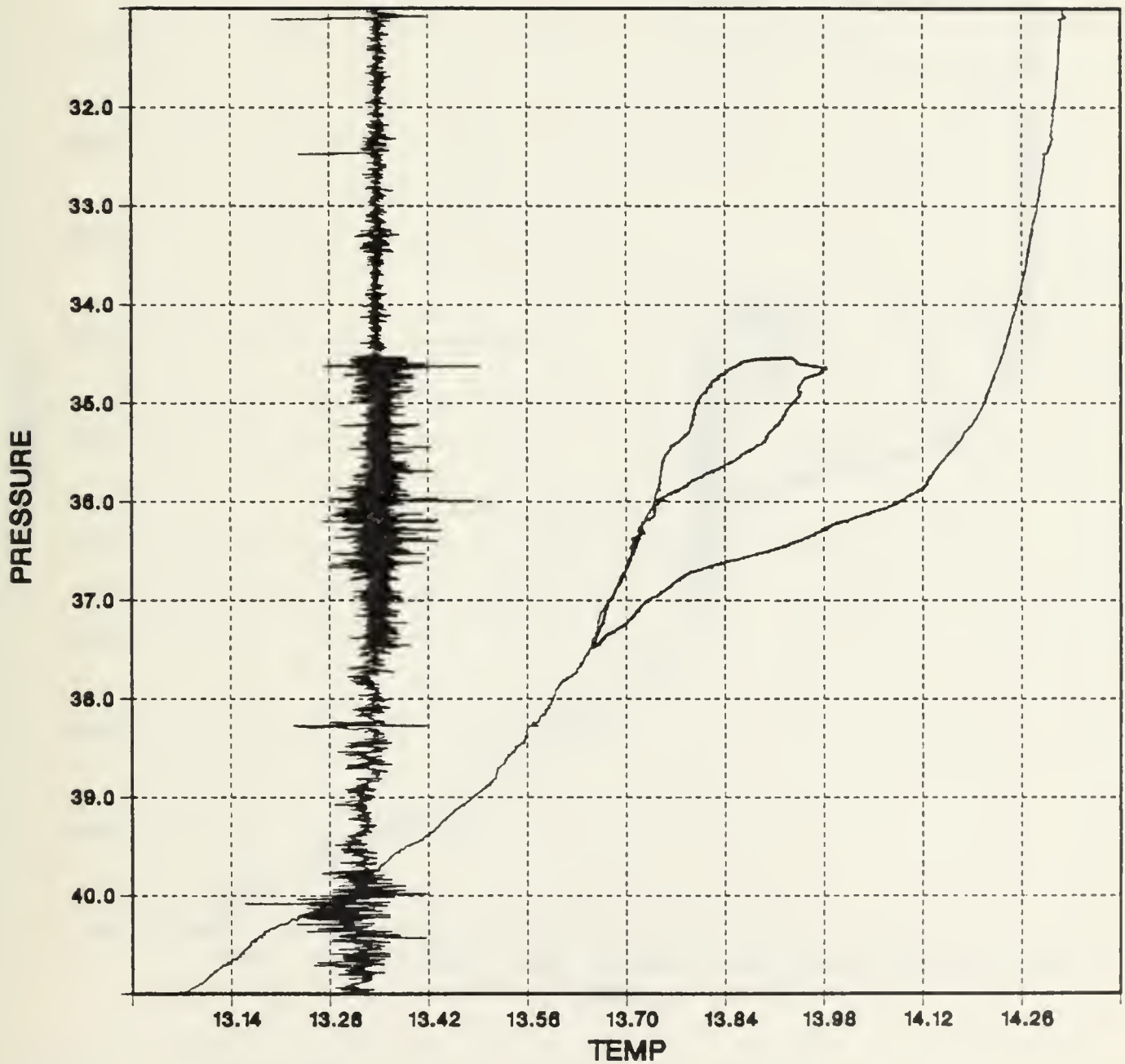


Figure 8. Enhanced Temperature Profile with  $\delta = 1$ . The vertical data trace is the difference between the enhanced temperature and the fast temperature multiplied by 30 and plotted relative to  $13.3^{\circ}\text{C}$ .





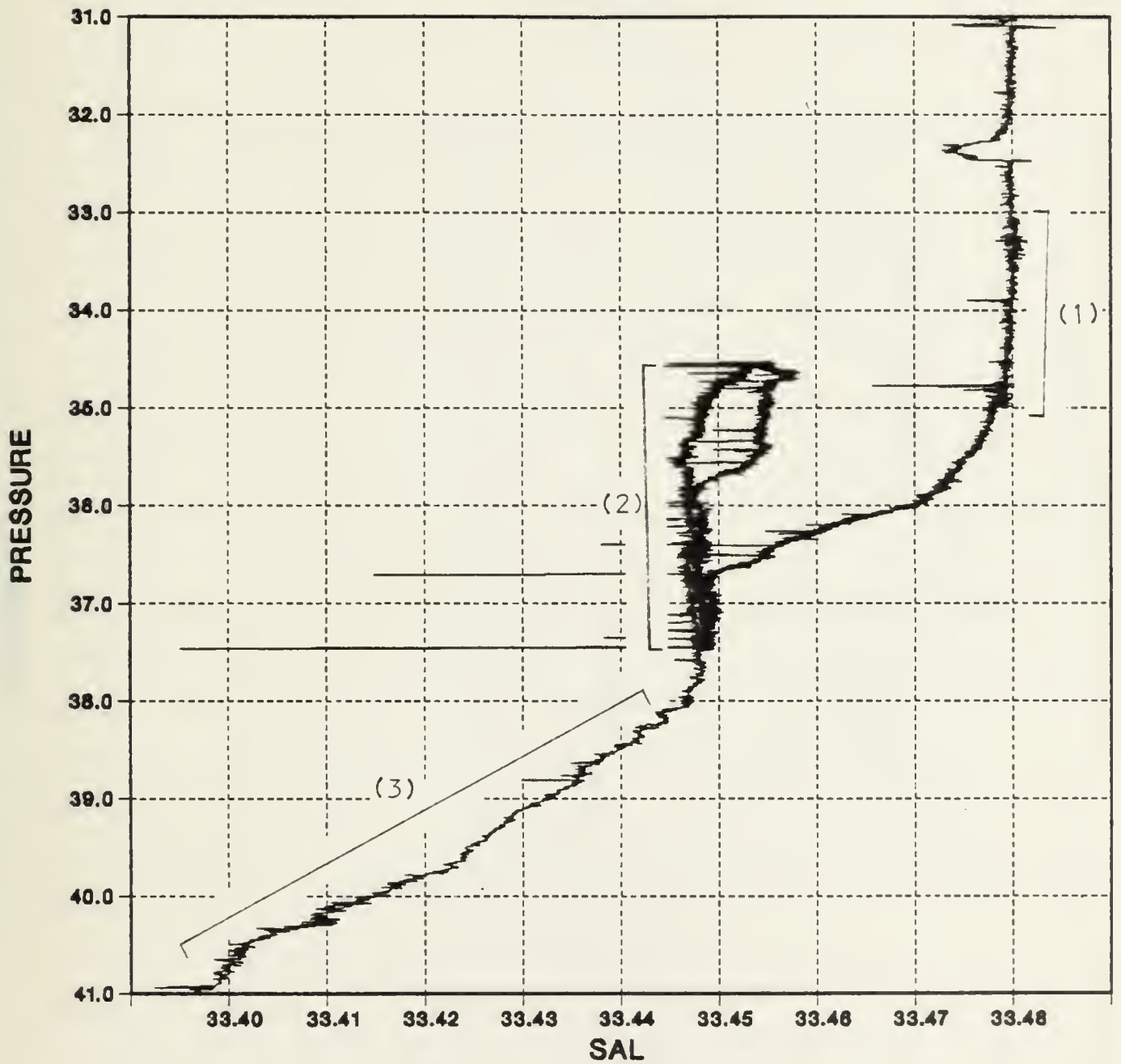


Figure 9. Salinity Profile with  $\delta = 1$ . Salinity spikes are reduced at the small temperature gradient (region (3)), but not in regions (1) and (2) compared to Figure 7 (with  $\delta = 0$ ).



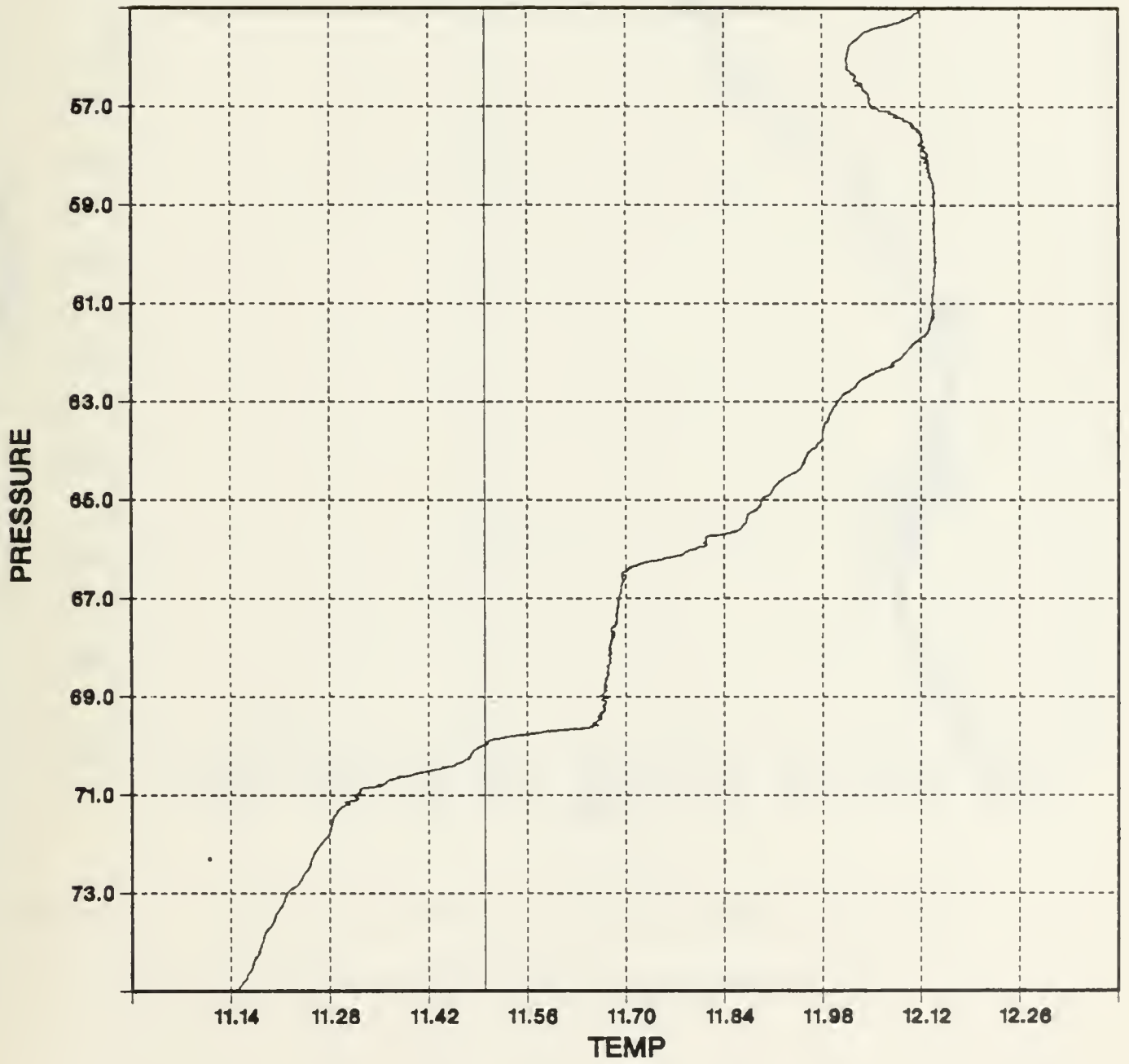


Figure 10. Temperature Profile (55m to 75m) with  $\delta = 0$ .



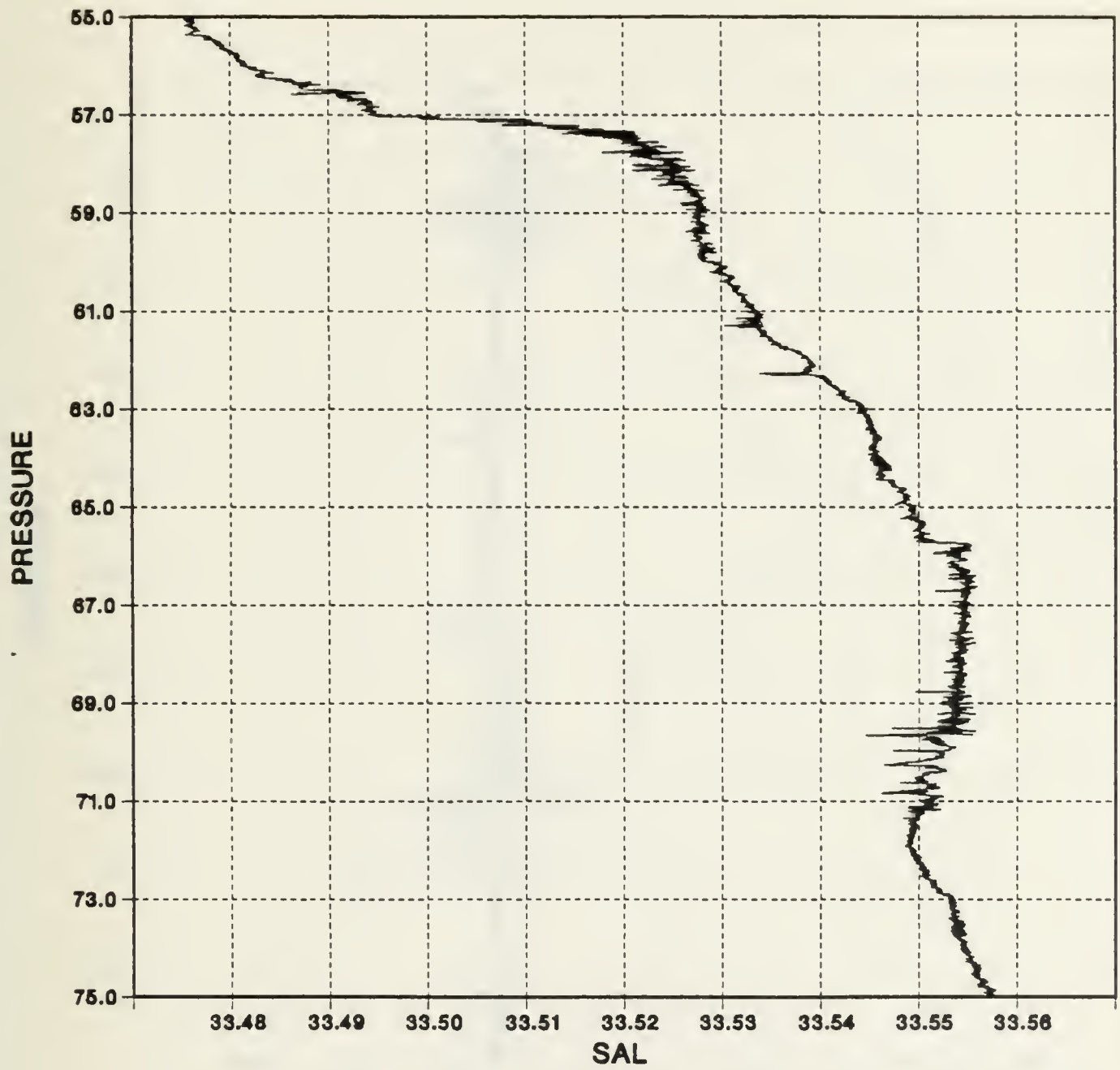


Figure 11. Salinity Profile (55m to 75m) with  $\delta = 0$ .



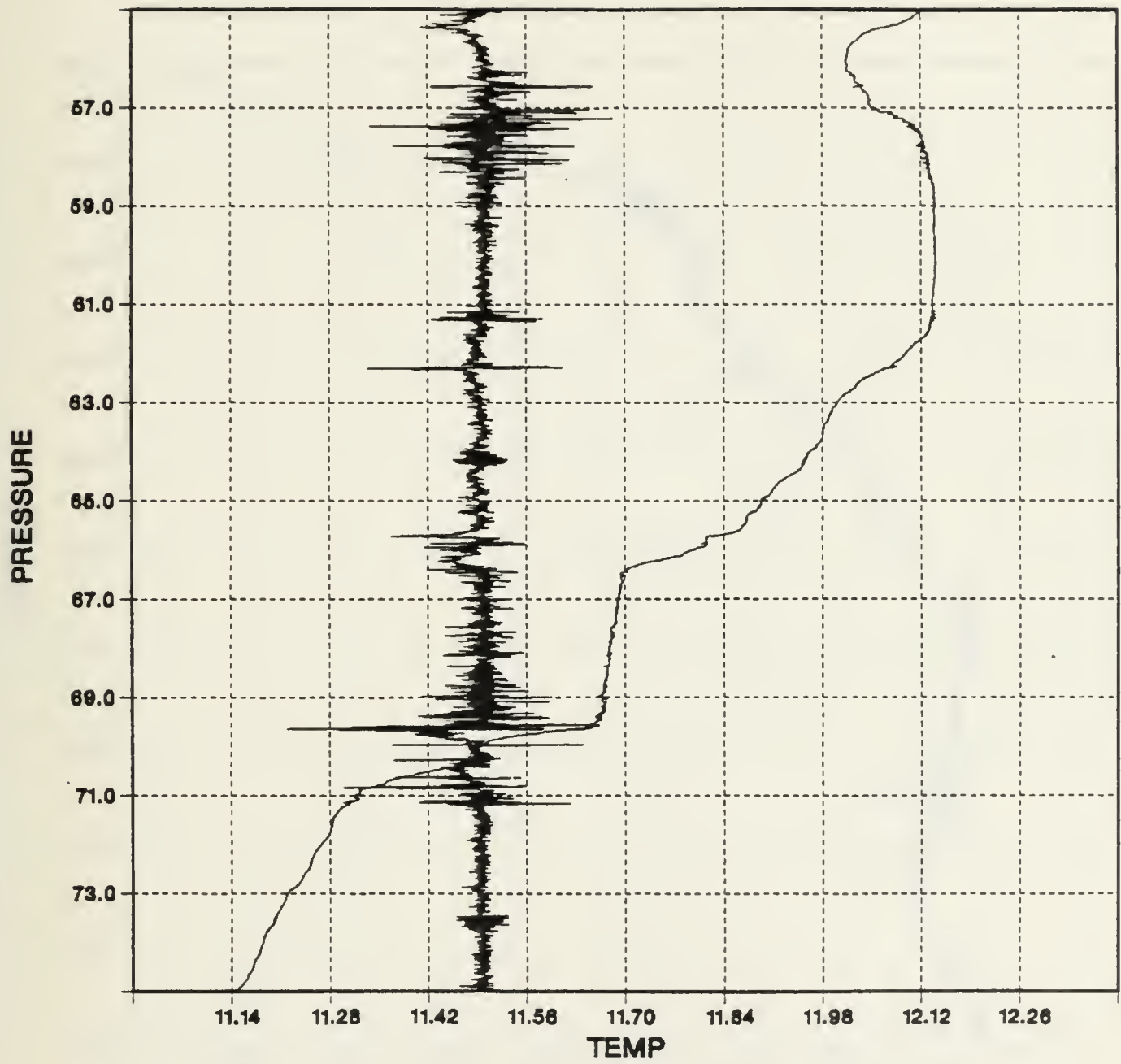


Figure 12. Enhanced Temperature Profile with  $\delta = 1$ .





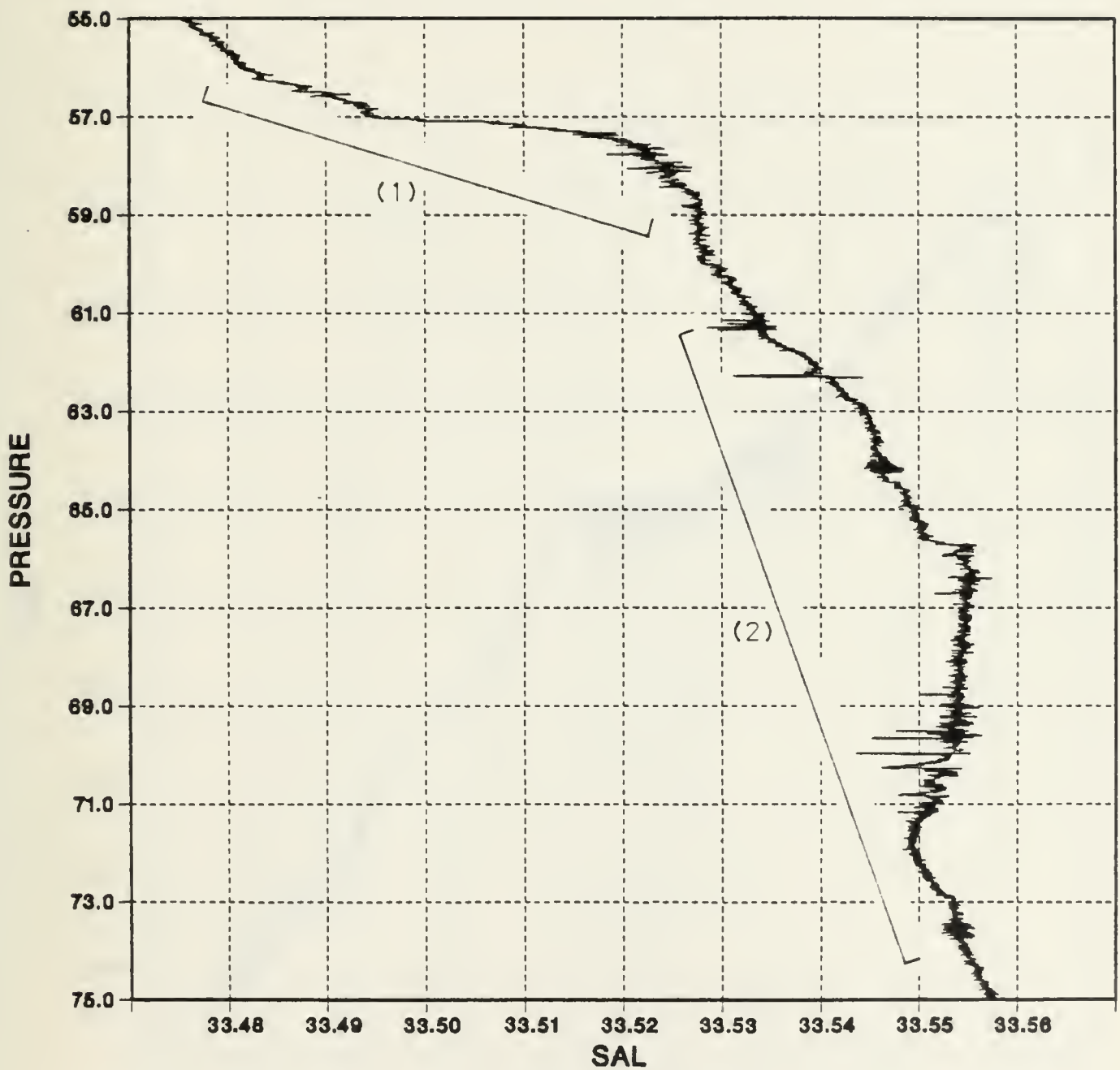


Figure 13. Salinity Profile with  $\delta = 1$ . This profile shows the reduction in salinity spiking where the salinity gradient is small (region (1)), but not in region (2), where it is large. Comparison can be made to Figure 11 where  $\delta = 0$ .



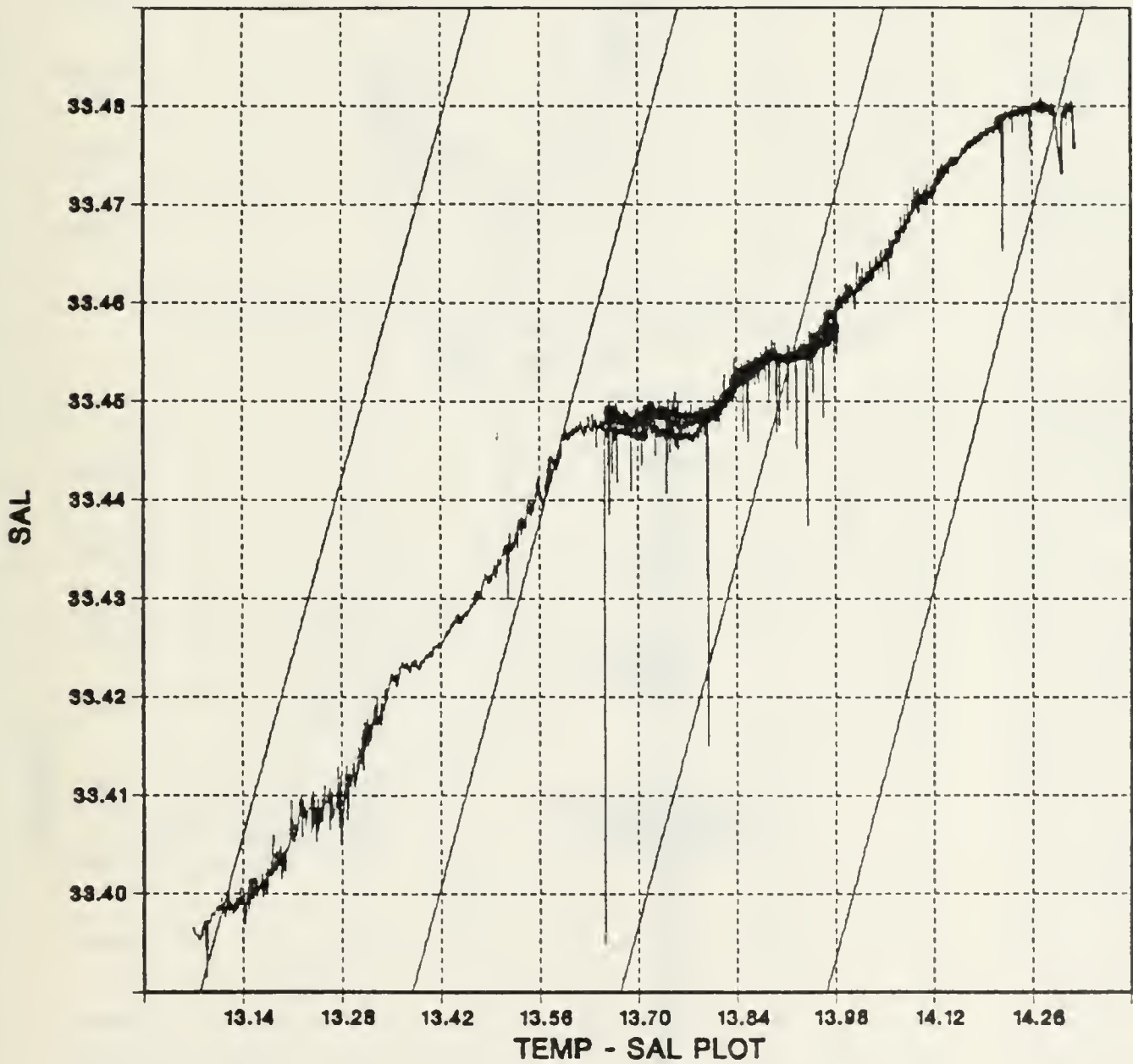


Figure 14. Temperature-Salinity Diagram. This curve shows the fast temperature plotted against the salinity. The solid lines are constant density lines.



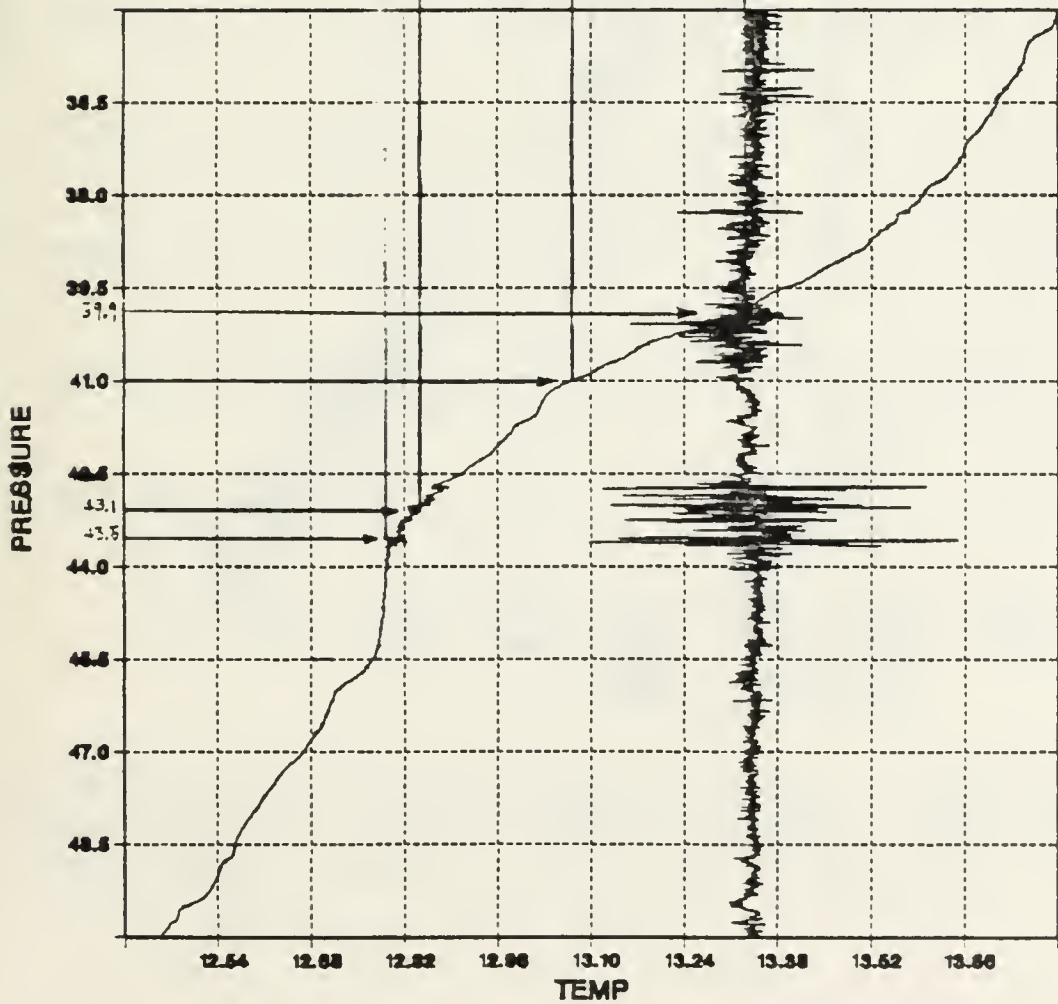
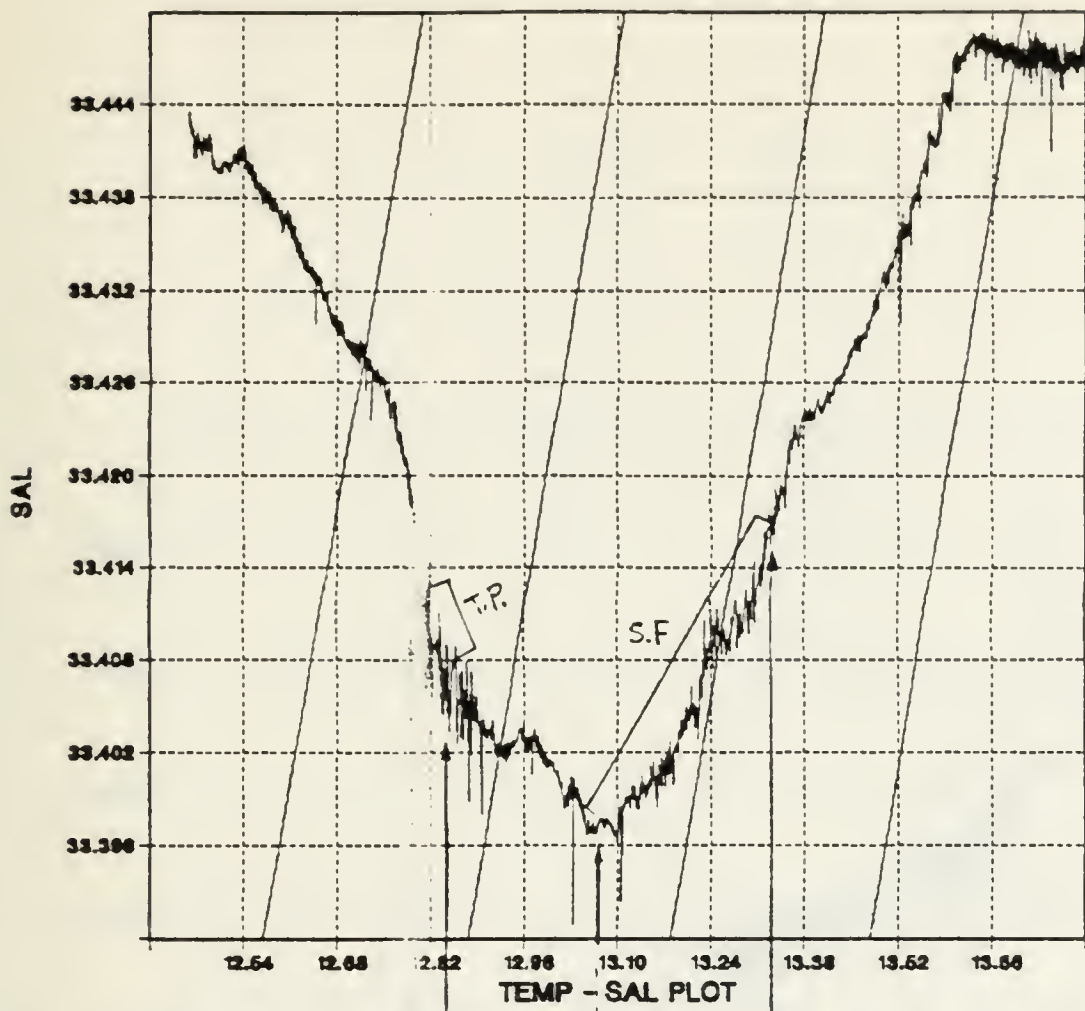


Figure 15. The CTD Data for the Two Different Signatures Shown in Figure 3. The upper patch (salt fingers (S.F.)) shows the value of  $R$  less than 2 in upper portion, and about 2 in lower portion. The thickness of the upper patch is almost the same as in Figure 3, but the lower patch is different from the one in Figure 3 due to the spatial variations of the turbulent patch (T.P.)





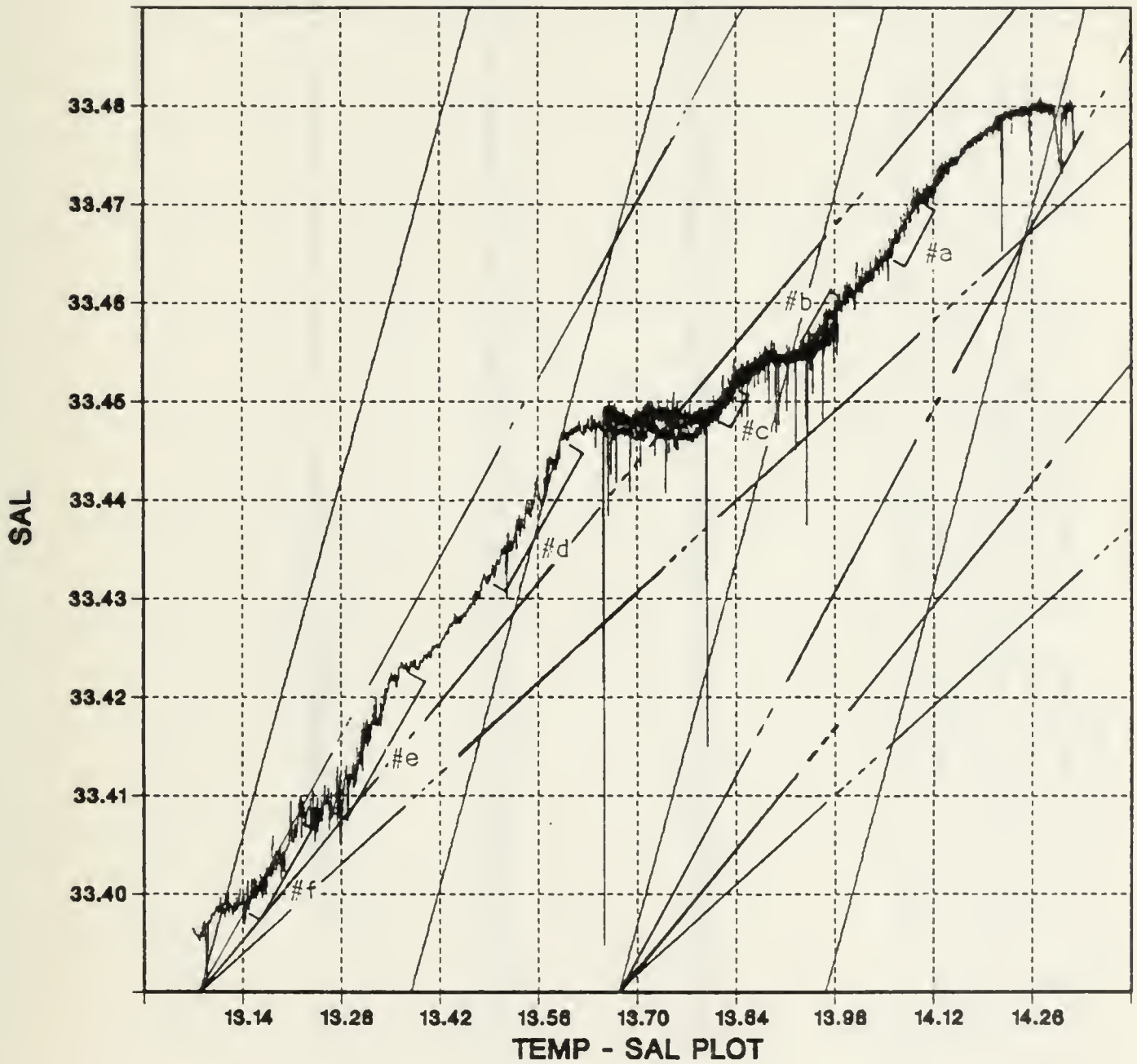


Figure 16. T-S Profile from CTD Data. Regions #a through #f are possible sites for salt fingers. For region #e,  $R$  is less than 2; while for the other regions,  $R$  is about 2.



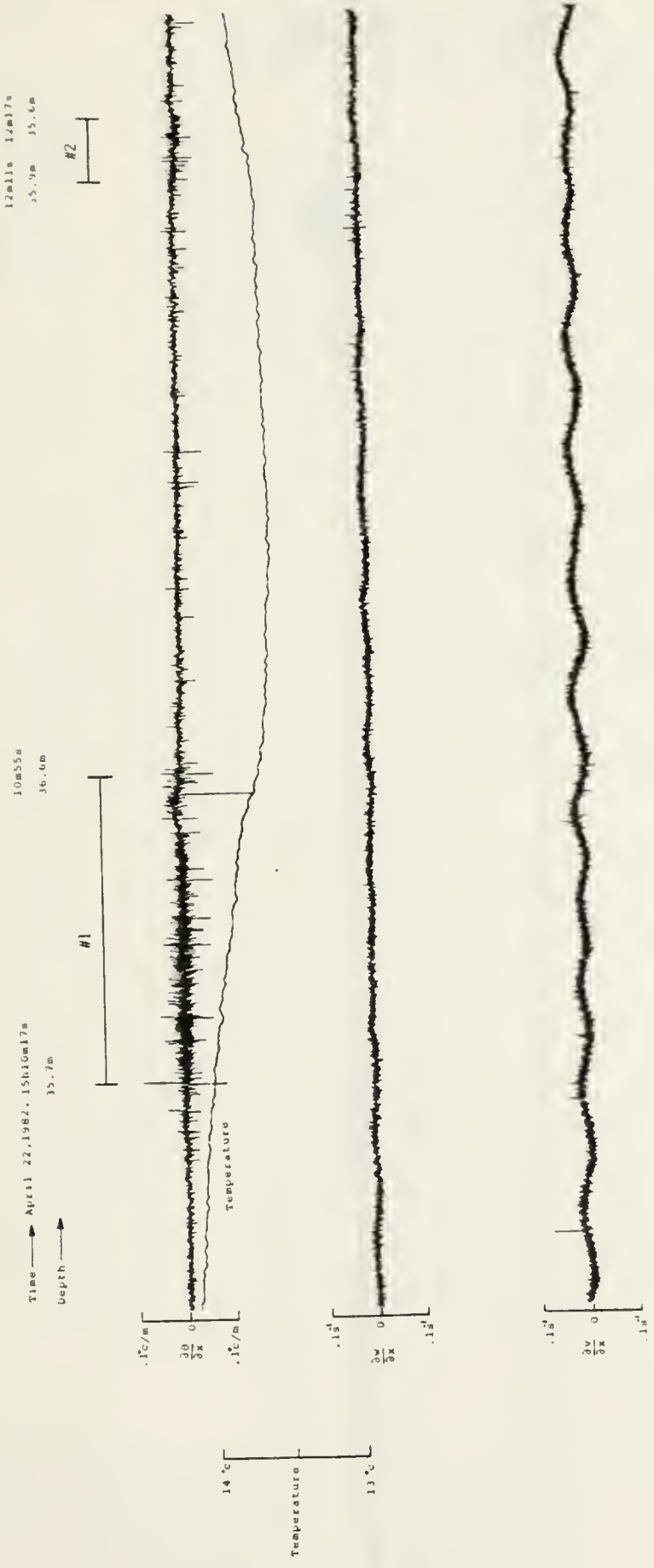
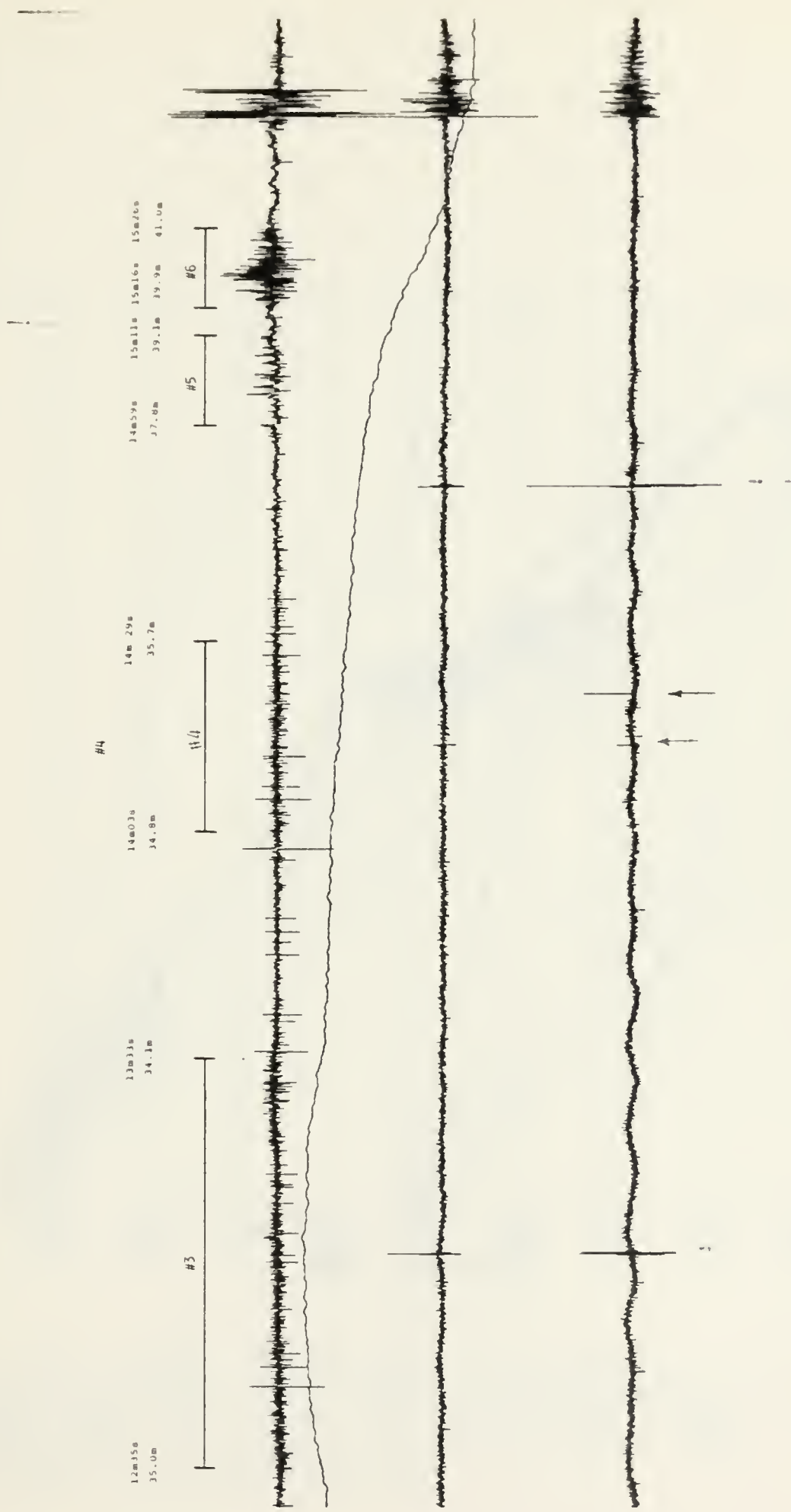


Figure 17. Analog Traces of Variables Measured from the Turbulence Patch (31m to 41m). The data are the temperature gradient ( $\partial\theta/\partial x$ ), the temperature, the downstream variations of the vertical velocity fluctuation ( $\partial w'/\partial x$ ) and the downstream variations of the lateral velocity fluctuation ( $\partial v'/\partial x$ ). Salt finger signatures are identified in regions #1 through #6. The noise due to biological fouling is indicated by the vertical arrows. The figure continues on the next page, where the scale is the same.



Figure 17 continued

data shown in figure 3







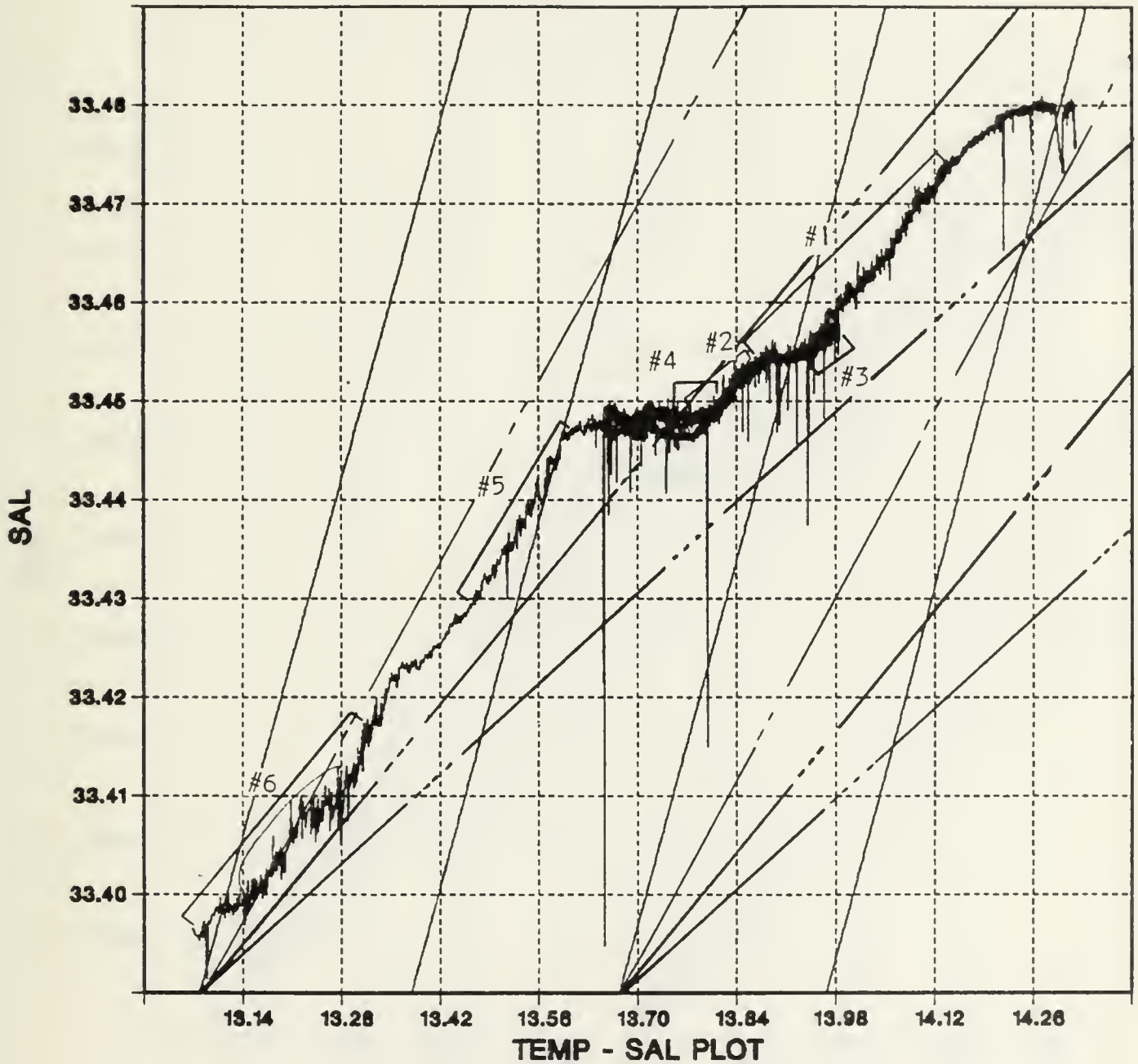


Figure 18. T-S Diagram Transferred from Figure 17. T-S diagram for the portion of the water column where the salinity decreases with depth from 35m to 41m. Dash-dot lines are drawn for values of  $R=1, 2$  and  $4$ . Solid lines are lines of constant density.



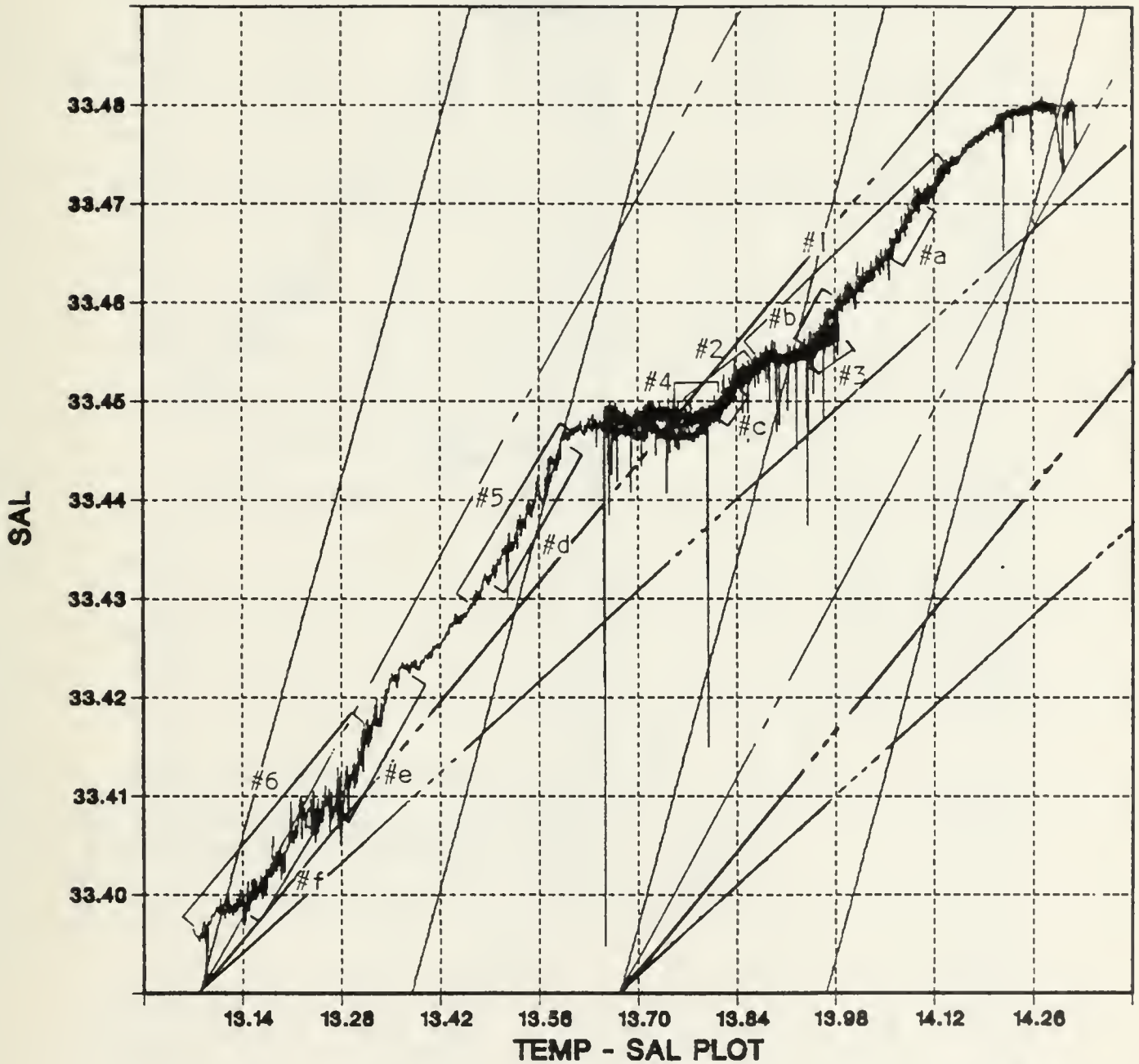


Figure 19. T-S Diagram Combined Figures 16 and 18. T-S diagram from Figure 18 with the location marked for the salt finger patches from Figure 15.



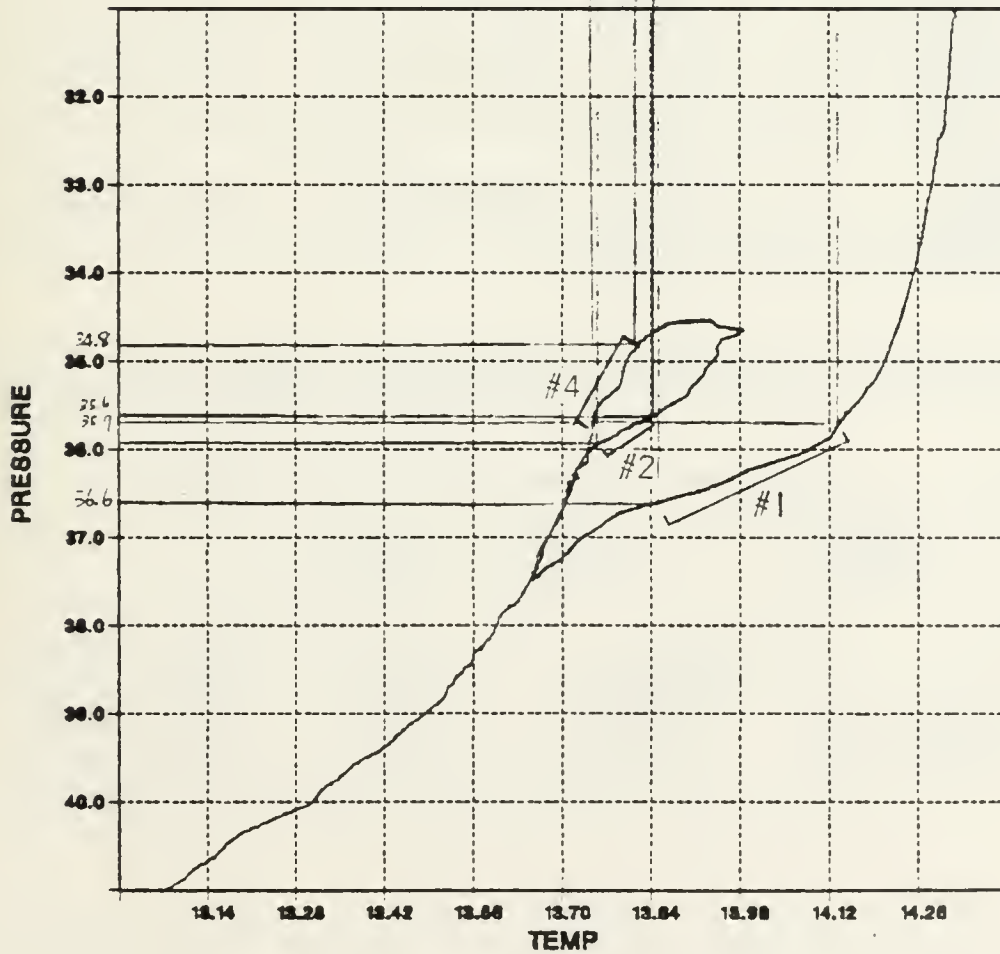
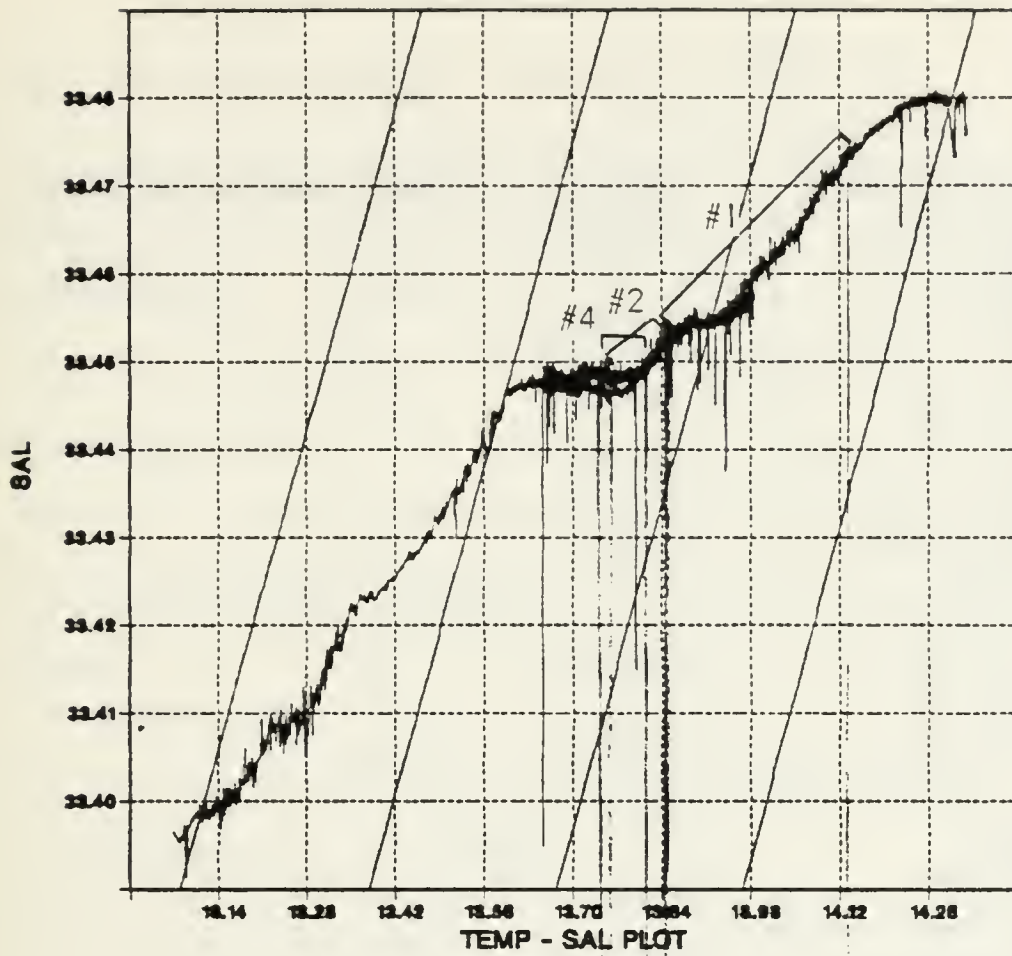


Figure 20. Vertical Extent of Salt Finger Regions #1, #2 and #4. The vertical extent of region #1 is 0.9m, region #2 is 0.3m and region #4 is 0.9m. The differences in the vertical extent are due to the spatial variation of salt fingers.





APPENDIX A

1. Nominal Calibration values for NBIS CTD

variable name	units	counts	engineering units
pressure	db	+262143	+655.35
		0	0.00
		-262143	-655.35
temperature	c	+262143	+32.767
		0	0.000
		-262143	-32.767
conductivity	mmho	+262143	+65.535
		0	0.000
fast temperature	c	+262143	+32.767
		0	0.000
		-262143	-32.767
velocity - x	cm/sec	+4095	+51.18
		0	0.00
		-4095	-51.18
velocity - y	cm/sec	+4095	+204.75
		0	0.00
		-4095	-204.75
velocity - z	cm/sec	+4095	+51.18
		0	0.00
		-4095	-51.18

2. The 3rd order polynomial correction formula  
(coefficients for power of x)

	0th power	1st power	2nd power	3rd power
0th order	+0.200			
1st order	-0.2886	+0.1915D-1		
2nd order	+0.2883	-0.6907D-1	+0.2238D-2	
3rd order	-0.2479	+0.1542	-0.1360D-1	+0.2963D-3



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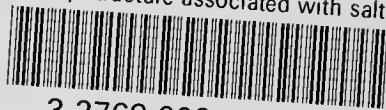
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