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GATE

CTD DATA MEASURED ON THE F.R.G. SHIPS
SHIPBOARD OPERATIONS-CALIBRATION-EDITING

Technical-Report
by
HARTMUT PETERS

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Kiel

1976

Die Berichte aus dem Institut für Meereskunde erscheinen in unregelmäßiger Folge und sind gedacht als Arbeitsunterlagen für den sich mit dem jeweiligen Thema befassenden Personenkreis. Die Hefte werden fortlaufend nummeriert. Sie sind unredigierte Beiträge und geben allein die Meinung des Verfassers wieder.

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G A T E

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Shipboard Operations - Calibration - Editing

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Introduction

The primary aim of this report is to inform the interested GATE scientist about the complete procedures of gaining, calibrating and editing the CTD data from the three F.R.G. research vessels involved in GATE. It is thought to be an integral part of the data sets, and will form part of the documentation sent with the data to the data centers. This report was written according to the recommendations given by the U.S. GATE B/C-Scale Workshop at Miami, Fl., Feb. 2 - 6, 1976.

The user of the data should note that in several respects both the instruments and the ship-board procedures were non-standard. This situation led to special routines for editing the data. Attention should also be given to the comments on the data quality. However, the process of data validation is not finished. An investigation about the interconsistency of the C-scale CTD data is presently underway.

1. Shipboard Operations

1.1 R.V. "Meteor"

Shortly after the beginning of phase I the ship had to be moored due to problems with towing the meteorological buoy. In order to avoid twisting the CTD around the anchor wire no deep casts were taken afterwards during routine work on station. Instead, hourly casts were taken during all three phases. Only down-cast measurements were made, as the instrument gives optimal results only while being lowered. It was intended to have a lowering speed of about 30 m/min, which was about the minimum possible. However, during the long term routine labour, higher speeds occurred.

The taking of cast measurements for the calibration of the CTD was a rather complicated procedure, as an ordinary Nansen bottle had to be fixed to the CTD cable. There always was the risk that a messenger might get stuck on the cable with possible loss of the CTD during the rapid hoisting of the instrument. Therefore not too many calibration data are available. For taking the Nansen bottle data, the CTD was stopped in a depth with low temperature gradients, (The bottle was about 2-3 m above the sensors of the CTD.) and after about 5 minutes the

bottle was released. Two protected thermometers were used.

1.2 R.V. "Planet"

On this ship, too, only downcast measurements were performed for the same reason as on "Meteor". A lowering speed of about 10 m/min was chosen for the top 100 m of the sea, and about 30 m/min down to 500 m depth. This procedure was meant to minimize the amount of data.

For the calibration a remote control reversing bottle and thermometer frame was used. Here, too, the CTD was stopped, and the bottle was not released before a time sufficient for the thermometers to come to equilibrium with the surrounding temperature. One protected and one unprotected thermometer were used in the frame.

1.3 R.V. "Anton Dohrn"

While the ship made its drift station along the equator, upcast measurements were made at a speed of 30 m/min in order to get a good coverage of the upper meters of the ocean. At the station M2 downcast measurements with about 60 m/min were taken. The other procedures were similar to those of "Planet" and "Meteor".

2. Technical data of the used CTD instruments

All the data following are taken from the manufacturers' manuals.

2.1 Multisonde

The "Multisonde" is a prototype instrument developed by the "Institut für Angewandte Physik" of Kiel, F.R.G. The instrument was described by W. Kroebel (1973).

Sensors: temperature: precision	:	\pm	0.01 °C
resolution ¹⁾	:		0.01 °C
time constant	:		100 ms

conductivity: precision : ± 0.01 m mho/cm
 (inductive cell)
 resolution¹⁾ : 0.01 m mho/cm
 pressure : precision : $\pm 2.5^{\circ}/\infty$ of total range
 range : 8000 dbar
 resolution¹⁾ : 1 dbar
 sound velocity : precision : ± 1 cm/s
 light attenuation : precision : ± 0.001 m⁻¹

Sampling interval : - 0.1 s, simultaneous sampling of the 6 parameters

The sampling interval selected throughout the experiment was 1 sec. This is the lowest possible value while registering the data on paper tape. The Multisonde was used on board of R.V. "Meteor" during all three phases of GATE. About 1100 profiles were taken. The sound velocity sensor malfunctioned during a couple of profiles. The light attenuation sensor failed during phase 2; no data of the optical attenuation will be sent to the NPC as the calibration of the sensor was a problem throughout the experiment.

1) These values are the round-off errors in the file.
The digitization is done to 16 bit.

2.2 Bathysonde

The "Bathysonde T 87/3" is manufactured by the Howaldtswerke-Deutsche Weft A.G., Kiel, F.R.G.

sensors: temperature: precision : ± 0.01 °C
 resolution : 0.01 °C
 time constant: 60 ms
 conductivity: precision : $\pm 1.5^{\circ}/\infty$ of total range
 (inductive cell)
 resolution : 0.01 m mho/cm
 non-linearity: 0.3 °/∞ of range
 range : 0 - 80 mmho/cm
 pressure : precision : ± 0.25 % of total range
 range : 6000 dbar
 ("Anton Dohrn" and "Meteor")
 800 dbar
 ("Planet")

resolution : 1 dbar

("Anton Dohrn" and "Meteor")

<1 dbar

("Planet")

sampling interval: 1 s or greater

Three different sondes were operated on "Anton Dohrn", "Planet" and "Meteor". The first two were equipped with a remotely controlled Nansen bottle and thermometer frame. They gave a reading of the real time. The digitization is accomplished in the underwater unit by means of a set of mechanical relays. This limits the maximum sampling rate to less than 2/s. The parameters are sampled simultaneously except of the temperature, which is sampled 60 ms in delay in order to correct the temperature for the time constant of the sensor.

3. Static Calibration

3.1 Methods

The CTD instruments had been calibrated in the laboratories. The aim of the in situ calibration was to check these calibrations. Despite the fact that the Platinum thermometers and inductive conductivity cells have a high stability, the results (3.3) show how necessary this check was.

The deep-sea reversing thermometers had a remarkable stability. The thermometers used on R.V. "Planet" were recalibrated after the cruise, and showed no significant change in the calibration within up to ten years.

Two independent measurements of the salinity of the bottle samples were made using a Beckmann RS 78 lab salinometer. The measurements were carried out after the cruise at Kiel. During the measurements, the salinometer started to malfunction. As a result a correction by 0.03 ‰ had to be applied.

For the calibration a linear relationship between the true value and the reading of the CTD was assumed for pressure, temperature and conductivity. No multiple regression was attempted, as the amount of calibration data was too small. Also, in several cases additional assumptions about some of the parameters α or β (see below) had to be made.

The salinity S as a function of pressure P , temperature T and conductivity C was calculated by means of routines developed by N. Fofonoff in Woods Hole (1974). Conductivity $C = C(P, T, S)$ was calculated by an iterative reversal of the same scheme using Newton's formula.

The readings P_c , T_c and C_c of the CTD were compared with the corresponding values of the bottle samples and linear relations determined.

$$\begin{aligned} P &= \alpha_P P_c + \beta_P \\ T &= \alpha_T T_c + \beta_T \\ C &= \alpha_C C_c + \beta_C \end{aligned}$$

Subsequently the 'true' salinity $S = S(P, T, C)$ was compared with the Nansen bottle value S_N for a check of the consistency of the calibrations.

Ship : instrument P dbar T °C C m mho/cm S °/oo

Planet: Bathysonde

assumption $P = \alpha P_C + 1 \text{ dbar}$ $T = T_C - \beta T$ $C = \alpha C_C$

result $P = (1.018 \pm 0.015) \times P_C + 1 \text{ dbar}$ $T = T_C - (0.06 \pm 0.03)$ $C = (0.997 \pm 0.001) \times C_C$

mean error $\frac{P - P_N}{P_N} = + 0.2 \text{ dbar}$ $\frac{T - T_N}{T_N} = + 0.002$ $\frac{C - C_N}{C_N} = + 0.00025$ $\frac{S - S_N}{S_N} = - 0.002$

mean quadratic deviation = 5.7 dbar = 0.03 = 0.04 = 0.025

number 13 13 12 12

Meteor: Multisonde

assumption no calibration

result $T \approx T_C$ $C \approx C_C$

mean error $\frac{T - T_N}{T_N} = - 0.0027$ $\frac{C - C_N}{C_N} = - 0.0065$ $\frac{S - S_N}{S_N} = - 0.0007$

mean quadratic deviation = 0.027 = 0.022 = 0.024

number 15 13 13

Anton Dohrn: Bathysonde

assumption $P = P_C + \beta$ $T = \alpha T_C + \beta T$ $C = \alpha C_C + \beta C_C$
least mean square

result $P = P_C - 18 \text{ dbar}$ $T = 1.0003 \times T_C + 0.002$ $C = 1.0040 \times C_C - 0.0334$

mean error $\frac{P - P_N}{P_N} = 0.3 \text{ dbar}$ $\frac{T - T_N}{T_N} = + 0.002$ $\frac{C - C_N}{C_N} = - 0.0006$ $\frac{S - S_N}{S_N} = + 0.0007$

mean quadratic deviation = 14.7 dbar = 0.02 = 0.03 = 0.03

number 13 59 57 57

3.3 Comments

Obviously wrong calibration data were generally rejected. The quality of the data can in part be inferred from figures 1 - 3.

R.V. "Planet": Since the pressure reading was zero when the instrument was about 1 m below the surface, 1 dbar has been added to all pressure readings.

The standard deviation of the bottle pressure from the CTD reading shows a value that is to be expected from the known accuracy of thermometric depth determination.

The calibration of temperature was determined only in the range of about 8 - 12 °C.

R.V. "Meteor": The temperature sensor of the Multisonde used during phase I showed a hysteresis and was therefore exchanged prior to phase II. It will not be possible to calibrate the sensor.

The Bathysonde, used during phase I during malfunction of the Multisonde, was meant to be compared with the Multisonde. However, the Bathysonde broke down at the beginning of phase II and could not be repaired during GATE. No calibration data are available.

R.V. "Anton Dohrn": The pressure sensor had a marked hysteresis, which is also reflected in the value of the standard deviation of $P_N - P$. A better calibration than given in 3.2 was not possible.

The temperature calibration was done by means of a linear regression between T_N and T_c .

The conductivity, however, was calibrated by means of determination of the linear connection of the centers of two "point swarms" around 55 m mho/cm and 33 m mho/cm, of which the calibration data consisted.

4. Dynamic Correction and Data Reduction

4.1 Method

Compared to the almost instantaneous response of the inductive conductivity

sensors, the Platinum thermometers were relatively slow. This leads to a systematic error and to the well known "spikes" in the calculated salinity in regions of high vertical temperature gradients.

For the purpose of this paper, it is assumed that the temperature sensors respond linearly by so that the relation

$$\frac{\partial T}{\partial t} = \frac{1}{\mathcal{L}} (T_N - T)$$

holds, where T is the temperature of the sensor, T_N the surrounding water temperature and \mathcal{L} the time constant of the thermometer. The time derivative is approximated by the first order backward differences. The correction formula is thus

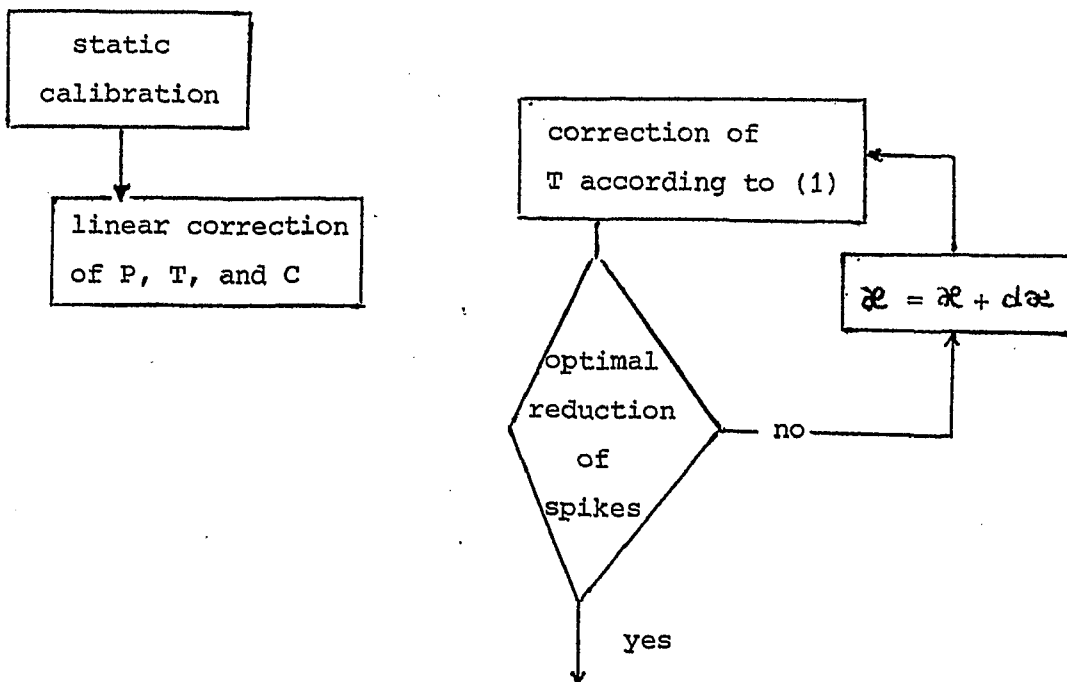
$$(1) \quad T_{ti} = T_i + \frac{\mathcal{L}}{\Delta t} (T_i - T_{i-1}),$$

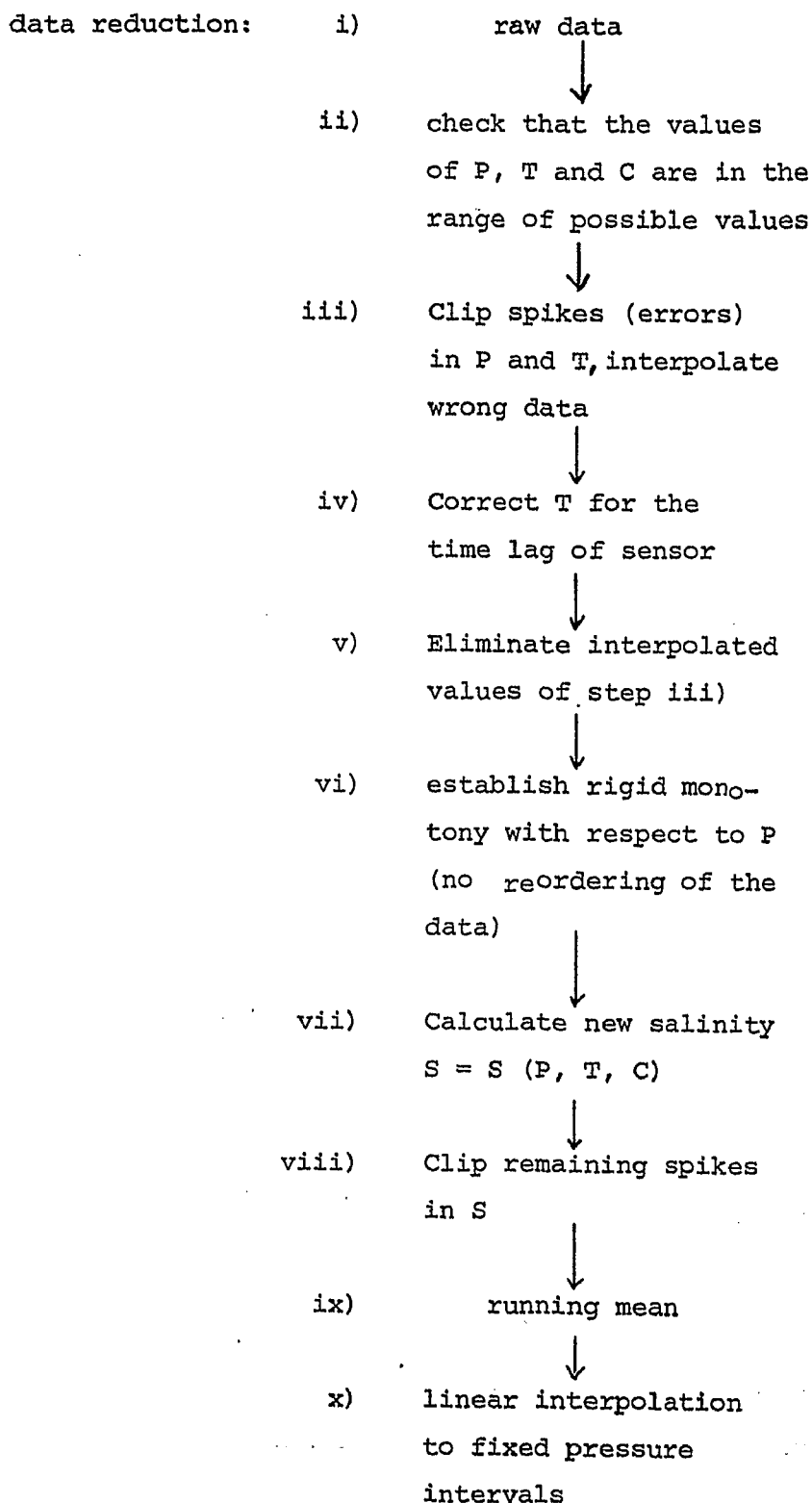
where T_{ti} is the corrected temperature at the time $i \cdot \Delta t$, Δt the sampling interval and T_{i-1} the temperature reading at the time $(i-1) \cdot \Delta t$.

The time constant \mathcal{L} is usually only approximately known, it depends among others on speed of the sensor through the medium. A value of \mathcal{L} was therefore chosen to achieve optimal reduction of the spikes.

The total procedure of data reduction is illustrated in the following figure:

preparations:





Comments:

Step vi) reduces most of the noise in the salinity. This shows the comparison of

figures 4 and 5.

Step viii) is necessary to eliminate further errors in T or C.

In step ix) the number of data in the running mean was chosen such that on an average the data within twice the interpolation interval of step x) were averaged ("Planet":5 samples (but see chapter 5), "Meteor":3 samples, "A.Dohrn":3 samples). The effect of the steps iv), ix) and x) can be seen from figures 4 - 11 for 3 different instruments. The other steps were not included in the experimental calculations.

4.2 Results

ship/instrument	time constant given by manufacturer	estimate from optimal spiker reduction	estimated error of the determination
Planet: Bathysonde	0.06 s	- 0.54 s ¹⁾	+ 0.05 s
Meteor: Bathysonde	0.06 s	+ 0.04 s ²⁾	+ 0.05 s
Anton Dohrn: Bathysonde	0.06 s	3) no determination possible due to bad data or low temperature gradients	
Meteor: Multisonde	0.1 s	0.15 s	+ 0.05 s

1) The Bathysonde is equipped with a time lag of 0.06 s in the temperature sampling compared to the simultaneous sampling of the other parameters. This was intended to correct the temperature internally before recording.

Obviously the time lag of T in the Bathysonde of R.V. "Planet" was not .06 s. This is the reason for the "negative time constant".

2) See 1)
The apparent time constant seems to be slightly greater than the nominal value. The data as recorded from the Bathysonde were corrected with the given value.

3) Corrected as for the Bathysonde of R.V. "Meteor"

5. Further Comments on the Data Quality

i) Noise on the conductivity channel of the Bathysonde of R.V. "Planet"

Below depths of 80 - 100 m the conductivity of the Bathysonde showed a pressure influence in form of sudden changes in the readings of about .05 mmho/cm. The effect is obvious in fig. 13 in comparison with the relatively smooth graph of the temperature (fig. 12). A probable explanation is that the increasing pressure caused abrupt changes in the structure of the ferrite core of the inductive cell. The effect on the salinity computed from the raw data (fig.14) is noise on a level nearly three times the magnitude of the digitization noise.

As the noise was not sufficiently suppressed by the filtering procedures described in the previous chapter, an additional running mean was applied to the data starting from 80 dbars onwards. Thus the mixed layer and most of the thermocline are not concerned by this procedure. A mean of 21 values of the data interpolated to 1 dbar intervals was taken.

Hopefully the errors induced by the noise are thus reduced, though a low vertical resolution is the consequence. But anyway the warning must be given to the user that none of the CTD data described in this report should be used to study fine structure on scales less than about 5 m.

ii) Errors - spiking

The raw data from the Multisonde contain only few erroneous values. The final data set is therefore thought to consist of nearly all "correct" data.

A number of obvious errors were removed (partly "by hand") from the "Planet" data, from those of "Anton Dohrn" and from those of the Bathysonde of "Meteor". However, plots of sigma-t versus pressure show that still a few incorrect values may be contained in the final data sets. A removal was not possible, as there did not seem to be any means to decide which of the data were wrong.

So far information has been given about the precision of the instruments and about the accuracy of the calibration. All the quoted error bounds are mean values. Besides random errors one important source of inaccuracies in the data remains to be discussed. An attempt to give an upper bound for the error in regions of high

temperature gradients is made.

The effect of "spiking", caused by the slow response of the temperature sensors used, cannot totally be removed by the procedures described above. One reason for this is the large value of the ratio between the sampling interval and the time constant of the thermometers. Another reason is the stem conduction of heat from the heavy hull of the CTD towards the thermometer. Thus the data partly contain inversions of σ_t caused by spiking.

The magnitude of this type of error will now be estimated. A linear dependence of the error in the computed salinity, ΔS , of the vertical temperature gradient $\frac{\partial T}{\partial z}$ is assumed:

$$\Delta S = c \cdot \frac{\partial T}{\partial z}$$

In the thermocline step-like structures in T often appear, which are associated with a "U-type" structure in S (fig. 15). If the latter is assumed to be an artifact, one can estimate ΔS .

The result is $c \approx 10 \text{ } ^\circ/\text{oo cm } ^\circ\text{C}^{-1}$ for the Bathysonde of "Planet" and for the Multisonde of "Meteor", too.

iii) Summary

The intention of this chapter is to summarize the information on the accuracy of the CTD data in a table containing numbers and/or formulas. A minimum of information may thus be gained at a glance.

In chapter 3.2 mean quadratic deviations between bottle and CTD readings are given. According to statistics the computed corrections should be better by a factor of $\frac{1}{\sqrt{n}}$, n = number of samples. Thus the statistical errors in the calibrations are rather low. Most important are the systematic errors of the reversing thermometers and the bench^B salinometer^K used for calibration. Those of the latter had to be guessed.

Not accounted for in the table is the inaccuracy of the UNESCO tables on salinity and of the formulas used to calculate salinity and density.

Few information is available on the accuracy of the pressure data. In addition to the values given in chapters 2 and 3.2 estimates of the hysteresis gained from successive hoisting and lowering of the CTD were taken into account.

Estimate of the accuracy of F.R.G. CTD data

parameter	instrument	Bathysonde R.V. "Planet"	Multisonde R.V. "Meteor"	Bathysonde R.V. "Anton Dohrn"
pressure	accuracy near surface	± 0.5 dbar	a few decibars	
	accuracy overall	± 2 dbar	$\leq \pm 20$ dbar	$\leq \pm 20$ dbar
temperature	precision	$\pm 0.002^\circ\text{C}$	$\pm 0.003^\circ\text{C}$	$\pm 0.003^\circ\text{C}$
	statistical error of calibration	$\pm 0.01^\circ\text{C}$	$\pm 0.01^\circ\text{C}$	$\pm 0.003^\circ\text{C}$
	systematic error of calibration	$\pm 0.02^\circ\text{C}$	$\pm 0.01^\circ\text{C}$	$\pm 0.01^\circ\text{C}$
	error due to slow response of thermometer	$0.1 \cdot \frac{\partial T}{\partial z} \left[\frac{^\circ\text{C}}{\text{m}} \right]$	$0.1 \cdot \frac{\partial T}{\partial z} \left[\frac{^\circ\text{C}}{\text{m}} \right]$	1)
salinity	precision	$\pm 0.004^\circ/\text{oo}$	$\pm 0.007^\circ/\text{oo}$	$\pm 0.007^\circ/\text{oo}$
	statistical error of calibration	$\pm 0.01^\circ/\text{oo}$	$\pm 0.01^\circ/\text{oo}$	$\pm 0.005^\circ/\text{oo}$
	systematic error of calibration	$\pm 0.03^\circ/\text{oo}^2)$	$\pm 0.03^\circ/\text{oo}^2)$	$\pm 0.03^\circ/\text{oo}^2)$
	error due to slow 3) response of thermometer	$+0.1 \cdot \frac{\partial T}{\partial z} \left[\frac{^\circ\text{C}}{\text{m}} \right]$	$-0.1 \cdot \frac{\partial T}{\partial z} \left[\frac{^\circ\text{C}}{\text{m}} \right]$	1)
6 _t 4)	precision	± 0.004	± 0.006	± 0.006
	statistical error of calibration	± 0.01	± 0.01	± 0.005
	systematic error of calibration	± 0.03	± 0.025	± 0.025
	error due to slow response of thermometer	$+0.05 \cdot \frac{\partial T}{\partial z} \left[\frac{^\circ\text{C}}{\text{m}} \right]$	$-0.1 \cdot \frac{\partial T}{\partial z} \left[\frac{^\circ\text{C}}{\text{m}} \right]$	1)

1) Not tested

2) See page 5

3) See page 11 for an exploration of the signs

4) Maximal effect of simultaneous errors in T and S

6. References

Fofonoff, N.P., S.P. Hayes and R.C. Millard Jr. (1974):

W.H.O.I./Brown CTD Microprofiler: Methods of Calibration and Data Handling;

W.H.O.I. Technical Report Ref.No. 74-89 (Unpublished manuscript)

Kroebel, W. (1973): Die Kieler Multimeeressonde

Ein Gerät zur in situ-Messung von Temperatur, Leitfähigkeit, Salzgehalt, Schallgeschwindigkeitsgradient und lichtoptischer Attenuation mit ersten Ergebnissen der "Meteor"-Fahrt Nr. 23 (1971) westlich von Gibraltar.

Meteor Forsch.-Ergebnisse, A 12, 53 - 57

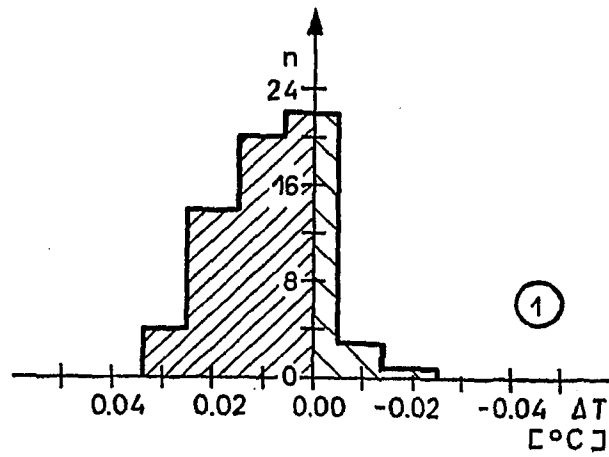


fig. 1: Difference of the readings of the two protected thermometers used in the remotely controlled frame of the Bathysonde of R.V. "Anton Dohrn"

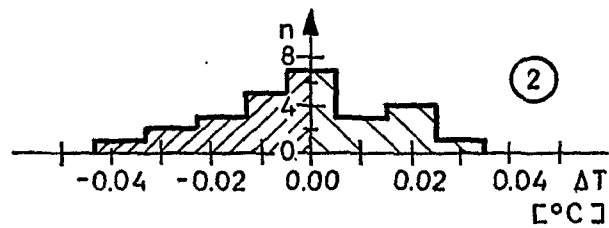


fig. 2: Difference of the readings of the two protected thermometers used with the Nansen bottle on the cable of the Multisonde of R.V. "Meteor"

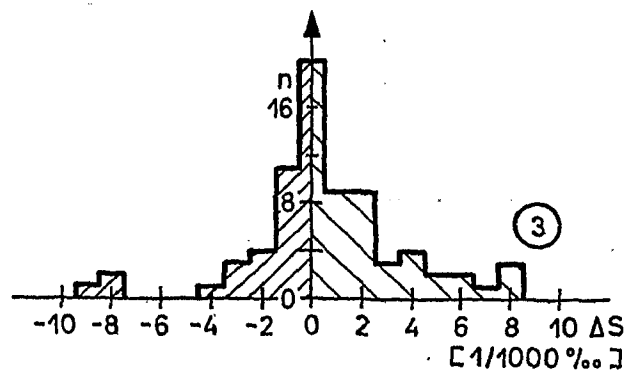


fig. 3: Difference of the salinity reading of the first minus the second sample of sea water from a Nansen bottle (Bathysonde "Anton Dohrn" and Multisonde "Meteor")

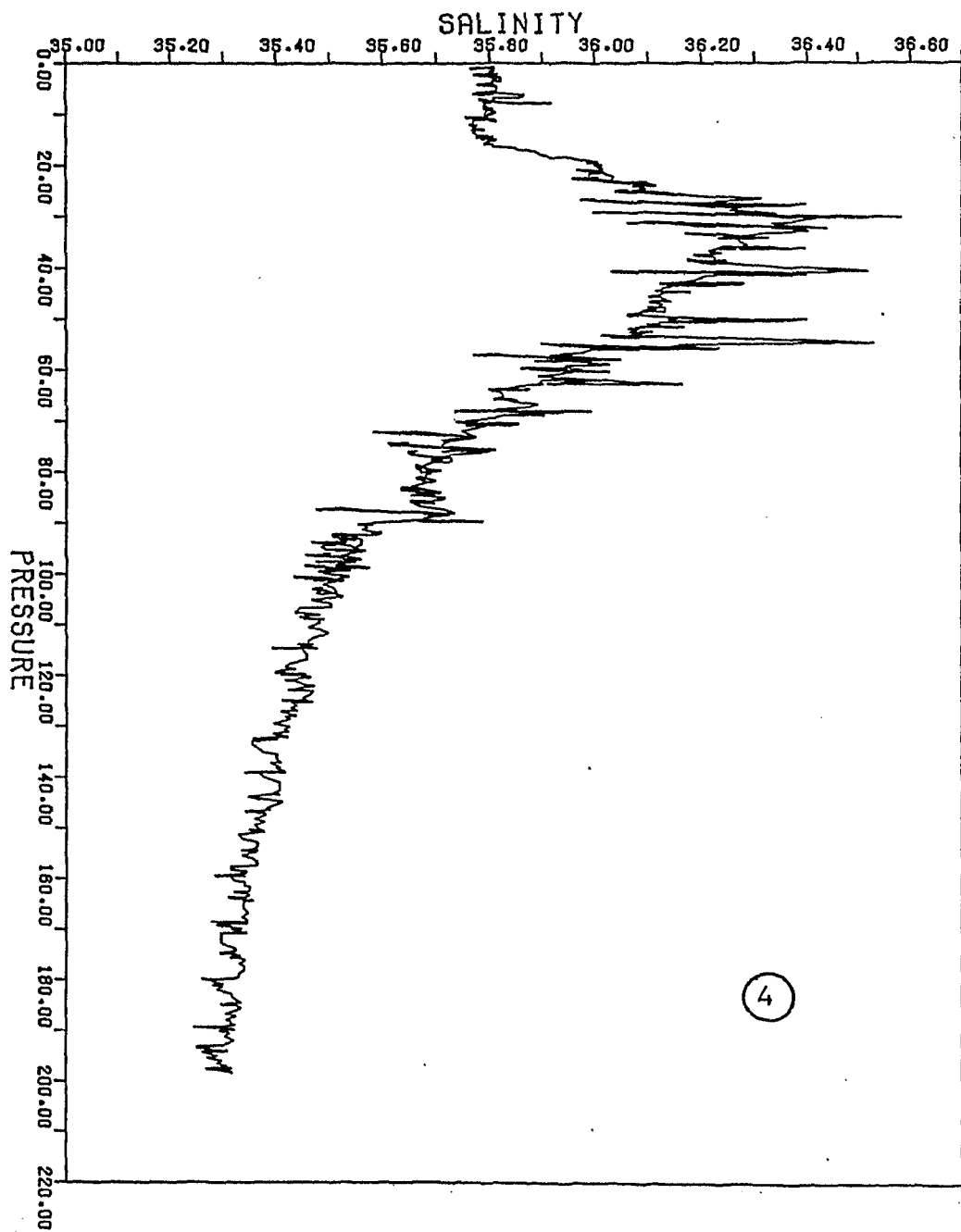


fig. 4: Bathysonde (CTD) cast ref. no. 80060 of R.V. "Planet", salinity as function pressure, raw data.

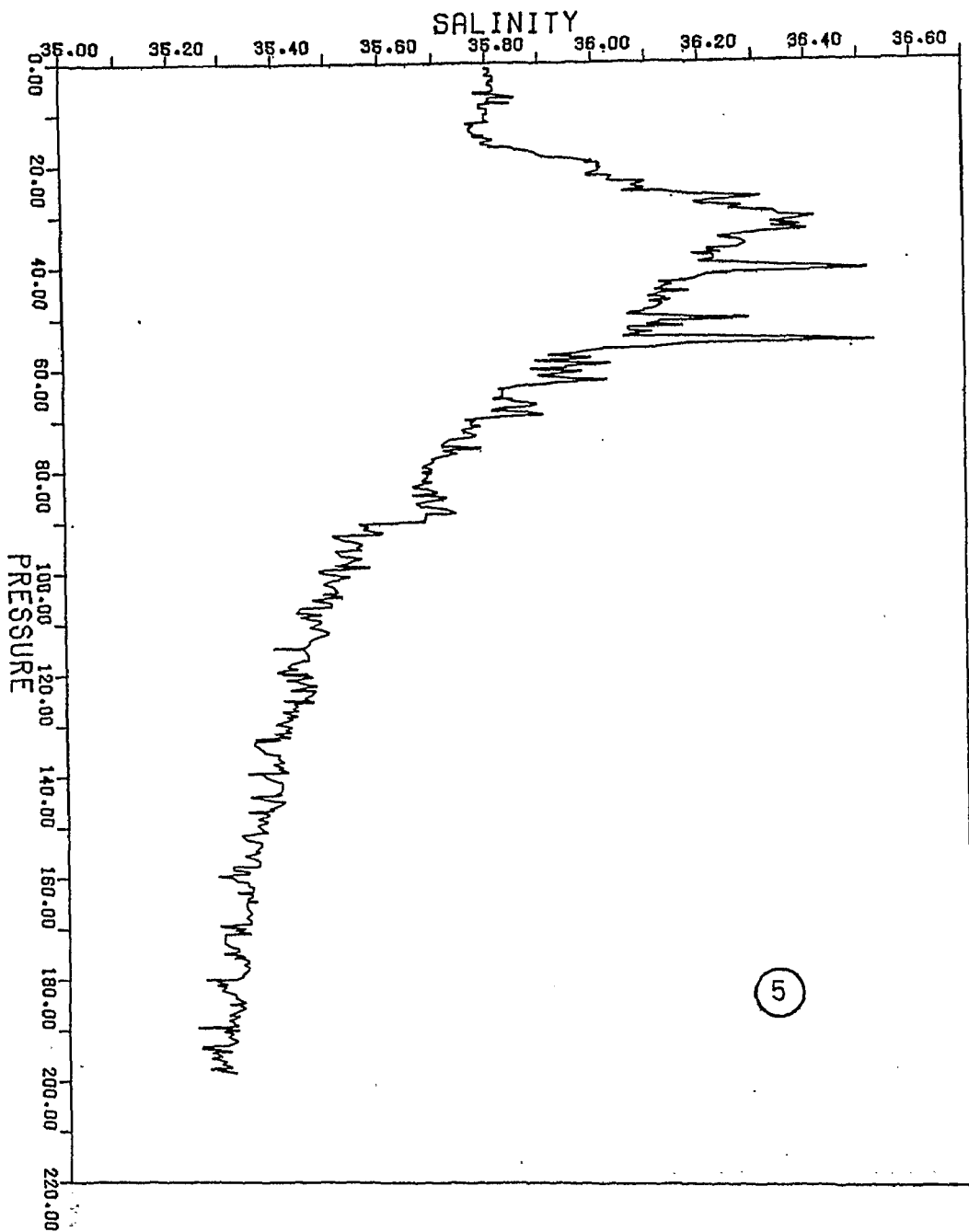


fig. 5: Bathysonde (CTD) cast ref. no. 80060 of R.V. "Planet", salinity salinity as function pressure, monotony with respect to pressure established.

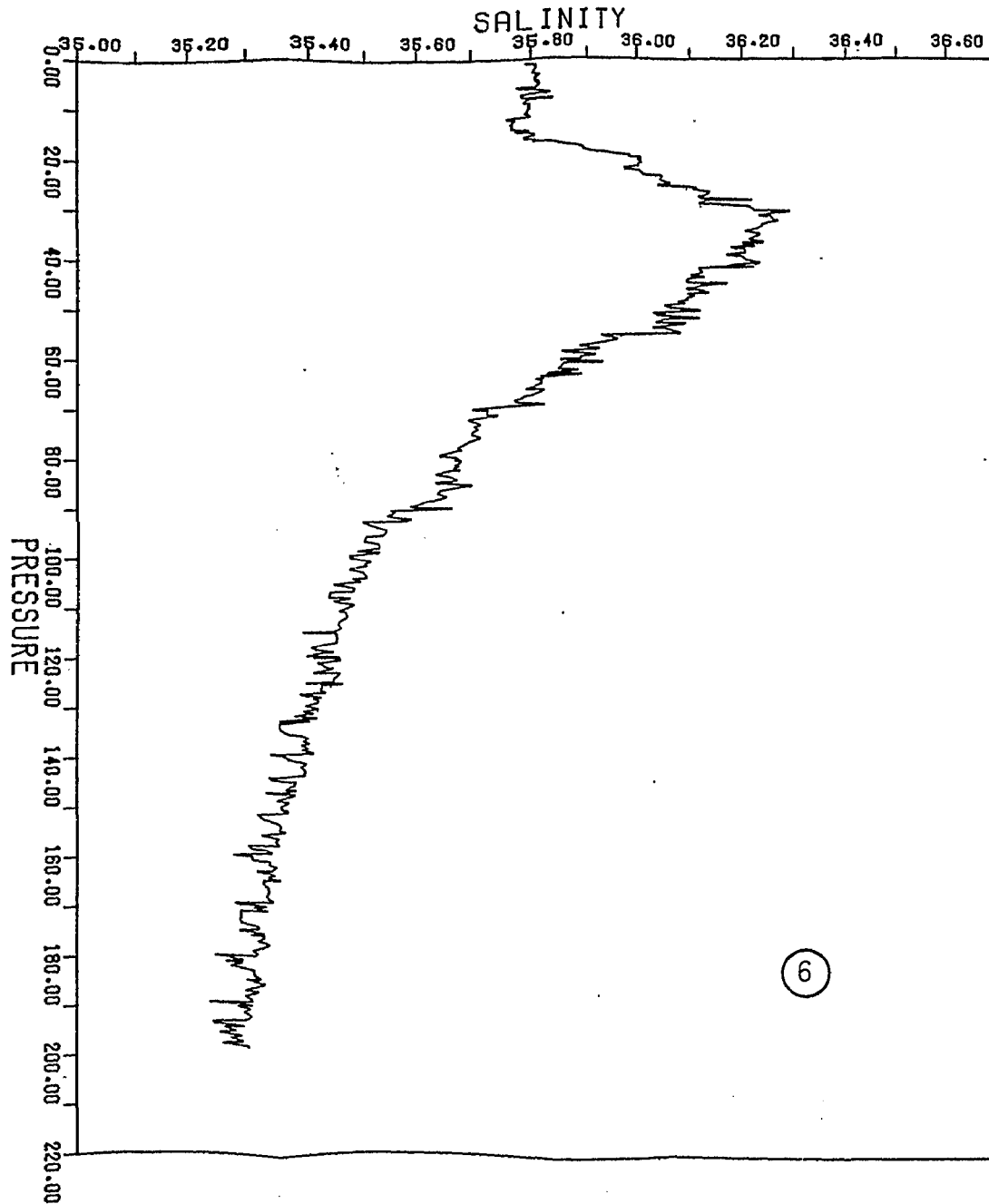


fig. 6: Bathysonde (CTD) cast ref. no. 80060 of R.V. "Planet", salinity as function pressure, corrected for time lag of temperature sensor, monotony with respect to pressure established.

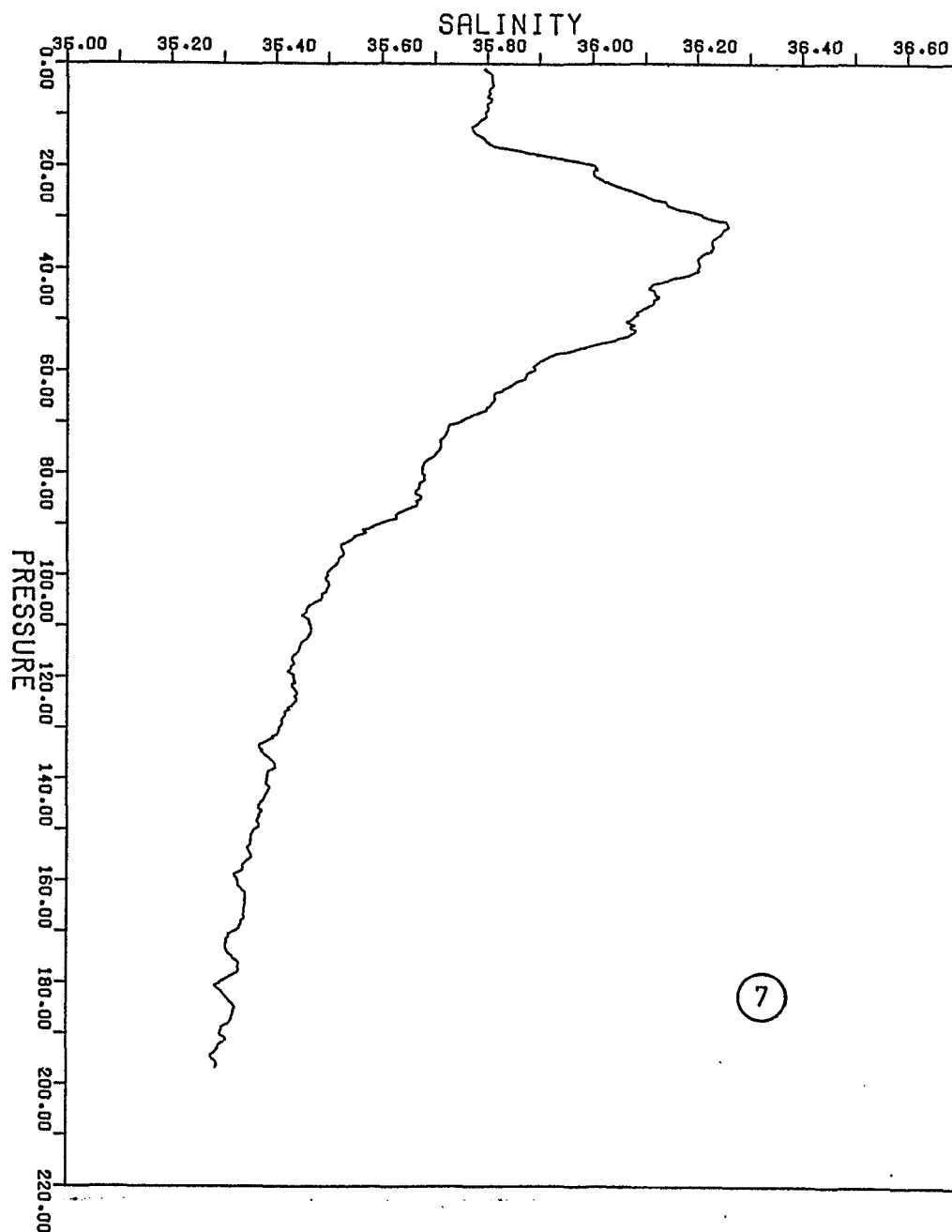


fig. 7: Bathysonde (CTD) cast ref. no. 80060 of R.V. "Planet", salinity as function pressure, corrected for time lag of temperature sensor, monotony with respect to pressure established, running mean over 7 values.

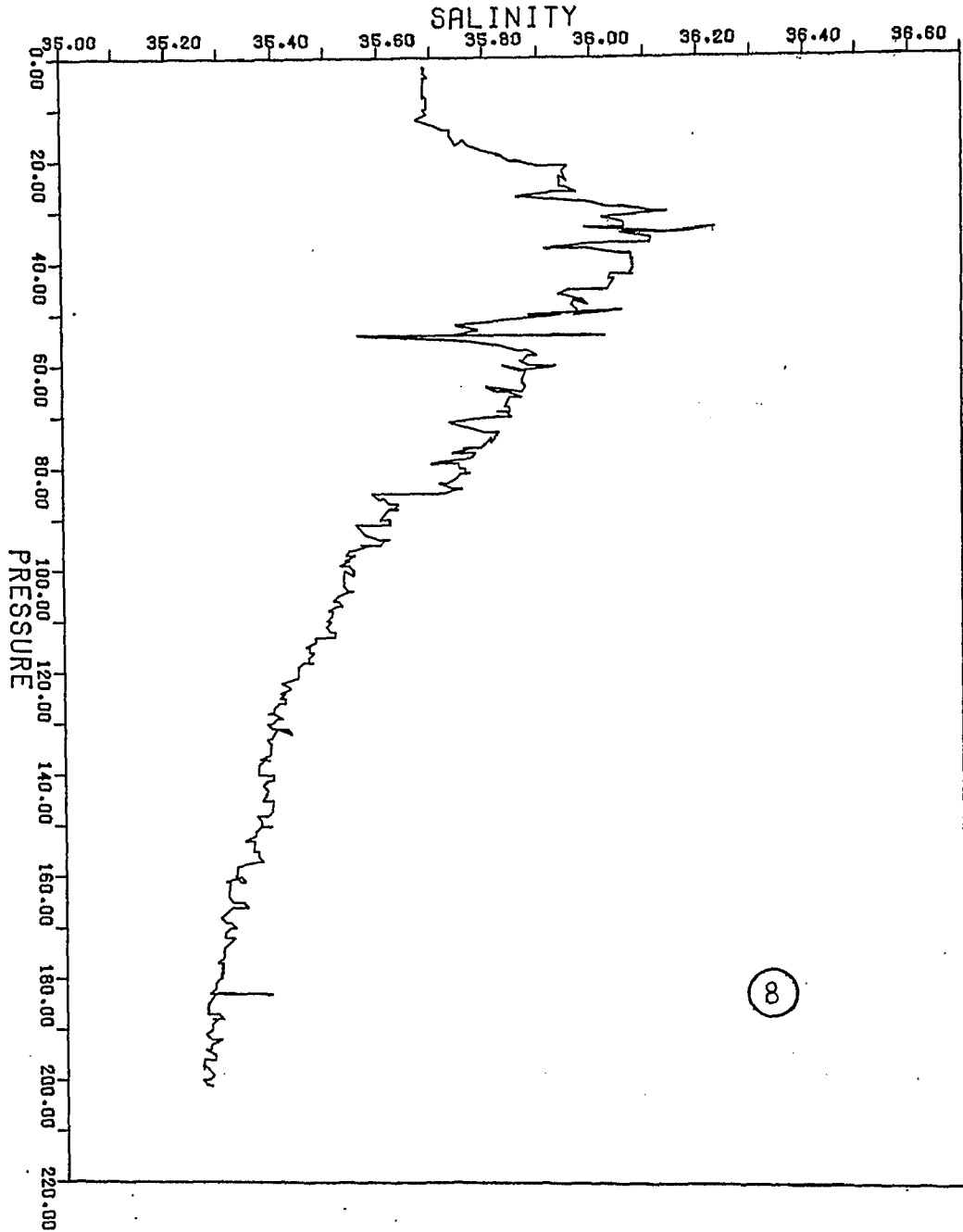


fig. 8: Multisonde (CTD) cast ref. no. 71940 of R.V. "Meteor", salinity as function of pressure, raw data.

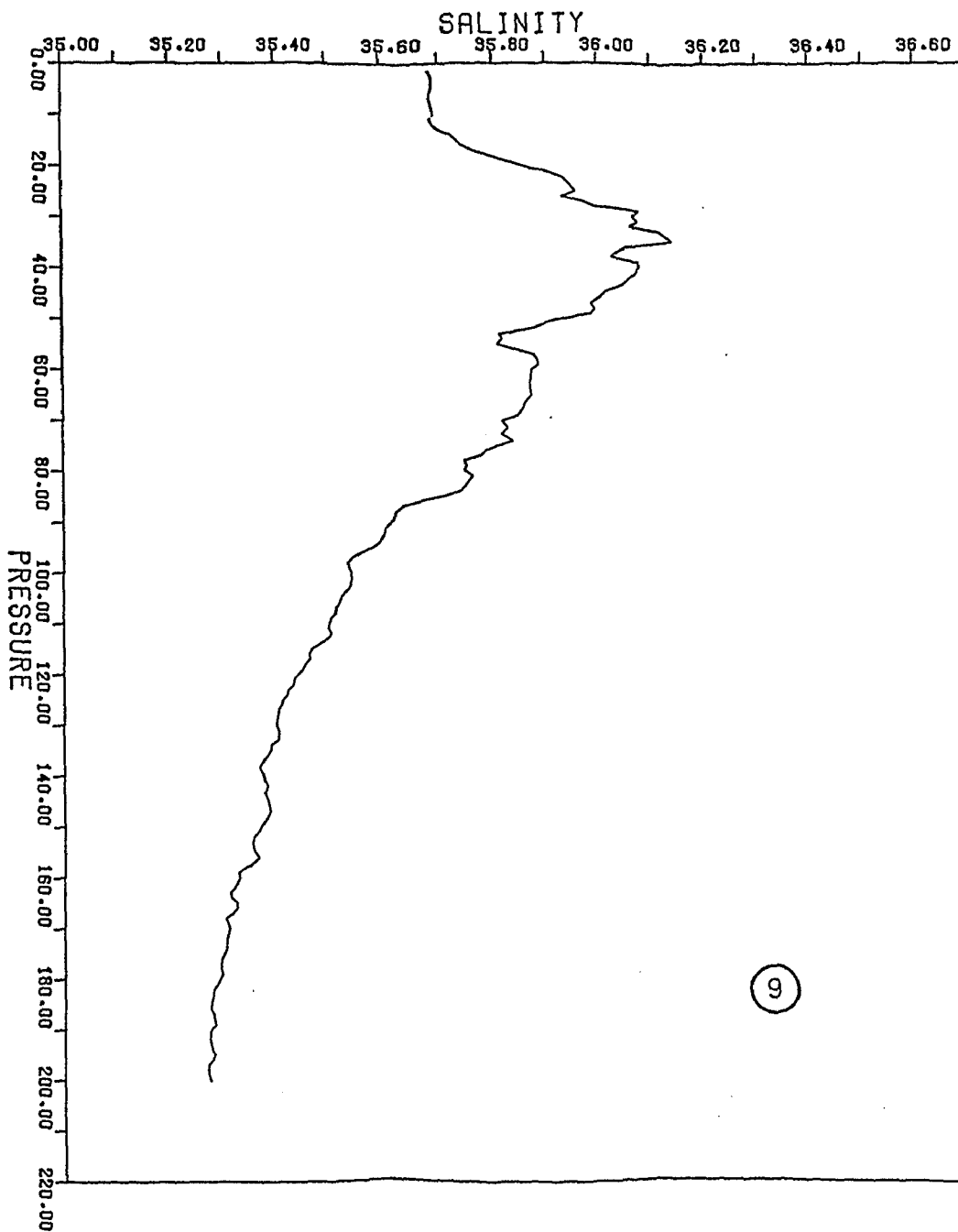


fig. 9: Multisonde (CTD) cast ref. no. 71940 of R.V. "Meteor", salinity as function of pressure, corrected for time lag of temperature sensor, monotony with respect to pressure established, running mean over 3 values.

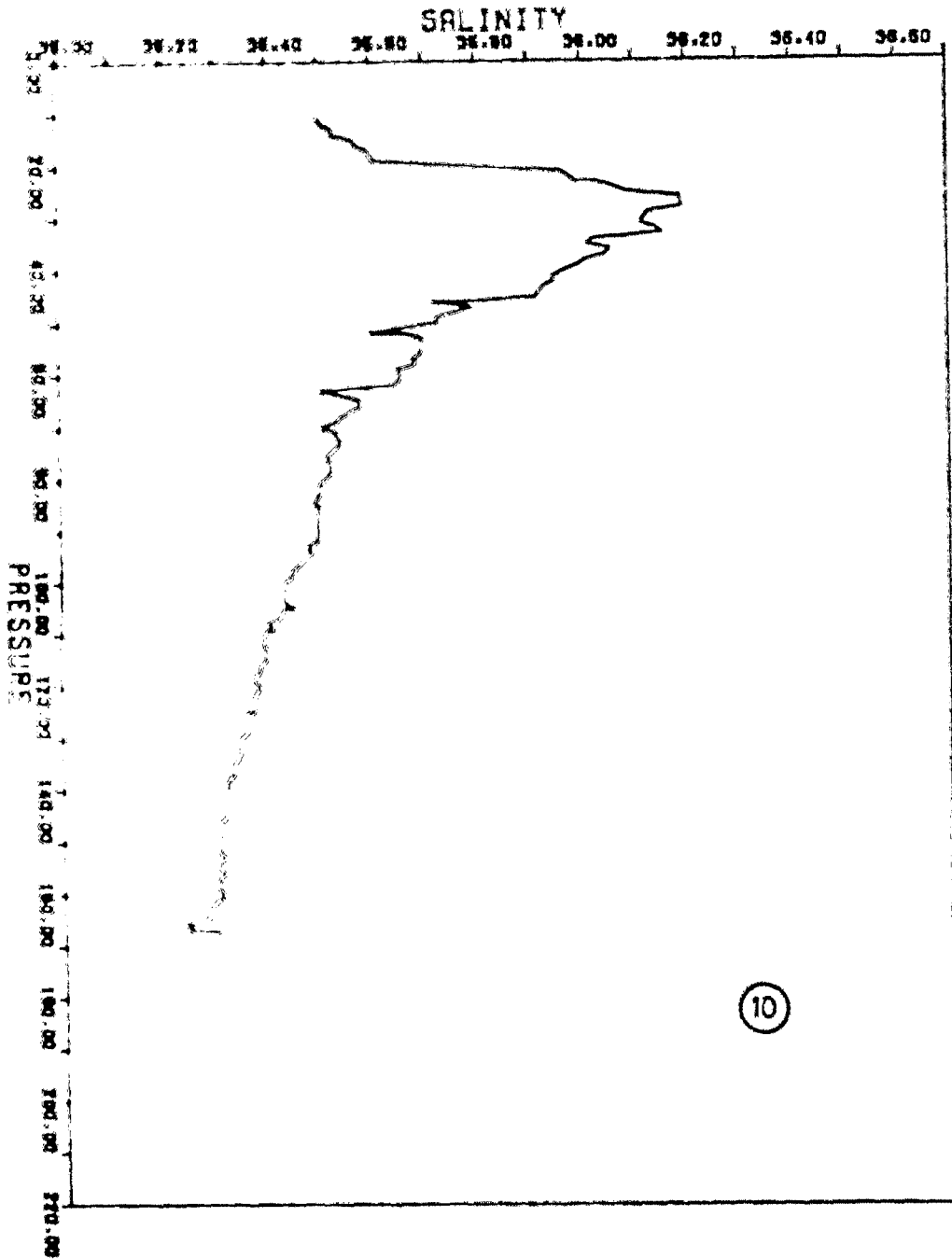


fig. 10: Bathysonde (CTD) cast ref. no. 70179 of R.V. "Meteor", salinity as function of pressure, raw data.

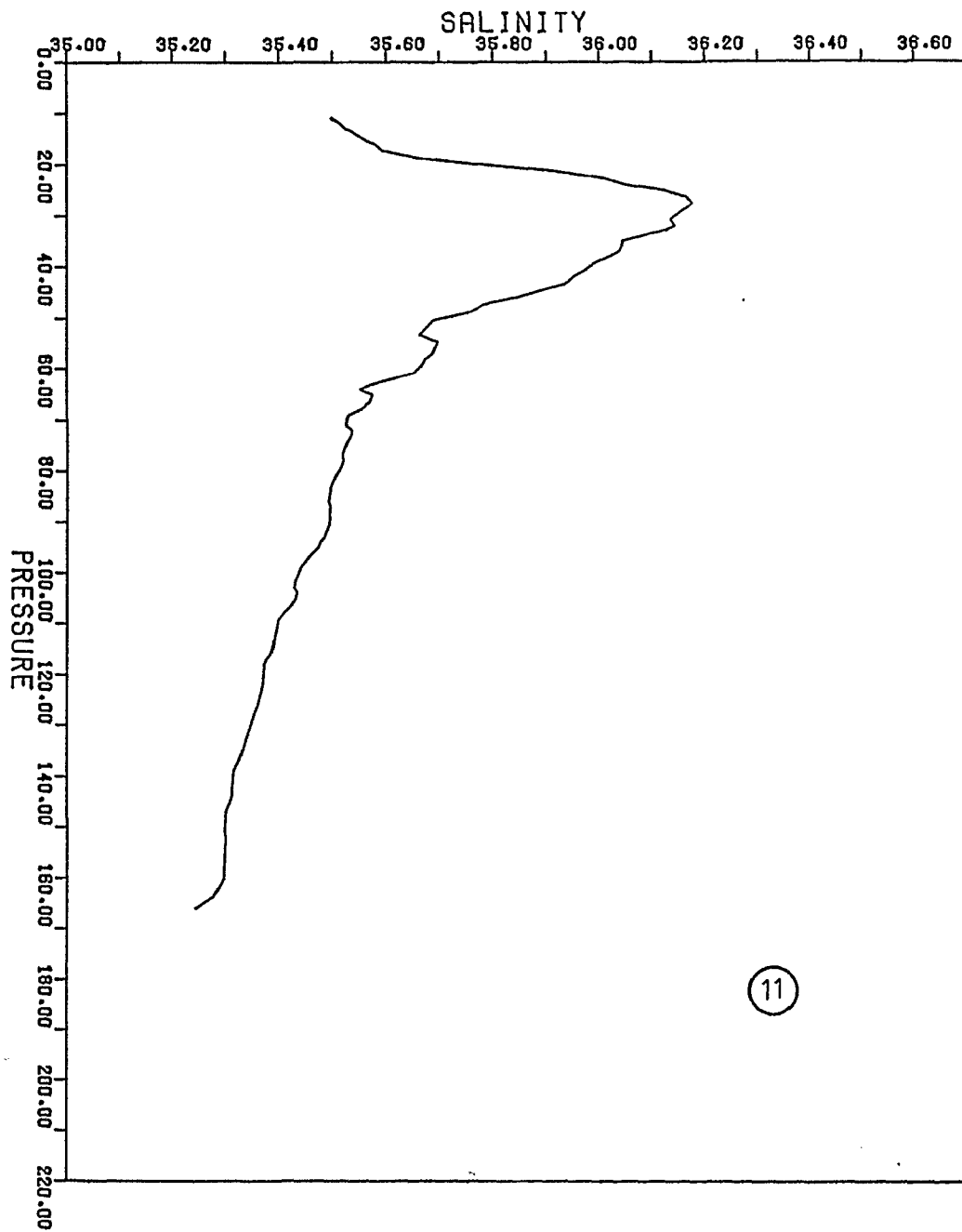


fig. 11: Bathysonde (CTD) cast ref. no. 70179 of R.V. "Meteor", salinity as function of pressure, corrected for time lag of temperature sensor, monotony with respect to pressure established, running mean over 3 values.

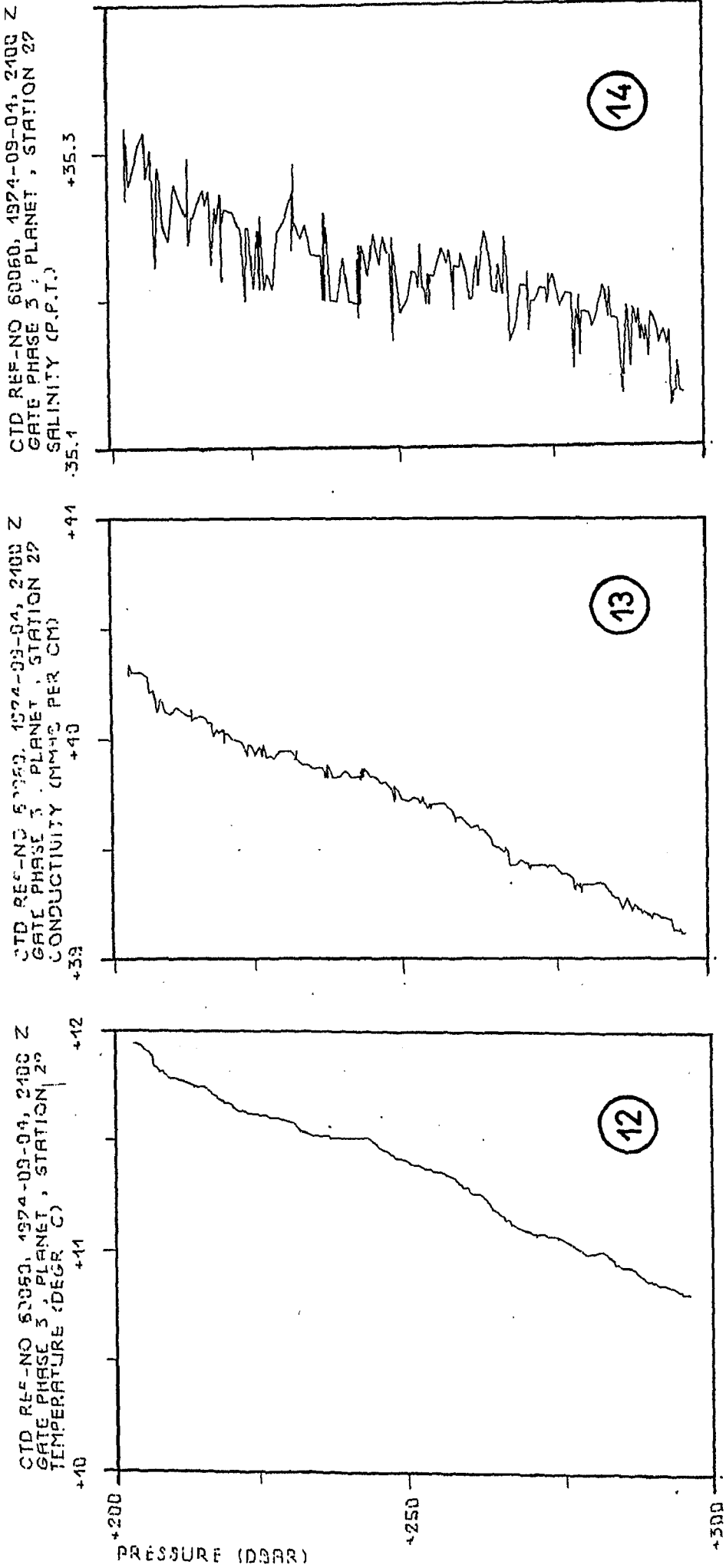


fig. 12: Bathysonde (CTD) cast ref. no. 80060 of R.V. "Planet", raw data, temperature as function of pressure (enlarged cut).

fig. 13: Bathysonde (CTD) cast ref. no. 80060 of R.V. "Planet", raw data, conductivity as function of pressure (enlarged cut).

fig. 14: Bathysonde (CTD) cast ref. no. 80060 of R.V. "Planet", raw data, salinity as function of pressure (enlarged cut).

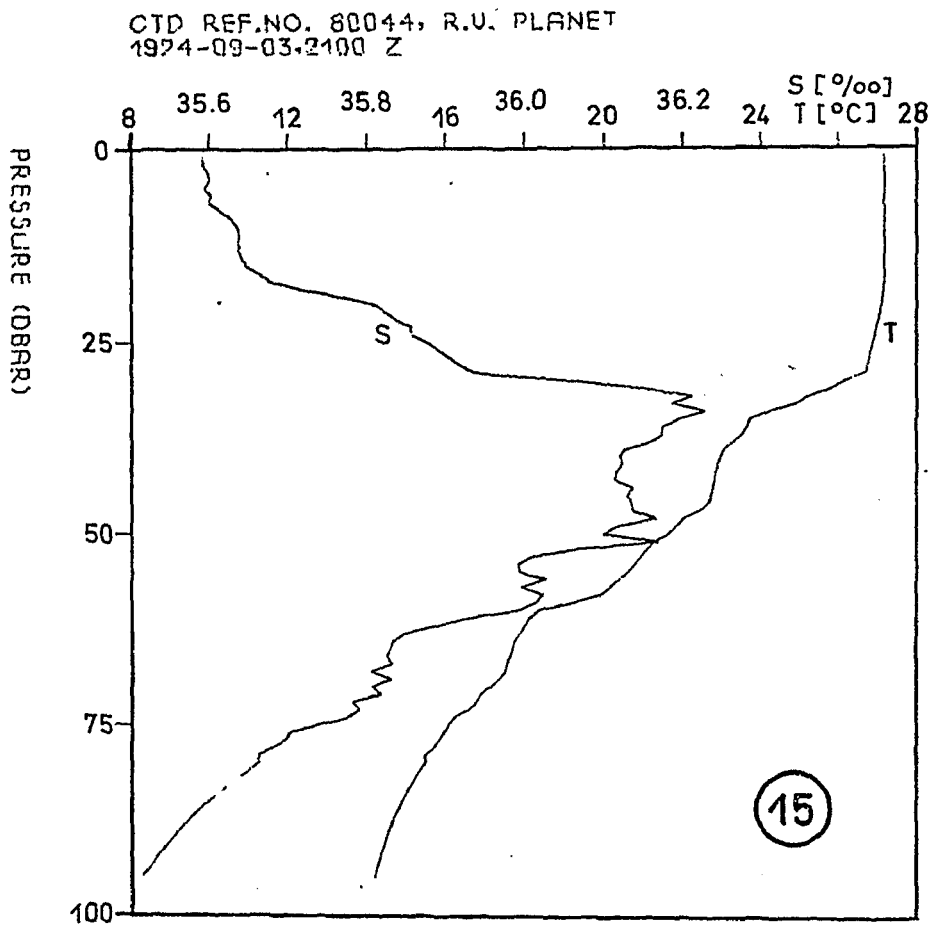


fig. 15: Bathysonde (CTD) cast ref. no. 80044 of R.V. "Planet", temperature and salinity as function of pressure, final data.