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OCEANOGRAPHY

Technical Report No. 289

Some Chemical and Physical Properties of the Eastern Tropical North Pacific with Emphasis on the Oxygen Minimum Layer

by

Louis A. Codispoti

National Science Foundation
Contracts GA-10084 and GA-24875

and

Office of Naval Research
Contracts Nonr-477(37) and
N-00014-67-A-0103-0014
Project NR 083 012

Reference M73-64
October 1973

seattle, washington 98195

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Francis A. Richards
Principal Investigator and
Assistant Chairman for Research

ABSTRACT

This report is basically an atlas presenting diagrams and charts of temperature, salinity, oxygen, nutrient, and relative baroclinic current data for the eastern tropical North Pacific. Special emphasis is on the oxygen deficient layer in this region and a number of the charts constitute an isentropic study of this layer. Two of the included properties, nitrate deficits and equivalent nitrate, are particularly appropriate for investigations dealing with denitrification in these waters, and the methods for calculating them are described.

A temperature-salinity, temperature-oxygen diagram presents evidence for significant respiration at depths of about 800 m.

ACKNOWLEDGEMENTS

It is impossible to mention everyone who contributed to this report. However, those who made special contributions include the following: Shirley Patterson, Dorothy Lowman, Susan Sugai, Dr. F. A. Richards, and Mssrs. J. Anderson, R. Cromoga, A. Devol, D. Doyle, and T. Owens.

Financial support was provided by the Office of Naval Research under contracts NONR-477(3) and N-00014-67-A-0103-0014, and by the National Science Foundation under grants GA-10084 and GA-24875-A1.

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INTRODUCTION

The diagrams and charts comprising the bulk of this report are primarily from a thesis on denitrification in the eastern tropical North Pacific Ocean (Codispoti, 1973). Some of the less useful figures have been excluded, some have been updated, and a new figure showing the relative baroclinic currents in the region of the California Undercurrent has been added.

This report has been prepared because the included figures form a useful atlas for some properties in the oxygen minimum layer of the eastern tropical North Pacific Ocean. Due to space limitations, only a fraction could appear in forthcoming publications dealing with the main results of the denitrification study.

DATA SOURCES

Except for Figure 1 which is redrawn from Reid (1965), the data sources for this report are listed in Tables 1 and 2. Additional information on the *Thomas G. Thompson* cruises is available in Dugdale and Healy (1970), University of Washington (1970), and Lowman and Codispoti (1973).

EXTENT OF THE OXYGEN DEFICIENT ZONE

Most of the evidence indicates that oxygen concentrations must be less than ∿0.1 mℓ/liter (∿10 μg-atoms/liter) before denitrification can be observed in marine environments (Brandhorst, 1959; Richards, 1965; Thomas, 1966; Fiadeiro and Strickland, 1968; Cline and Richards, 1972). If sulphate reduction has not begun but denitrification is proceeding, the term oxygen deficient is used to describe such environments. Figures 1 and 2 give some idea of the horizontal and vertical extent of the oxygen deficient layer in the eastern tropical North Pacific. The vertical extent also decreases with increasing distance from the coast.

VERTICAL AMMONIA DISTRIBUTION

The purpose of Figure 3 was to present additional evidence in support of Thomas' (1966) contention that ammonia does not appear to be the major end product of nitrate reduction and denitrification in the eastern tropical North Pacific.[1]

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[1] To be rigorous, the ammonia concentrations should have been expressed as μg-atoms/liter of ammonia nitrogen instead of μg-atoms/liter of ammonia. The reader should note that this type of "shorthand" has been used throughout this report. For example, reactive silicate in μg-atoms/liter should really be expressed as reactive silicate-silicon in μg-atoms/liter; nitrate in μg-atoms/liter should be nitrate-nitrogen in μg-atoms/liter; etc.

Table 1. Cruises sponsored by the University of Washington.

Vessel and Cruise No.	Year	Sources
R/V Thomas G. Thompson Cruise 1	1965	University of Washington, Dept. of Oceanography, Tech. Report 249, and the National Oceanographic Data Center
R/V Thomas G. Thompson Cruise 26	1968	University of Washington, Dept. of Oceanography, Tech. Report 250, and the National Oceanographic Data Center
R/V Thomas G. Thompson Cruise 35	1969	University of Washington, Dept. of Oceanography, Tech. Report 284, and the National Oceanographic Data Center
R/V Thomas G. Thompson Cruise 37	1969	
R/V Thomas G. Thompson Cruise 46	1969-70	
R/V Thomas G. Thompson Cruise 66	1972	

Table 2. Cruises sponsored by agencies other than the University of Washington.

Vessel and Cruise No. or NODC Ref. No.		Year	Source
R/V Horizon	STEP-I	1960	Scripps Institution of Oceanography
R/V Hugh M. Smith	Cruise TO-59-2	1959	U.S. Dept. of the Interior, Fish and Wildlife Service
R/V D.S. Jordon	Cruise 12	1967	EASTROPAC (National Marine Fisheries Service, Scripps Institution of Oceanography, Inter-American Tropical Tuna Commission)
R/V D.S. Jordan	CALCOFI Cruise 6804	1968	California Cooperative Oceanic Fisheries Investigations (Scripps Institution of Oceanography)
R/V D.S. Jordan	CALCOFI Cruise 6806	1968	California Cooperative Oceanic Fisheries Investigations (Scripps Institution of Oceanography)
NODC 90-0589		1959	National Oceanographic Data Center
NODC 31-1072		1966	National Oceanographic Data Center
NODC 31-1166		1967	National Oceanographic Data Center
R/V Proteus	Cruise 22	1970	Stanford University
R/V Proteus	Time-Series Station	1969-71	Stanford University
R/V Shoyo Maru	Cruise 13	1963-64	Inter-American Tropical Tuna Commission
R/V Te Vega	Cruise 13	1967	Stanford University
R/V Te Vega	Cruise 14	1967	Stanford University
R/V Te Vega	Cruise 16	1967	Stanford University
R/V Te Vega	Cruise 17	1968	Stanford University
R/V Cayuse	Cruise C7002D	1970	Oregon State University

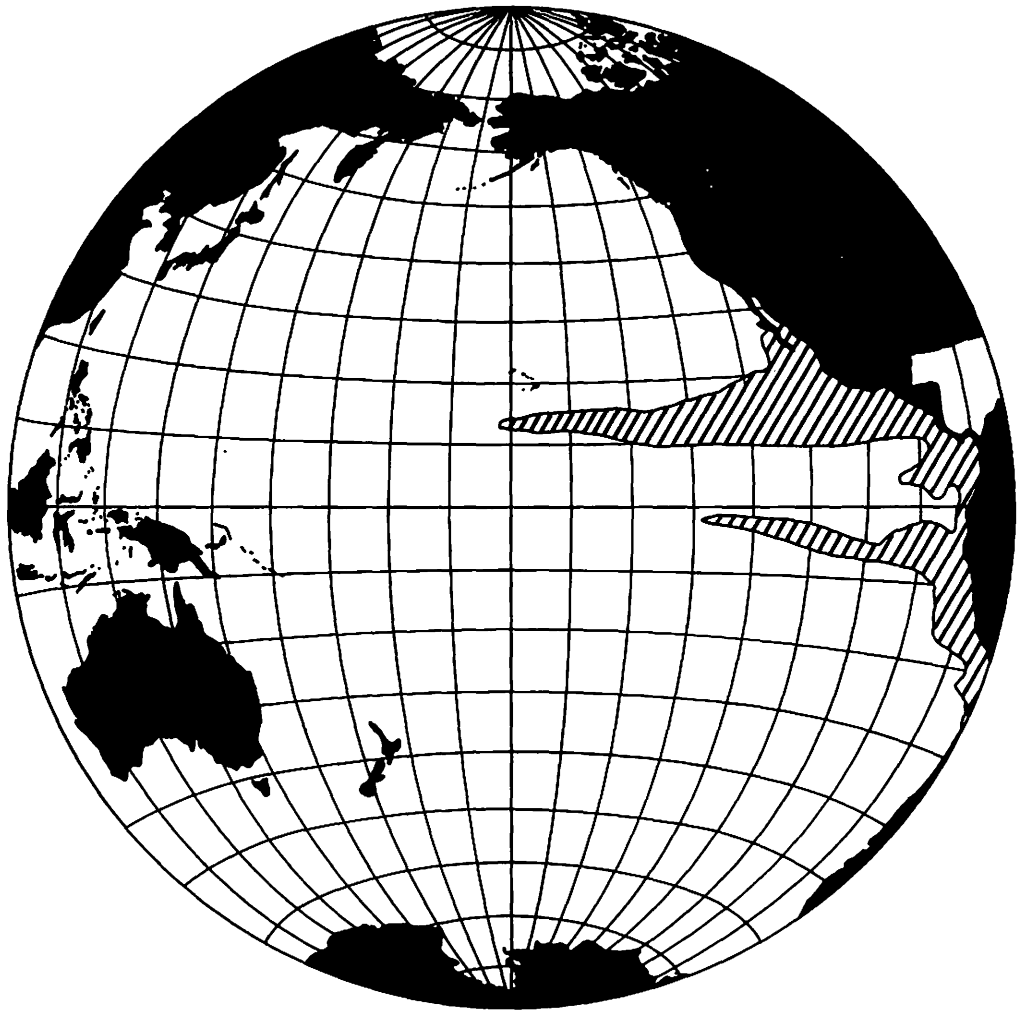


Figure 1. Extent of the oxygen deficient region in the eastern tropical Pacific. The shaded area indicates oxygen concentrations of less than 0.25 ml/liter on the 125 cl/ton thermosteric anomaly surface. This surface is at ∿ 400 m (after Reid, 1965).

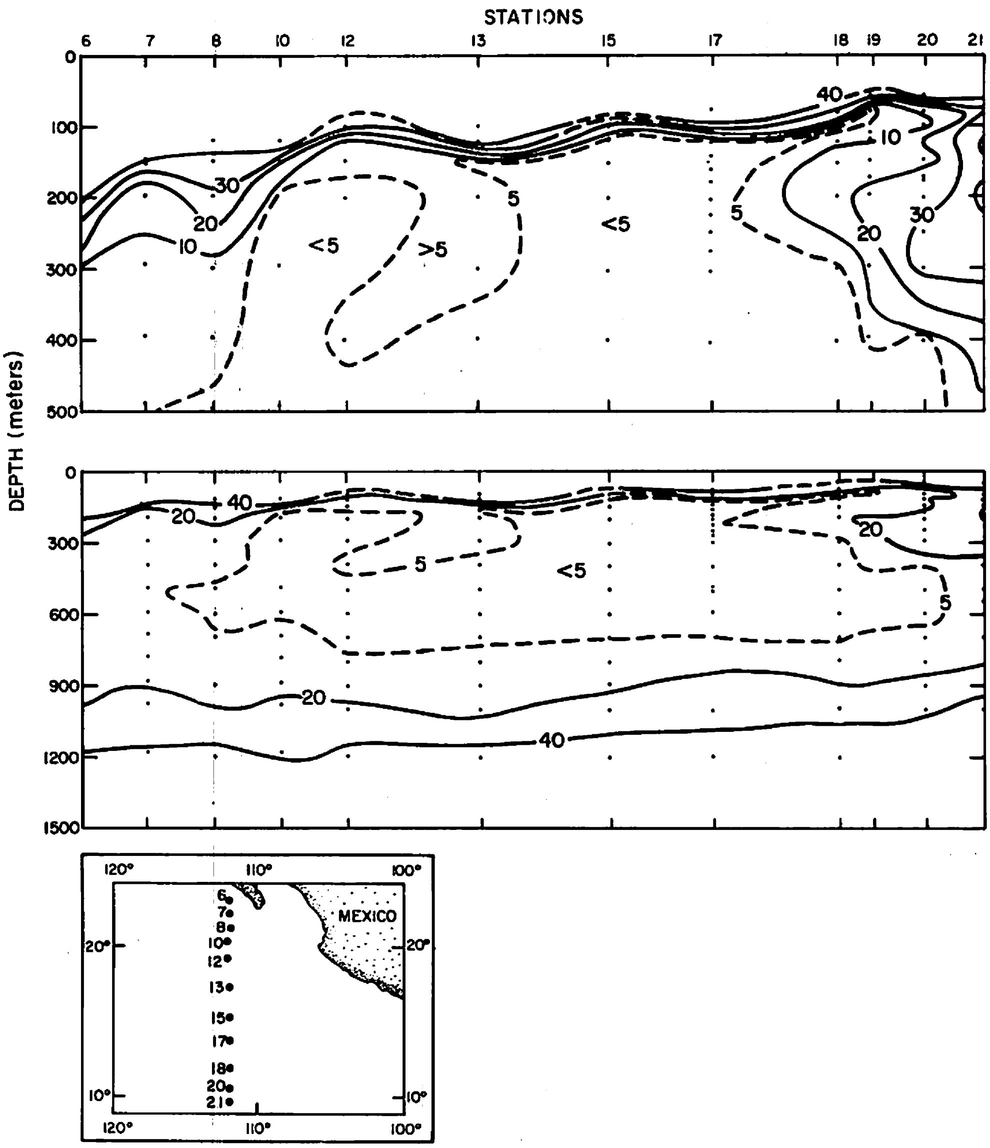


Figure 2. Dissolved oxygen distribution along 112°W. Concentrations are in μg-atoms/liter and were determined by the colorimetric method (Broenkow and Cline, 1969). The data are from *Thomas G. Thompson* Cruise 46.

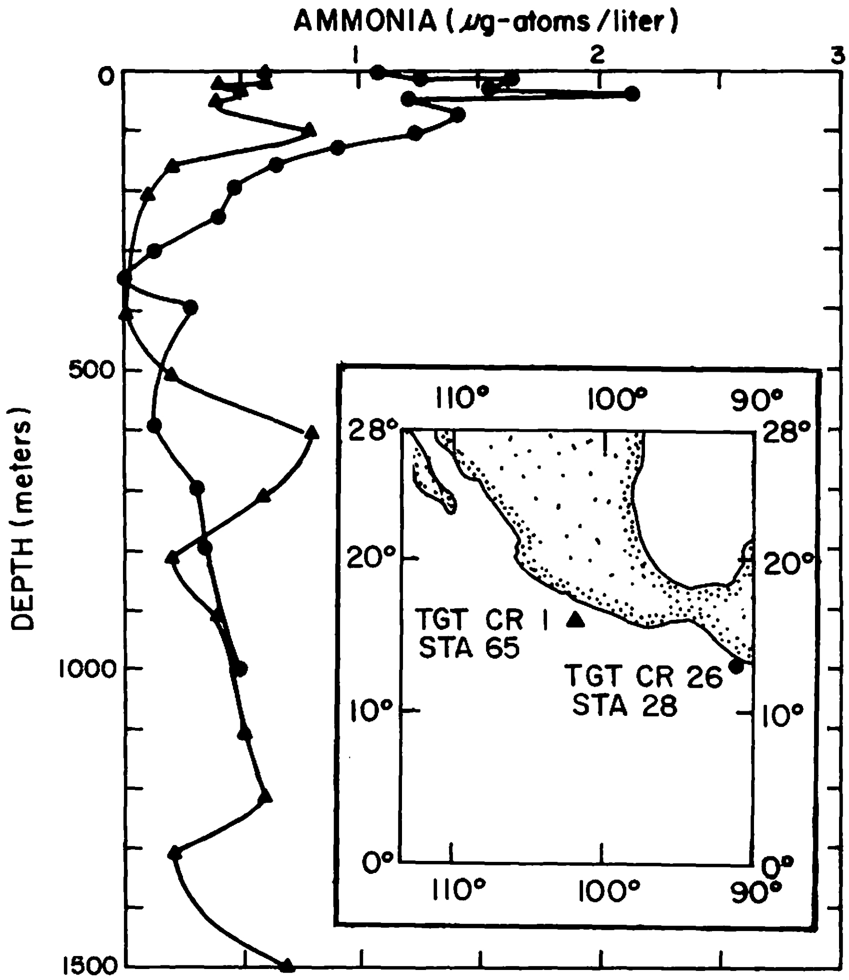


Figure 3. Vertical ammonia profiles.

TEMPERATURE-SALINITY AND TEMPERATURE-OXYGEN DIAGRAMS

Figure 4 is a conventional temperature-salinity diagram for the region investigated in the denitrification study. Except for station 71 which is to the north of the oxygen deficient layer, the diagram indicates considerable uniformity in the layers below ∿200 meters and in waters with σ_τ values exceeding ∿26.0. Figure 5 is a temperature-salinity, temperature-oxygen diagram for the $\sigma_\tau = 27.3$ surface. This surface is near the core of the salinity minimum and is generally found at a depth of about 800 meters. When the above factors are considered, this diagram presents strong evidence for significant *in situ* changes in non-conservative properties at the depth of the $\sigma_\tau = 27.3$ surface.

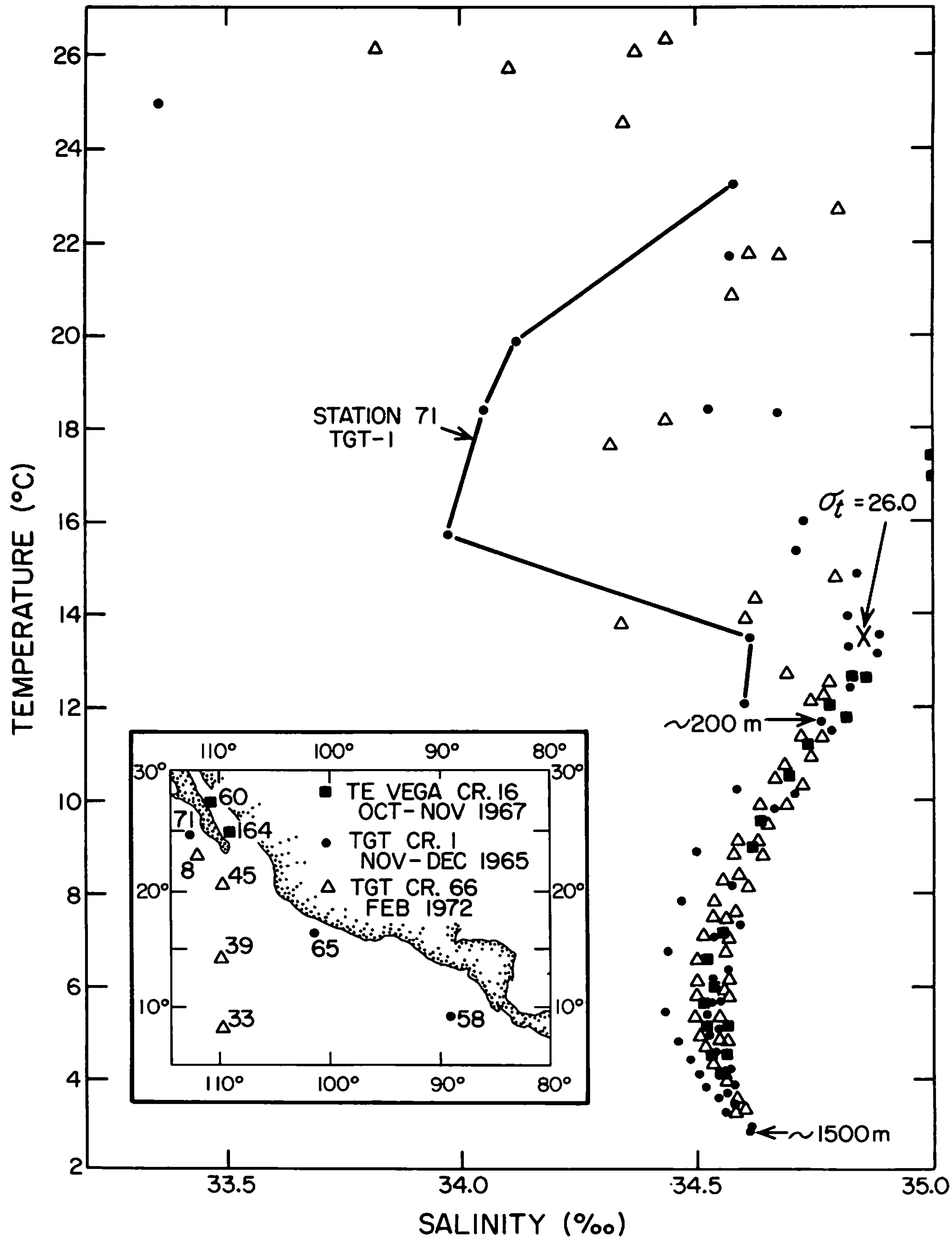


Figure 4. Temperature-salinity relationships in the study region. Some surface layer values have been excluded.

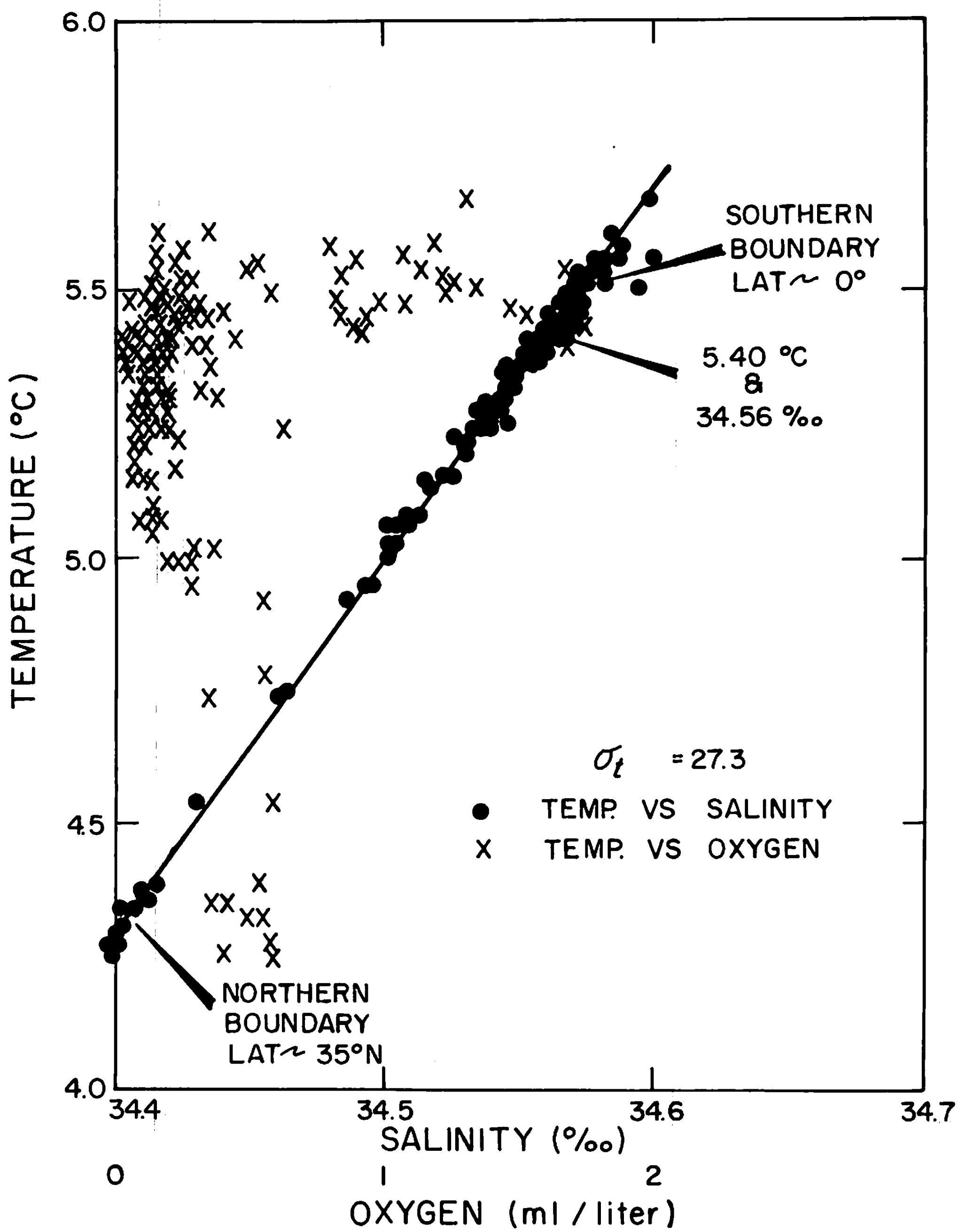


Figure 5. Temperature-salinity and temperature-oxygen diagram for the 27.3 σ_{τ} surface.

TEMPORAL VARIATION DIAGRAMS

These diagrams (Figs. 6-9) were designed to investigate temporal variations in nitrate, nitrite, and dissolved oxygen in the oxygen deficient region. Often, the agreement appears to be within the precision of the methods, particularly in the deeper layers. This suggests that a knowledge of the concentrations of non-conservative properties in the deeper layers for a given area could provide a rapid means for estimating data quality.

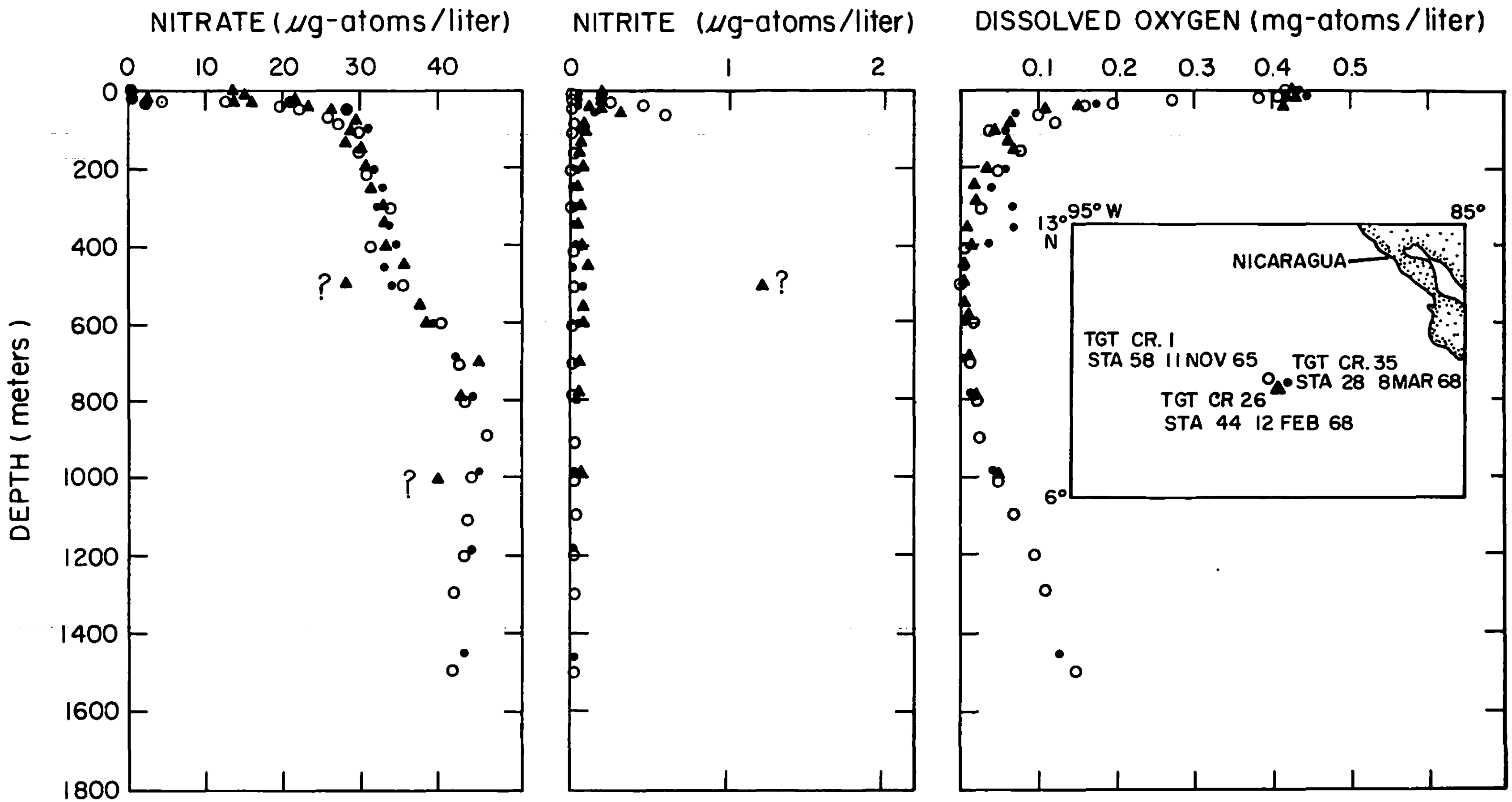


Figure 6. Variables versus depth for three stations near the southern boundary of the oxygen deficient region.

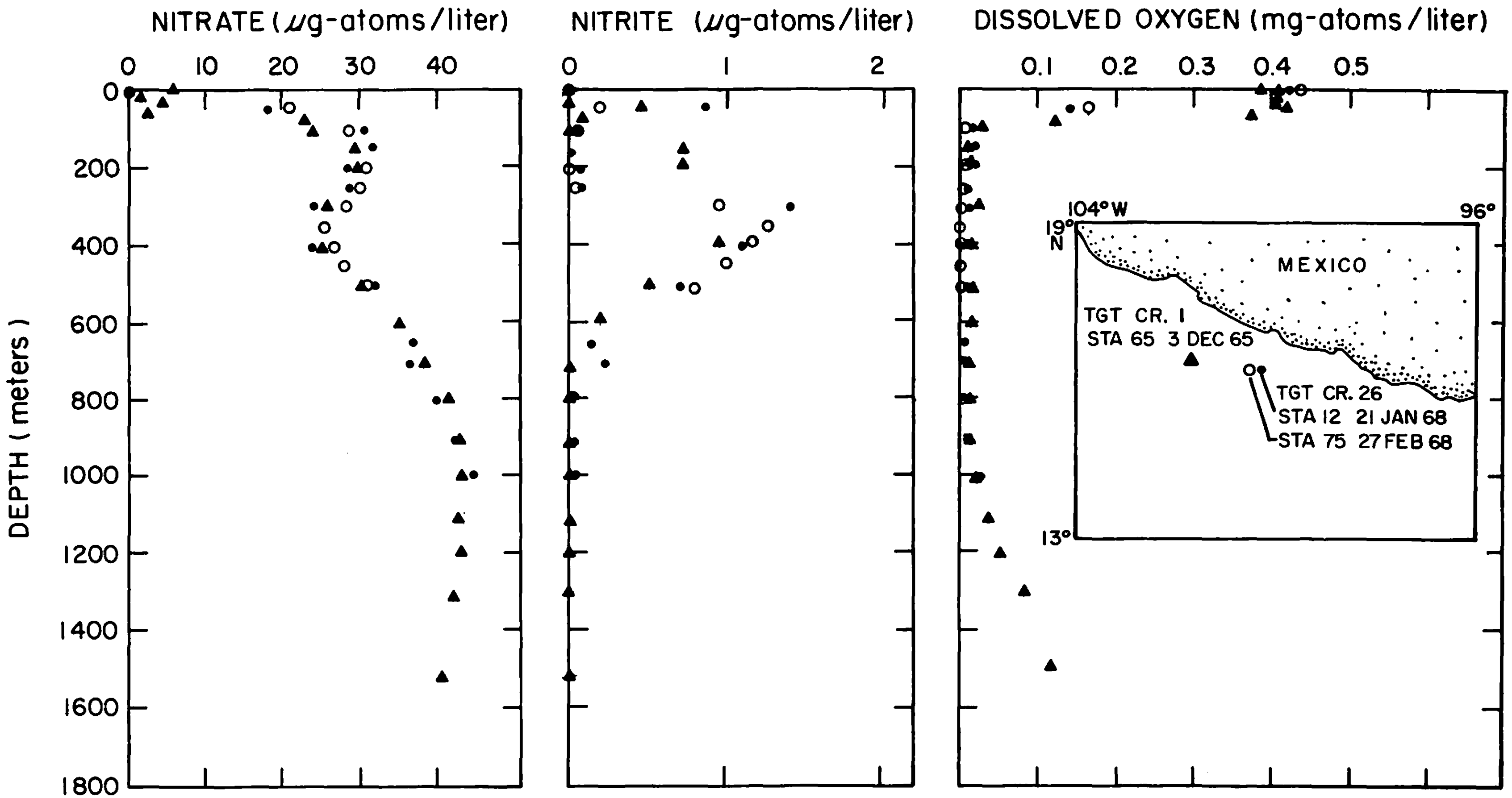


Figure 7. Variables versus depth for three stations in the interior of the oxygen deficient region.

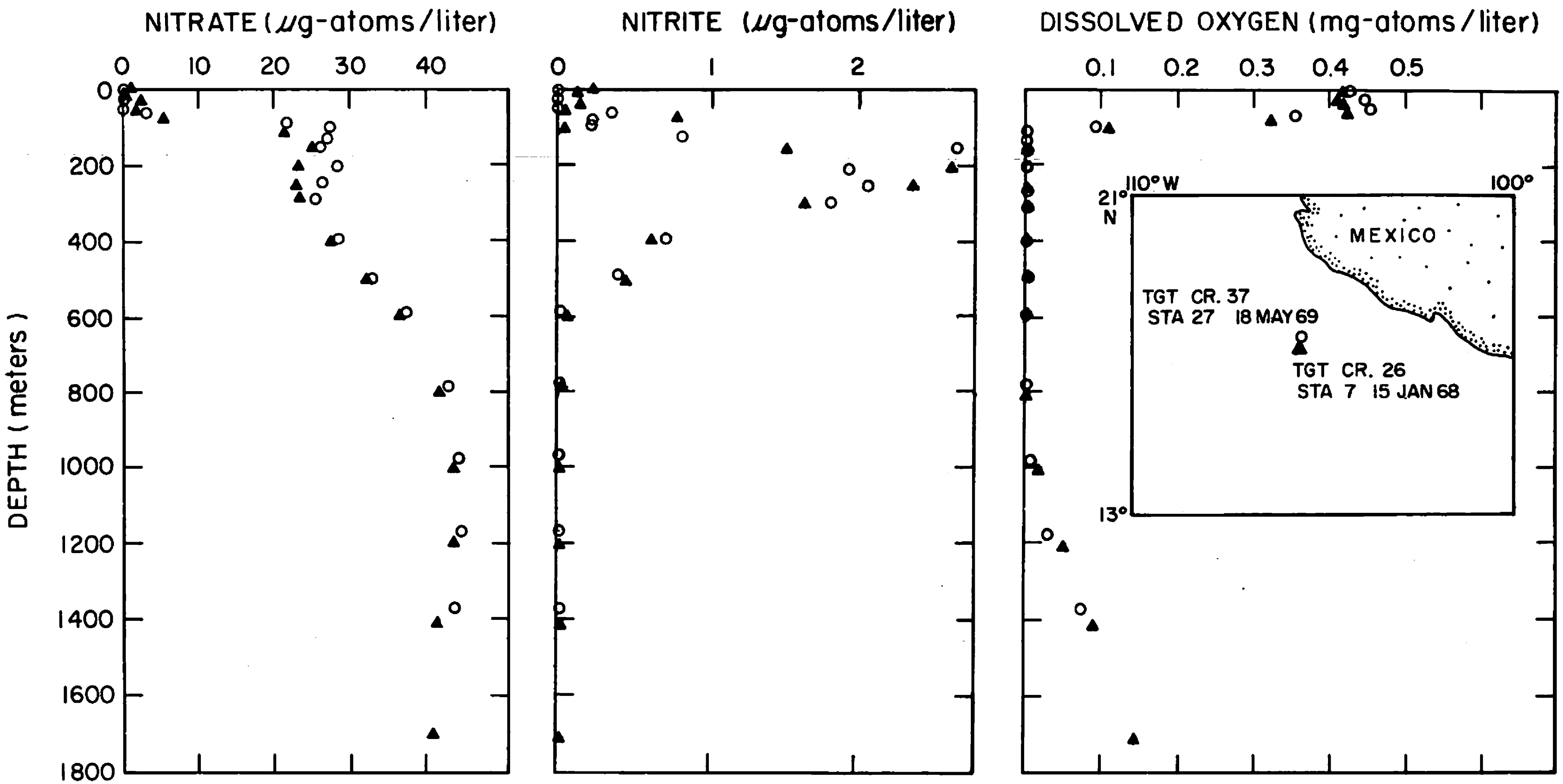


Figure 8. Variables versus depth for two stations in the interior of the oxygen deficient region.

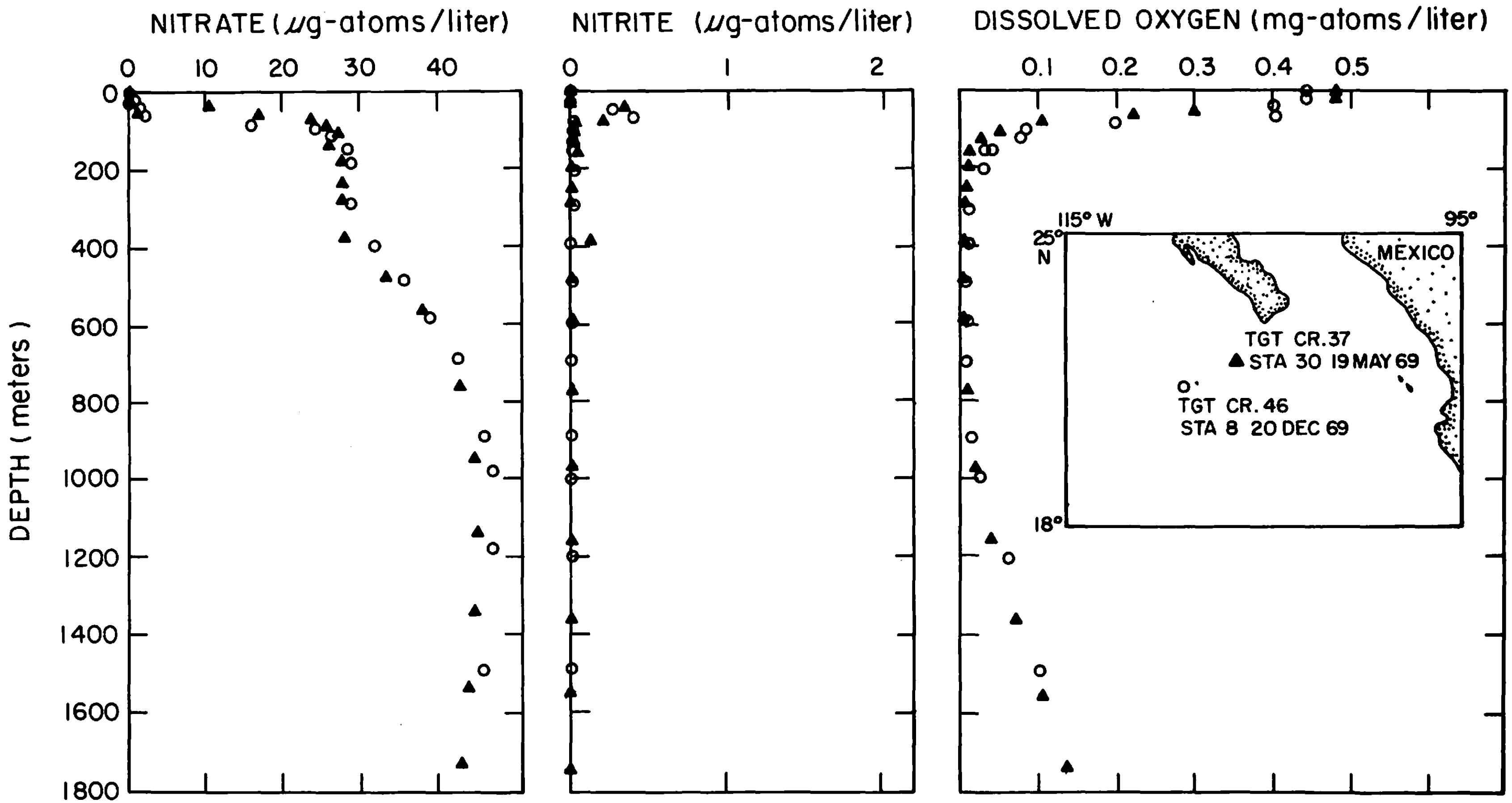


Figure 9. Variables versus depth for two stations near the northern boundary of the oxygen deficient region.

VERTICAL SECTIONS

These sections (Figs. 10-16) give some idea of the distribution of nitrite, nitrate deficits, temperature, salinity, reactive silicate, reactive phosphorus, and the relative baroclinic currents in portions of the region emphasized in the denitrification study (Codispoti, 1973). The nitrate deficit (Fig. 11) is an estimate of the amount of nitrate converted to free nitrogen by denitrification. The calculation and validity of this term will be briefly discussed later on in this report and in more detail in a forthcoming publication (Codispoti and Richards, in prep.).

The relative baroclinic current sections (Figs. 15 and 16) appear to present a reasonable picture of the currents. For example, nitrate deficit transports computed with the aid of these currents (and the use of reasonable estimates for the vertical and horizontal diffusive transports) yielded a denitrification rate which compared favorably with an independent estimate (Codispoti, 1973). These currents are, nevertheless, subject to the normal limitations of such representations. For example, the barotropic mode was neglected; the net westward transport in Figure 15 seemed somewhat low (Codispoti, 1973); and some significant baroclinicity may remain at the depths of the reference levels (Reed, 1970).

For the shallow area in Figure 16, Helland-Hansen's (1934) method was used to obtain the relative baroclinic currents. These values compared reasonably well with the currents obtained by using the deepest reference levels possible in the water column.

Two shallow stations (maximum sampling depth = 370 m) were occupied to the north of station 6 (Fig. 15). These stations were not included in the original calculations, but a preliminary analysis indicates a strong net flow towards the east.

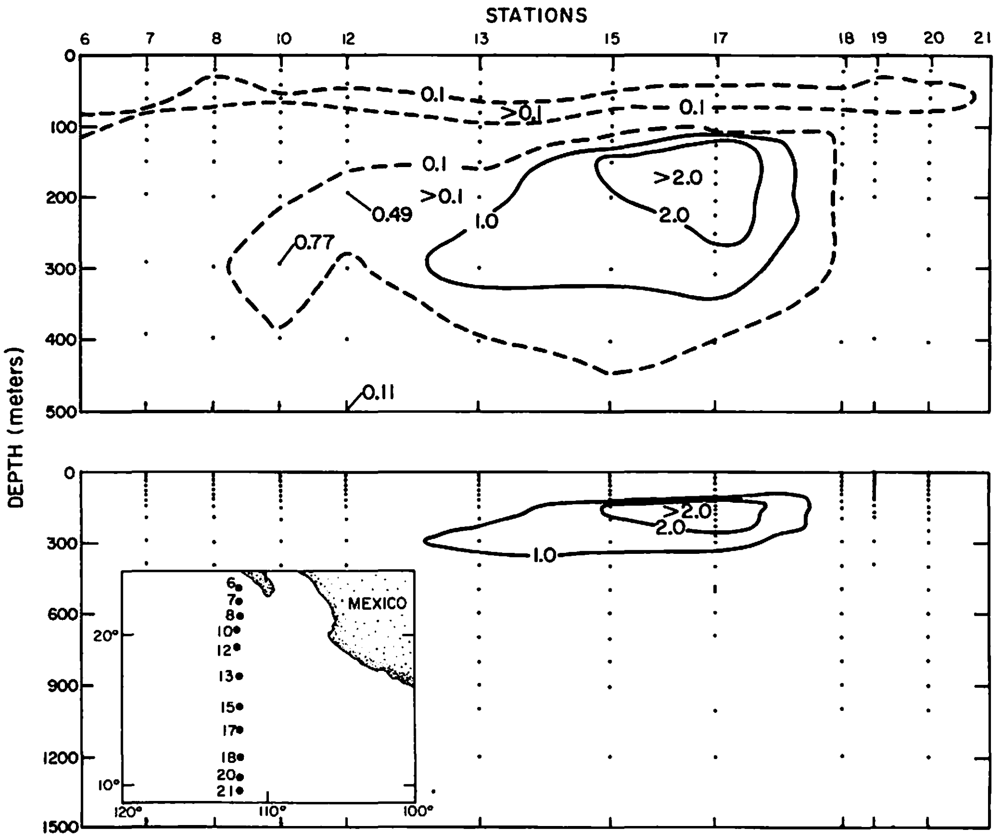


Figure 10. Nitrite distribution (in μg-atoms/liter) along 112°W. The data are from *Thomas G. Thompson* cruise 46.

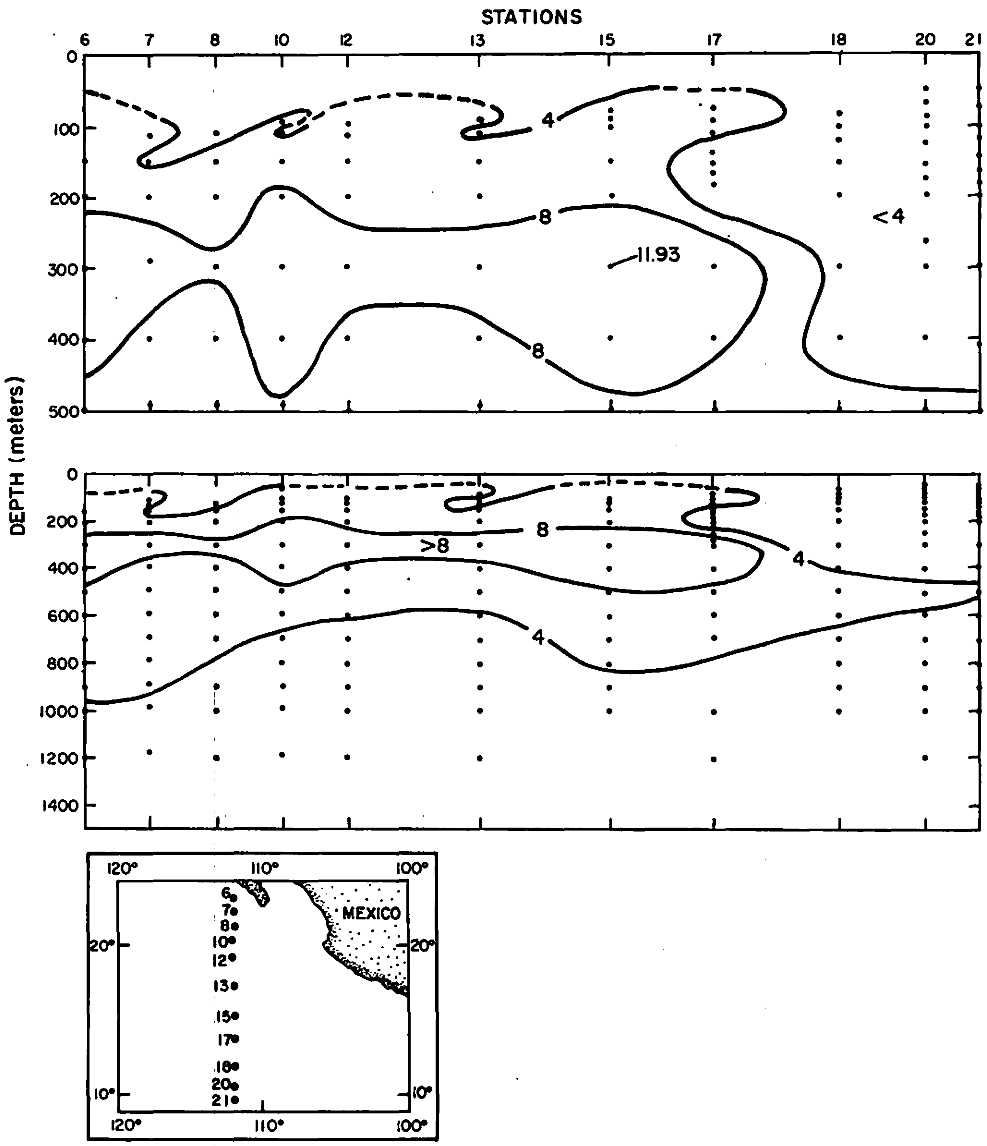


Figure 11. Nitrate deficit ($NO^-_{3\ ANOM\ II}$, in μg-atoms/liter) distribution along 112°W. The data are from *Thomas G. Thompson* cruise 46.

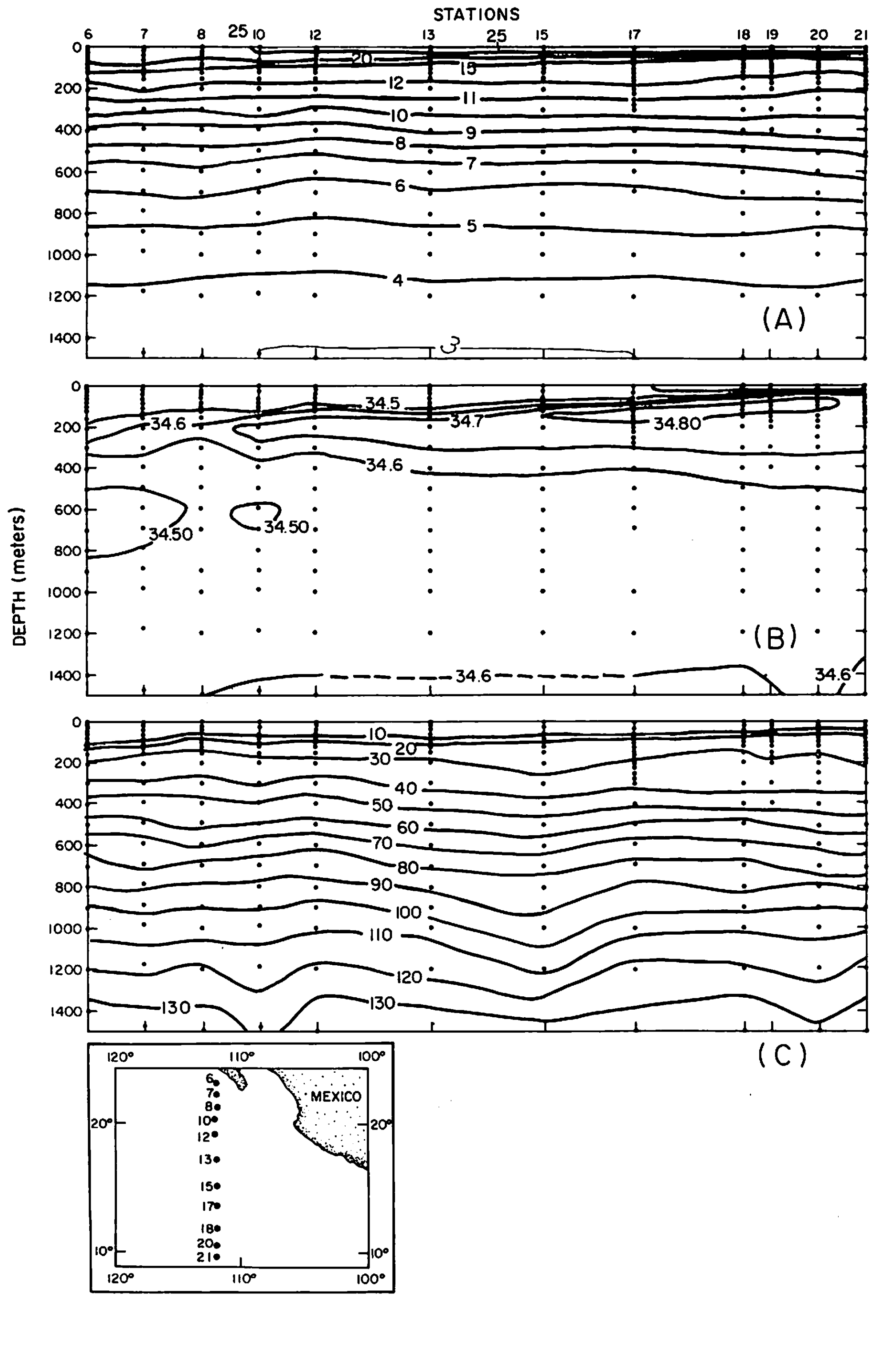


Figure 12. (A) Temperature (°C), (B) salinity (°/₀₀), and (C) reactive silicate distribution (µg-atoms/liter) along 112°W, *Thomas G. Thompson* cruise 46.

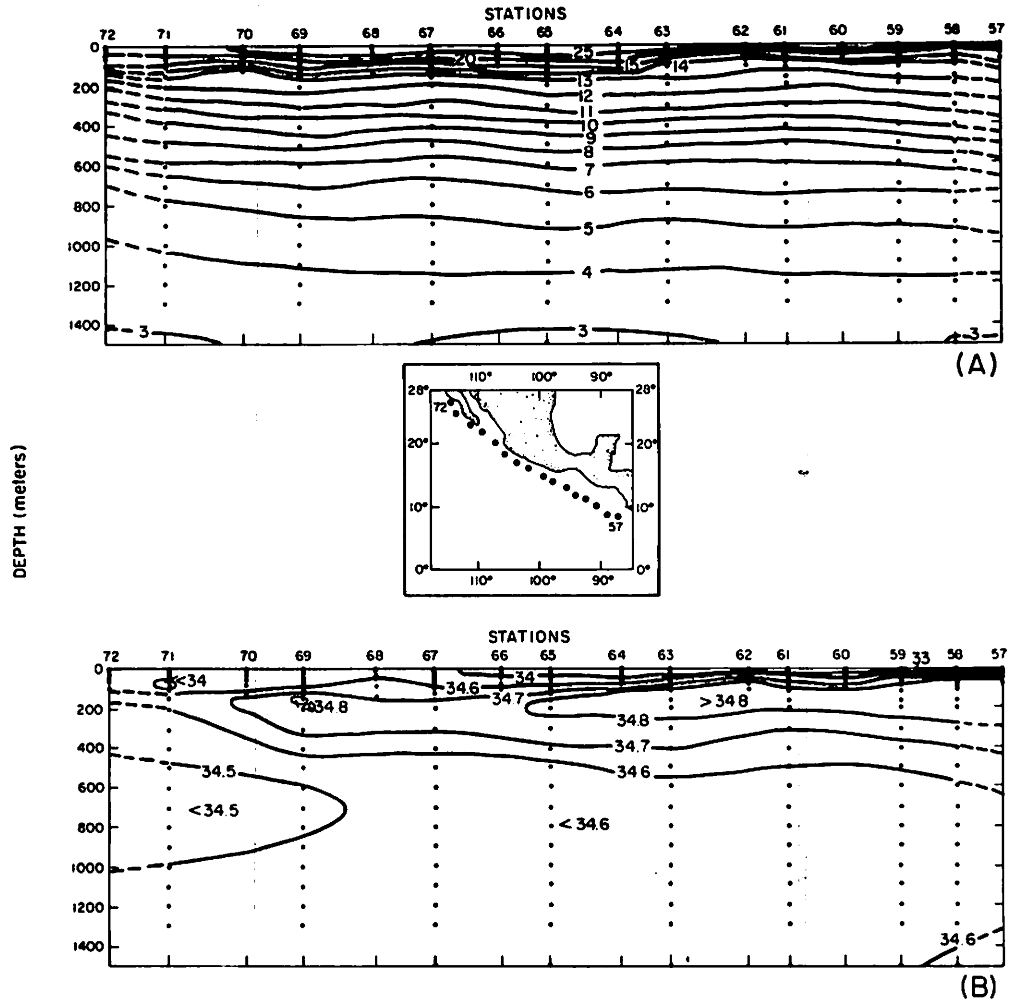


Figure 13. (A) Temperature (°C) and (B) salinity (°/₀₀) sections from data collected during *Thomas G. Thompson* cruise 1.

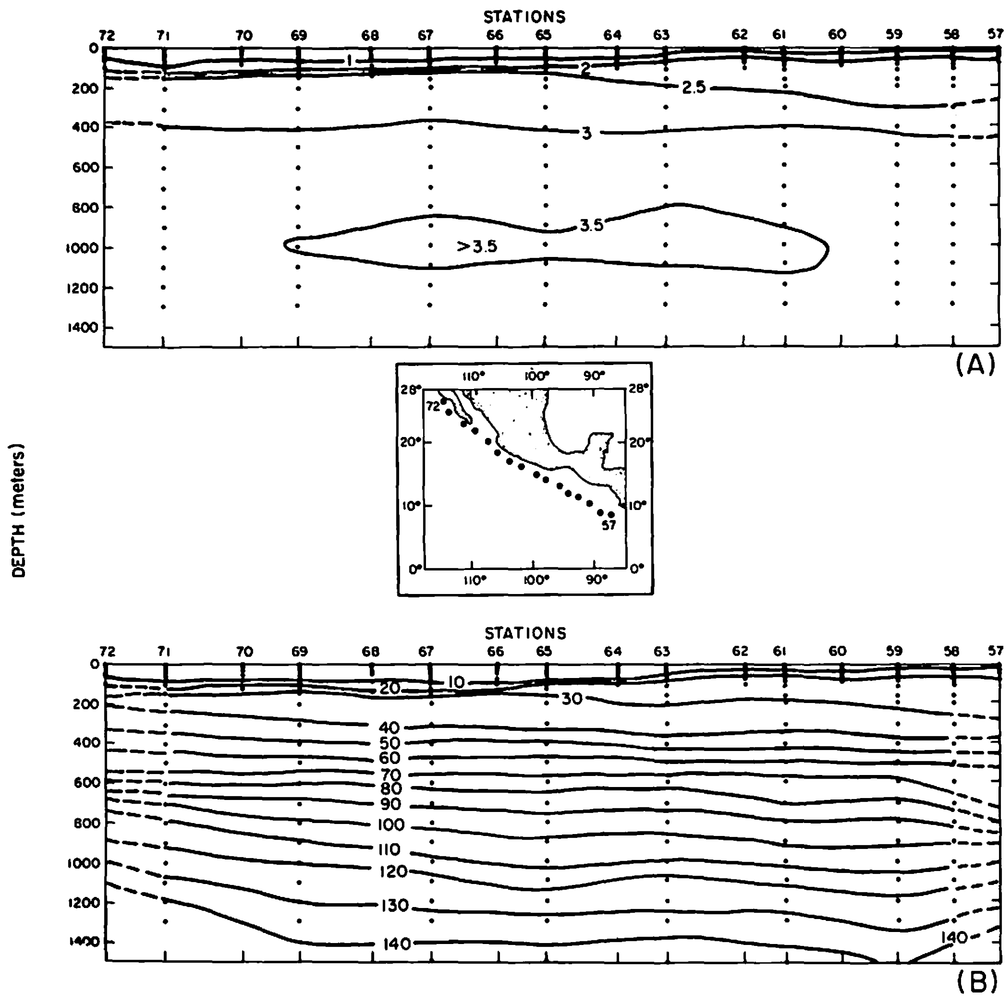


Figure 14. (A) Reactive phosphorus (μg-atoms/liter) and (B) reactive silicate (μg-atoms/liter) sections from data collected during *Thomas G. Thompson* cruise 1.

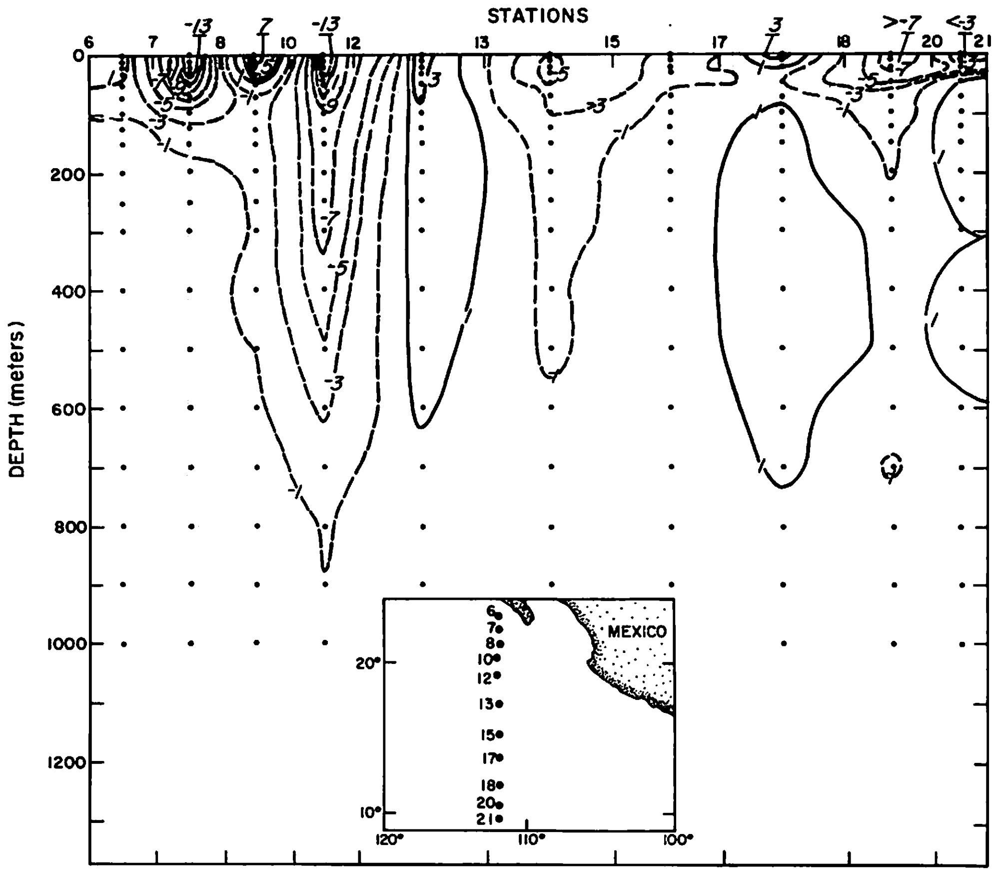


Figure 15. Relative baroclinic currents along 112°W (1000 decibar reference level). Contour lines are in cm/sec. Solid lines indicate eastward flow and dashed lines indicate westward flow.

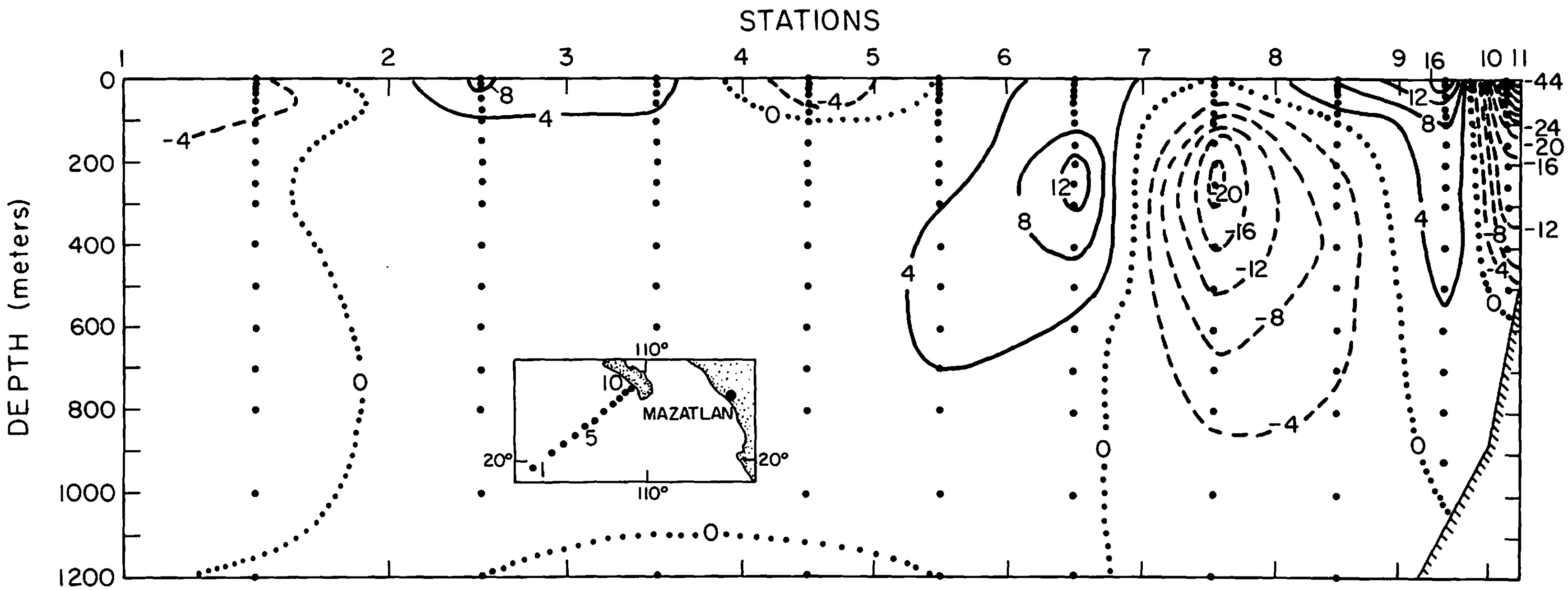


Figure 16. **Relative baroclinic currents adjacent to Baja California (1200 decibar reference level). ——— = Southeasterly flow. - - - = Northwesterly flow. Speeds are in cm/sec and the data are from *THOMAS G. THOMPSON* cruise 66.**

"ISENTROPIC" ANALYSIS CHARTS

Although these charts (Figs. 17-26) were used primarily to develop a method for estimating nitrate deficits and to assist in the determination of denitrification rates, they reveal many other interesting features. Table 3 lists the σ_T surfaces which were selected for the "isentropic" analysis and also gives some idea of the depth range of each surface. Nitrite values were contoured whenever there was a distinct manifestation of the deep nitrite maximum (the maximum associated with oxygen deficient waters). However, at two locations values in excess of 0.5 μg-atoms/liter and associated with low oxygen concentrations were found on 25.8 σ_T surface.

The equivalent nitrate charts represent a property defined as follows:

$$NO^-_{3_{EQUIV.}} = NO^-_3 + NO^-_2 + O_2 \times \frac{\Delta NO^-_3}{\Delta O_2} ,$$

where $NO^-_{3_{EQUIV.}}$ = equivalent nitrate,

NO^-_3 = the observed nitrate concentration,

NO^-_2 = the observed nitrite concentration,

O_2 = the observed dissolved oxygen concentration, and

$\frac{\Delta NO^-_3}{\Delta O_2}$ = the ratio of nitrate produced to oxygen consumed during aerobic respiration, 16/276 (by atoms) as suggested by Redfield, Ketchum, and Richards (1963).

In other words, equivalent nitrate is an estimate of the amount of nitrate which should be present in a water parcel when aerobic respiration has reduced the oxygen concentration to zero. Within a given water parcel, this quantity should be nearly constant until denitrification begins, provided that the ratio for the $\Delta NO^-_3/\Delta O_2$ term remains close to 16/276 (by atoms).[2]

---

[2] Because of this property, equivalent nitrate values, like preformed nutrient values, can often be used to assess data quality for aerobic subsurface water masses.

Table 3

Surfaces chosen for "isentropic" analysis

σ_τ	Thermosteric Anomaly	Approximate Depth Range in the Study Region (Meters)
25.5	249.1	40 - 120
25.8	220.6	50 - 140
26.1	192.1	50 - 200
26.4	163.6	100 - 300
26.6	144.6	175 - 375
26.8	125.6	300 - 475
27.0	106.7	450 - 560
27.3	78.2	770 - 880
27.5	59.3	1100 - 1350

The consensus of most recent investigators is that free nitrogen is the main end product of nitrate during marine denitrification (Codispoti, 1973). Since free nitrogen appears to be essentially conservative below the surface layers, areas of low equivalent nitrate values do not necessarily indicate active denitrification sites. For example, oxygen concentrations throughout the 25.5, 25.8 and 27.5 σ_T surfaces were generally too high to expect denitrification. Nevertheless, equivalent nitrate values on these surfaces display a minimum in the vicinity of the oxygen deficient region indicating the possibility of mixing with waters from denitrification zones.

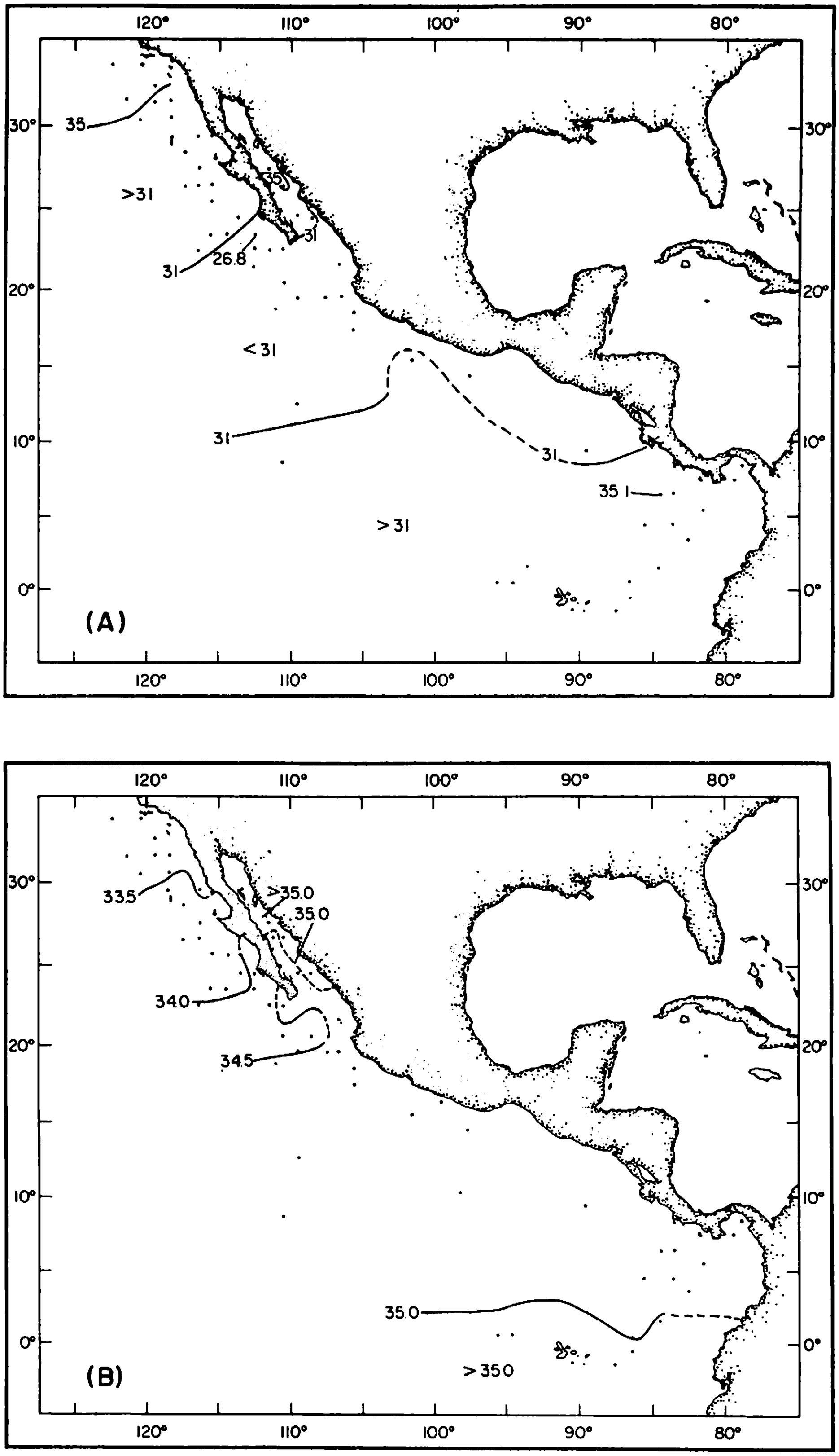


Figure 17. Equivalent nitrate in µg-atoms/liter (A) and salinity in °/₀₀ (B) on the 25.5 σ_T surface. Expected nitrate for this surface is 32.8 µg-atoms/liter.

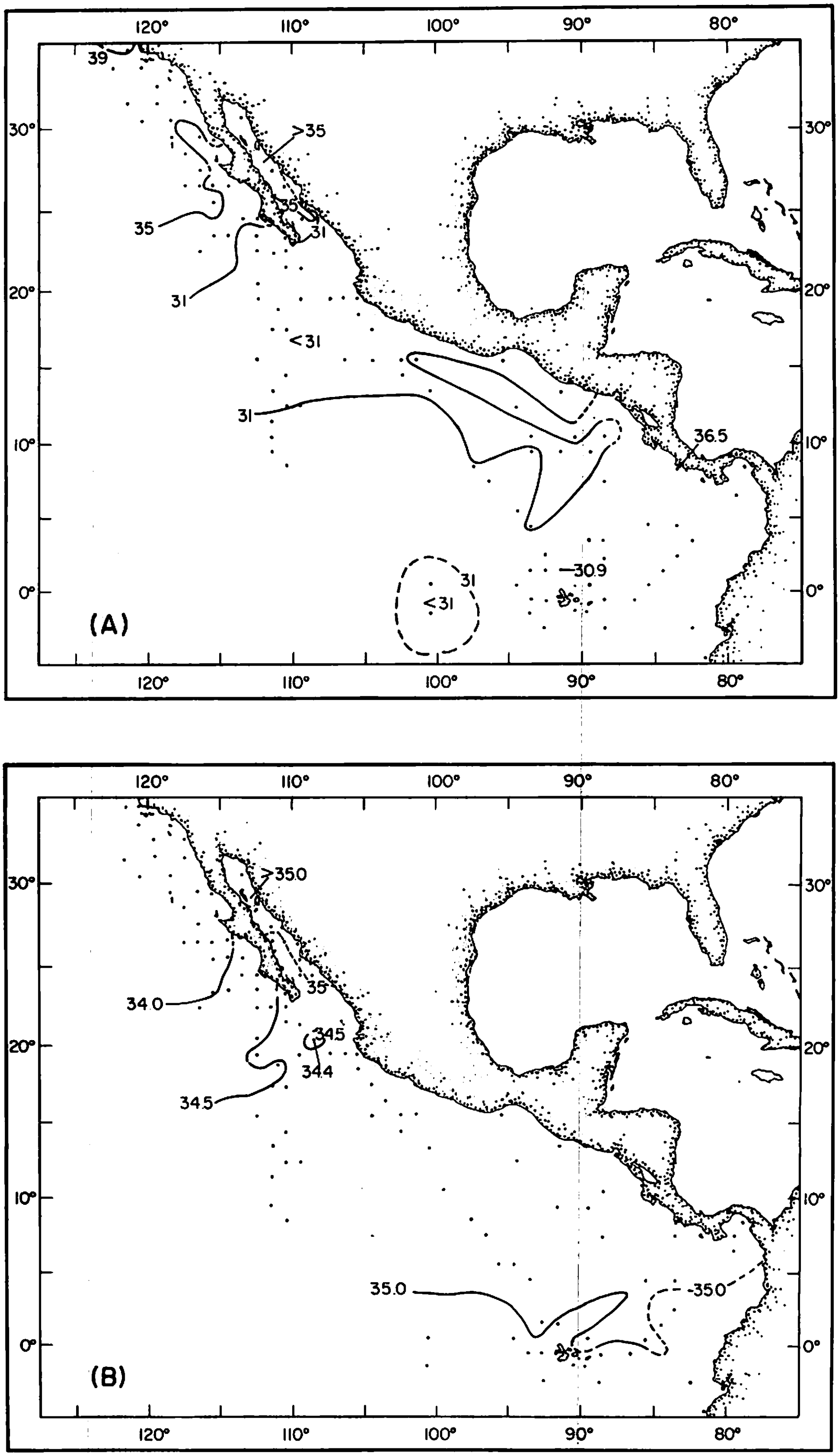


Figure 18. Equivalent nitrate in μg-atoms/liter (A) and salinity in °/oo (B) on the 25.8 σ_T surface. Expected nitrate for this surface is 33.6 μg-atoms/liter.

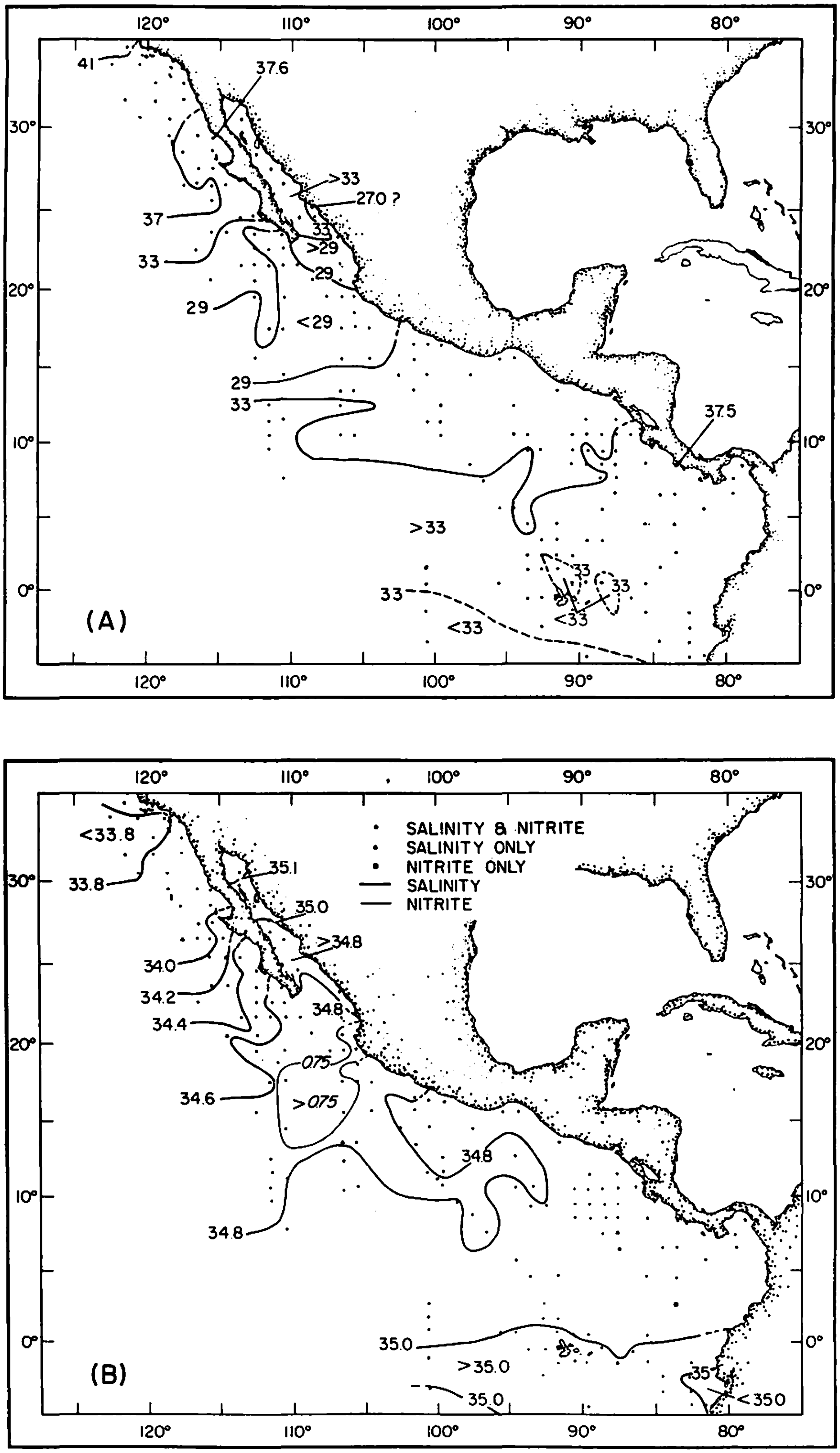


Figure 19. Equivalent nitrate in μg-atoms/liter (A), and salinity in °/₀₀ and nitrite in μg-atoms/liter (B) on the 26.1 σ_T surface. Expected nitrate for this surface is 34.6 μg-atoms/liter.

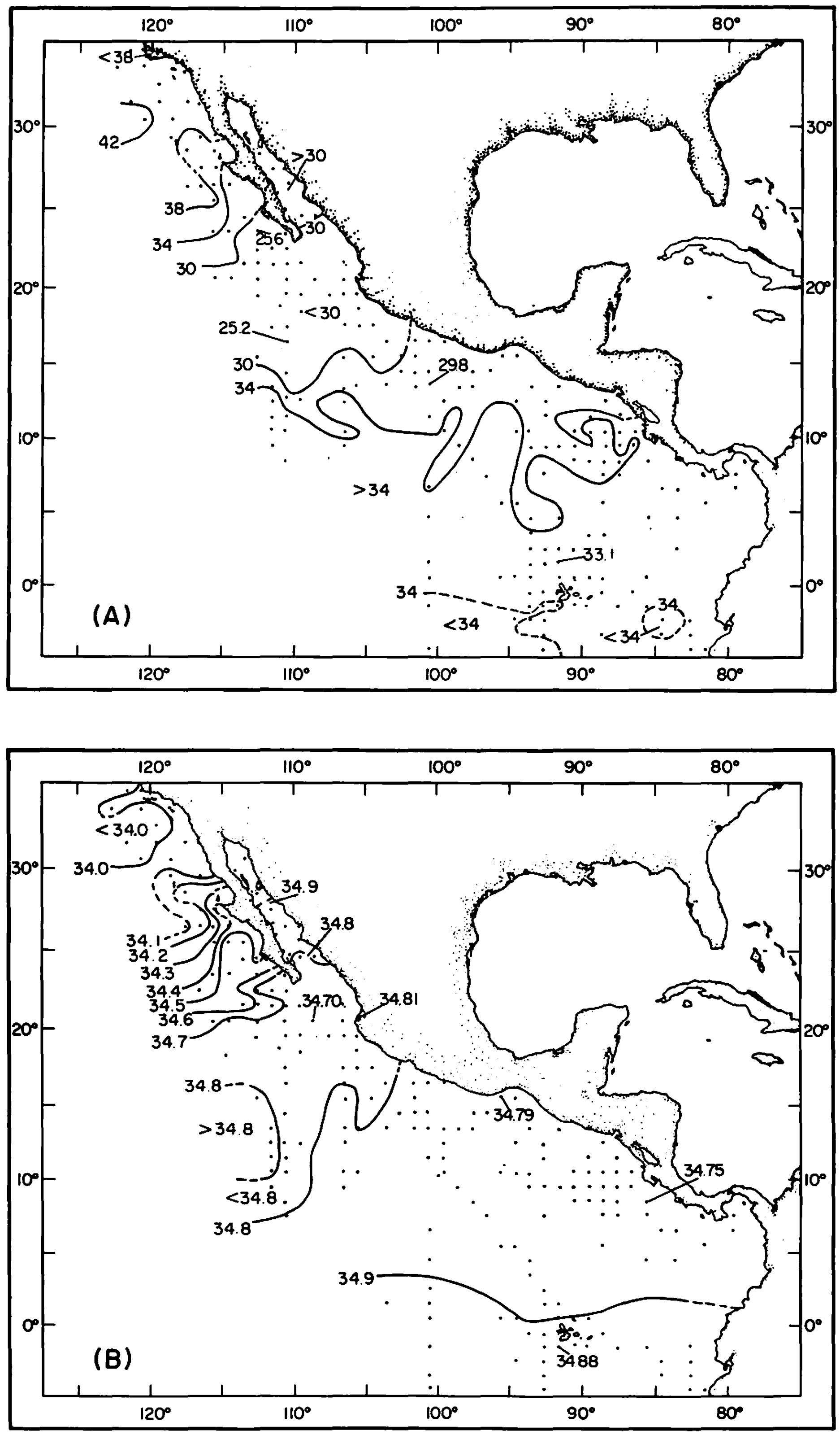


Figure 20. Equivalent nitrate in μg-atoms/liter (A) and salinity in °/₀₀ (B) on the 26.4 σ_T surface. Expected nitrate on this surface is 35.4 μg-atoms/liter.

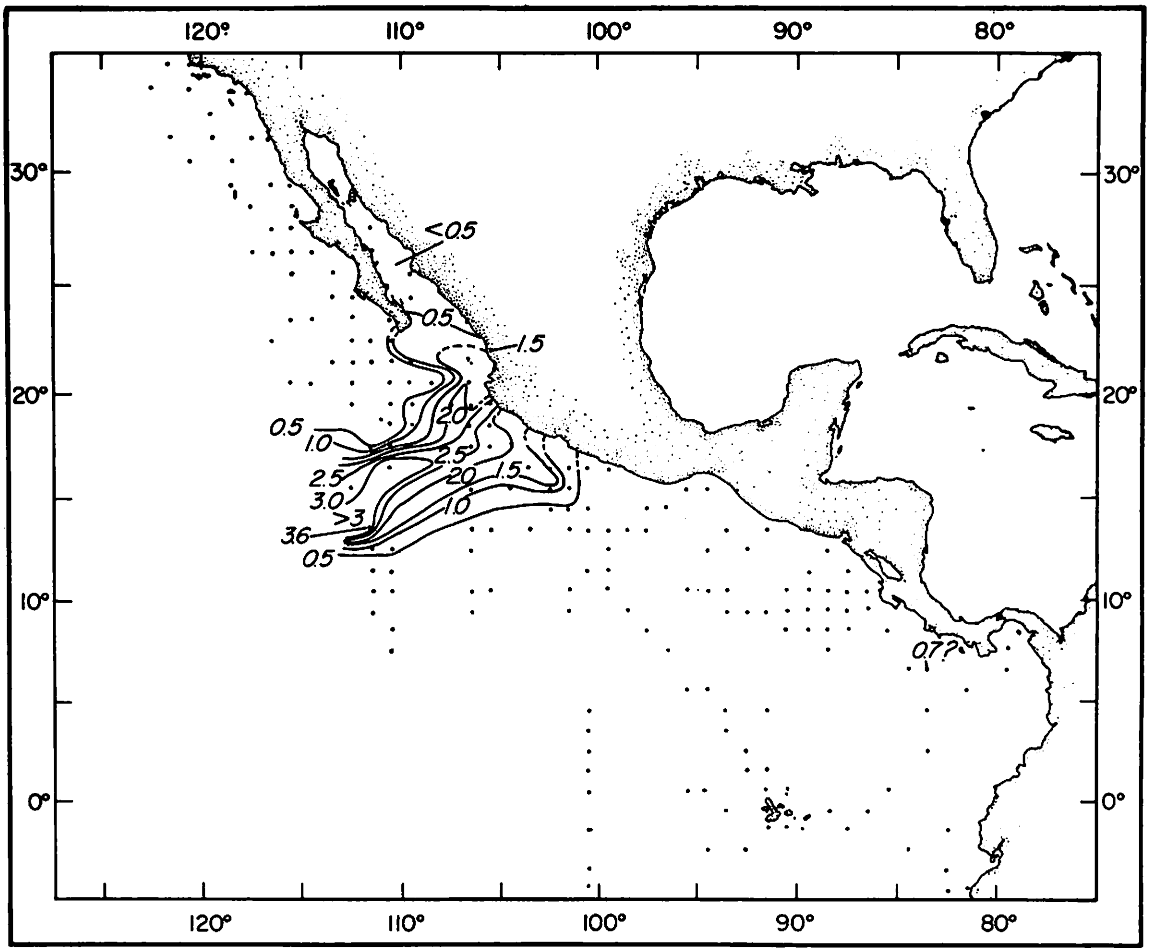
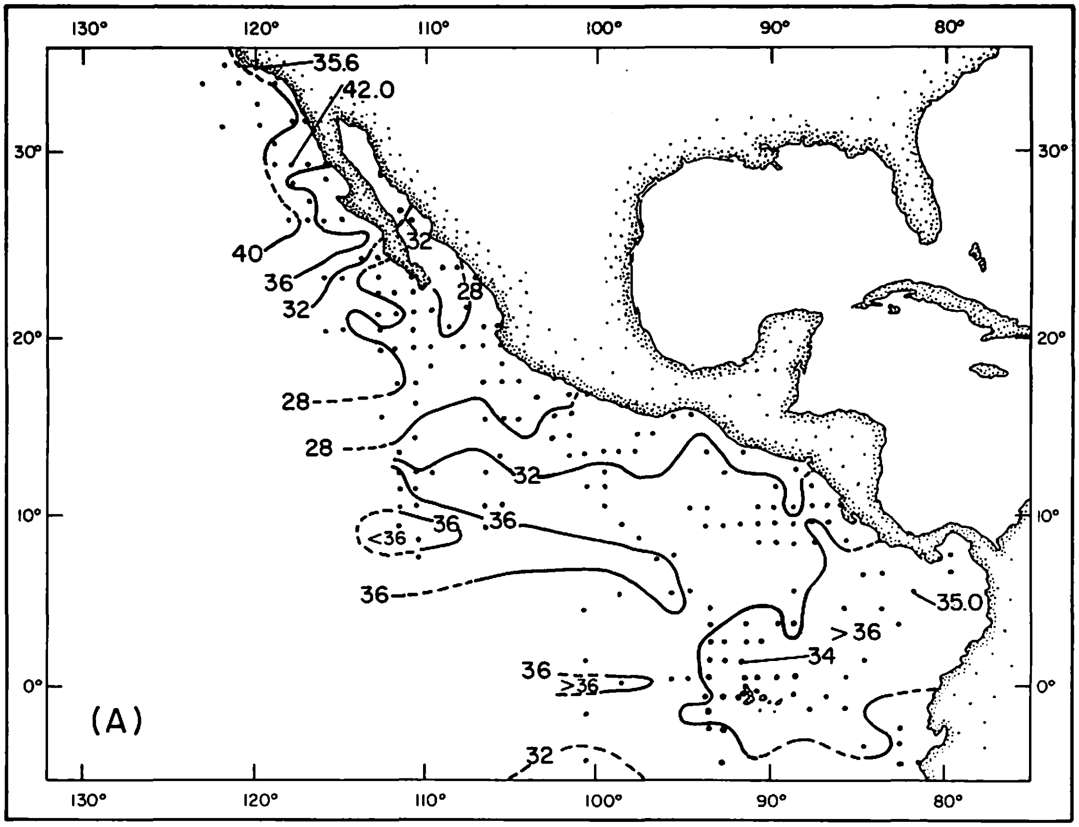


Figure 21. Nitrite (μg-atoms/liter) on the 26.4 σ_τ surface.



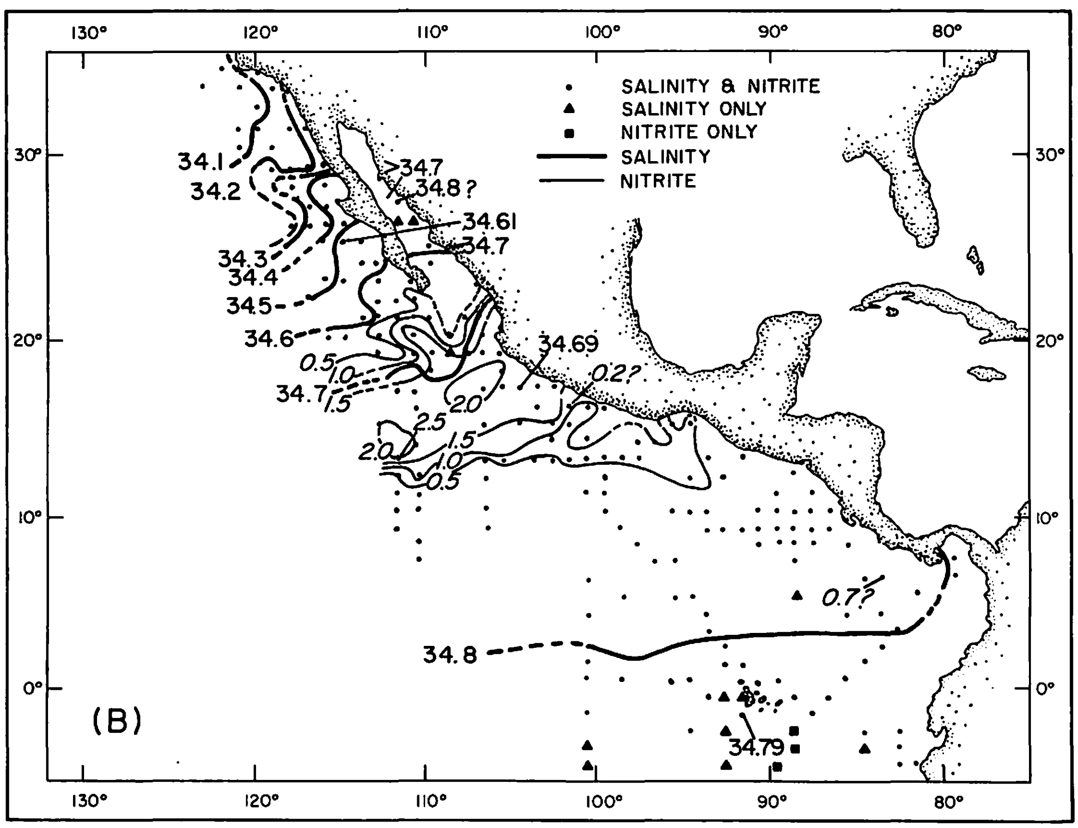


Figure 22. Equivalent nitrate in μg-atoms/liter (A), and salinity in °/₀₀ and nitrite in μg-atoms/liter (B) on the 26.6 σ_T surface. Expected nitrate on this surface is 36.4 μg-atoms/liter.

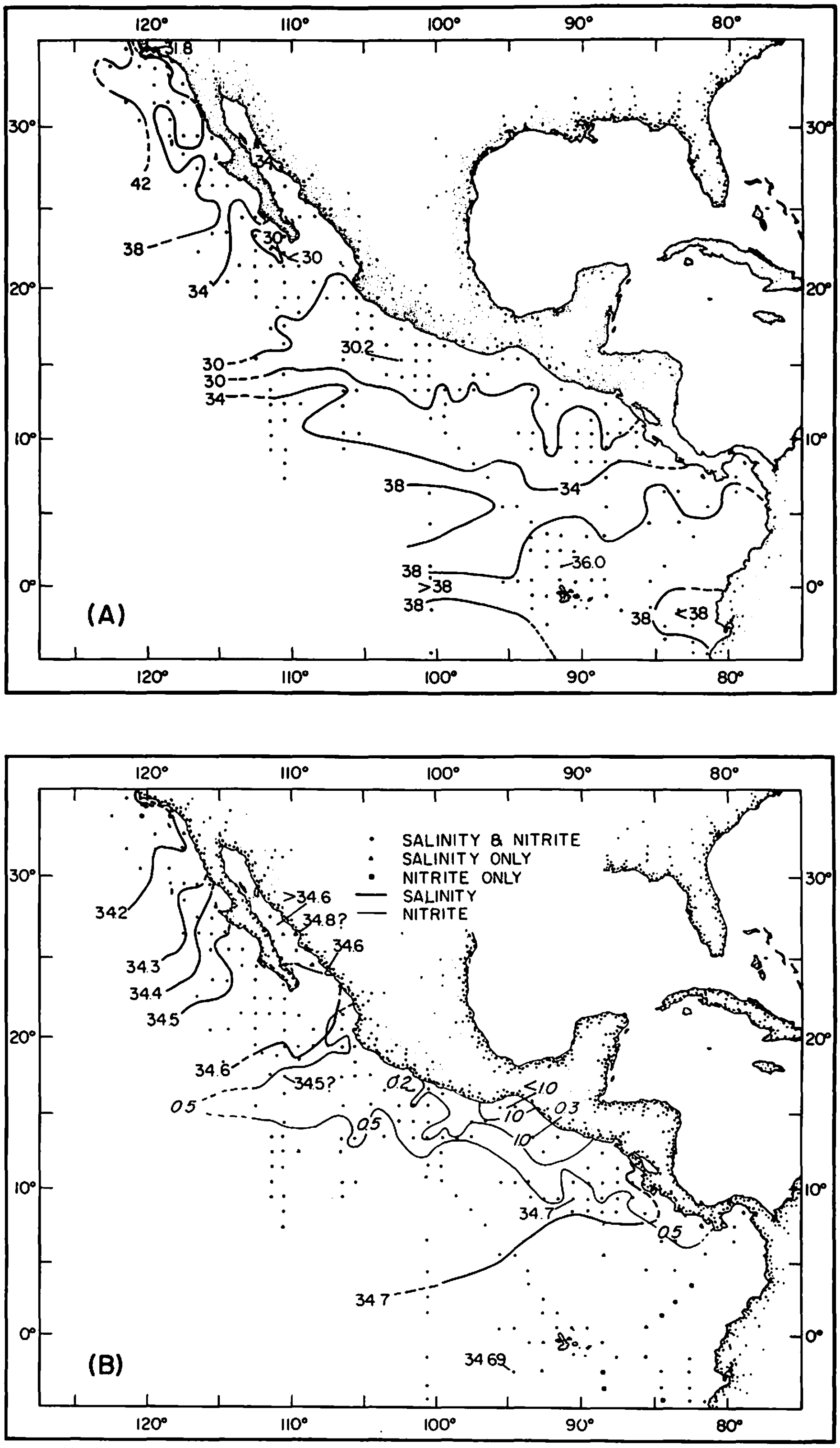


Figure 23. Equivalent nitrate in μg-atoms/liter (A), and salinity in °/oo and nitrite in μg-atoms/liter (B) on the 26.8 σ_T surface. Expected nitrate on this surface is 38.7 μg-atoms/liter.

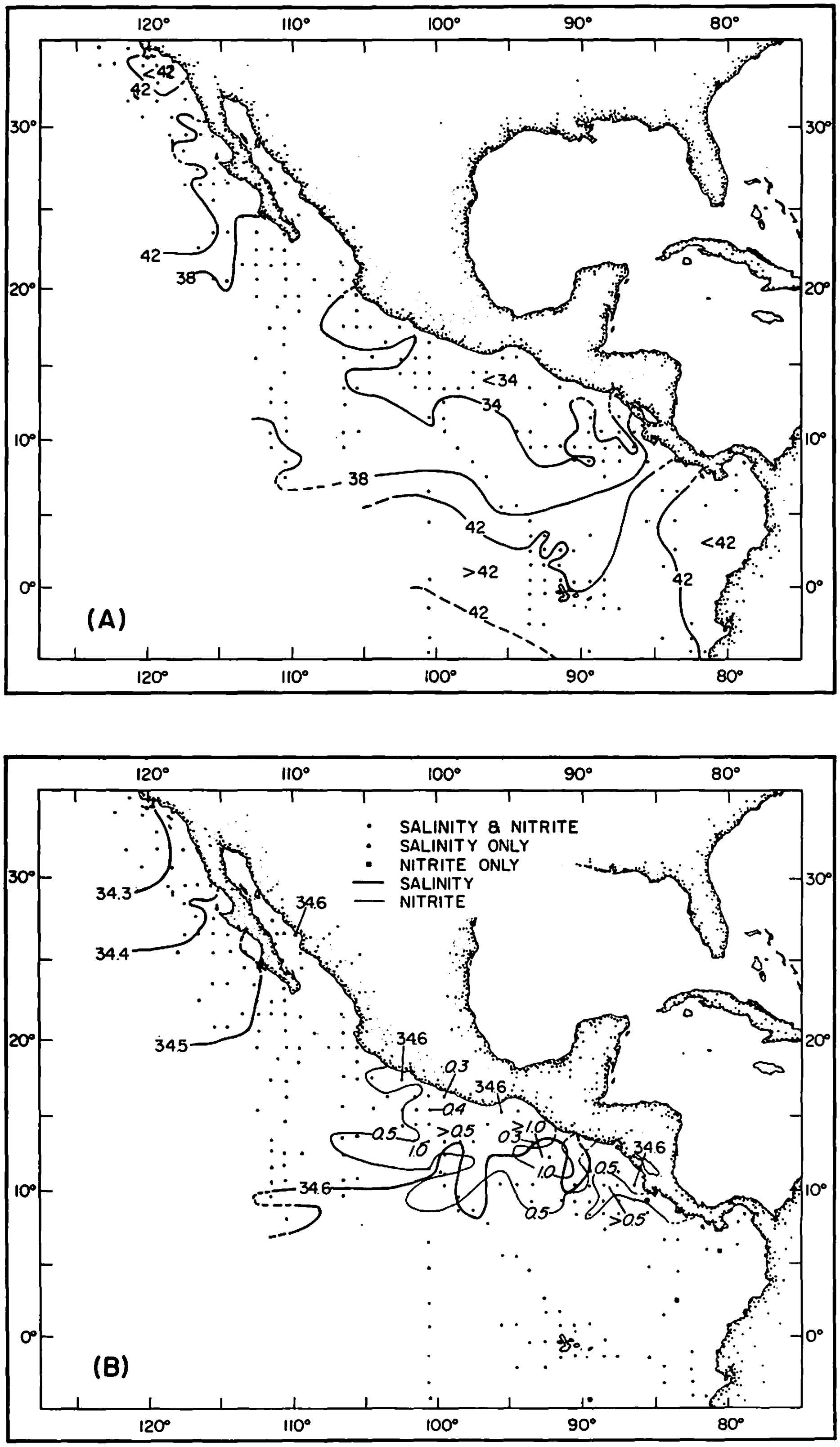


Figure 24. Equivalent nitrate in µg-atoms/liter (A), and salinity in °/₀₀ and nitrite in µg-atoms/liter (B) on the 27.0 σ_T surface. Expected nitrate for this surface is 42.5 µg-atoms/liter.

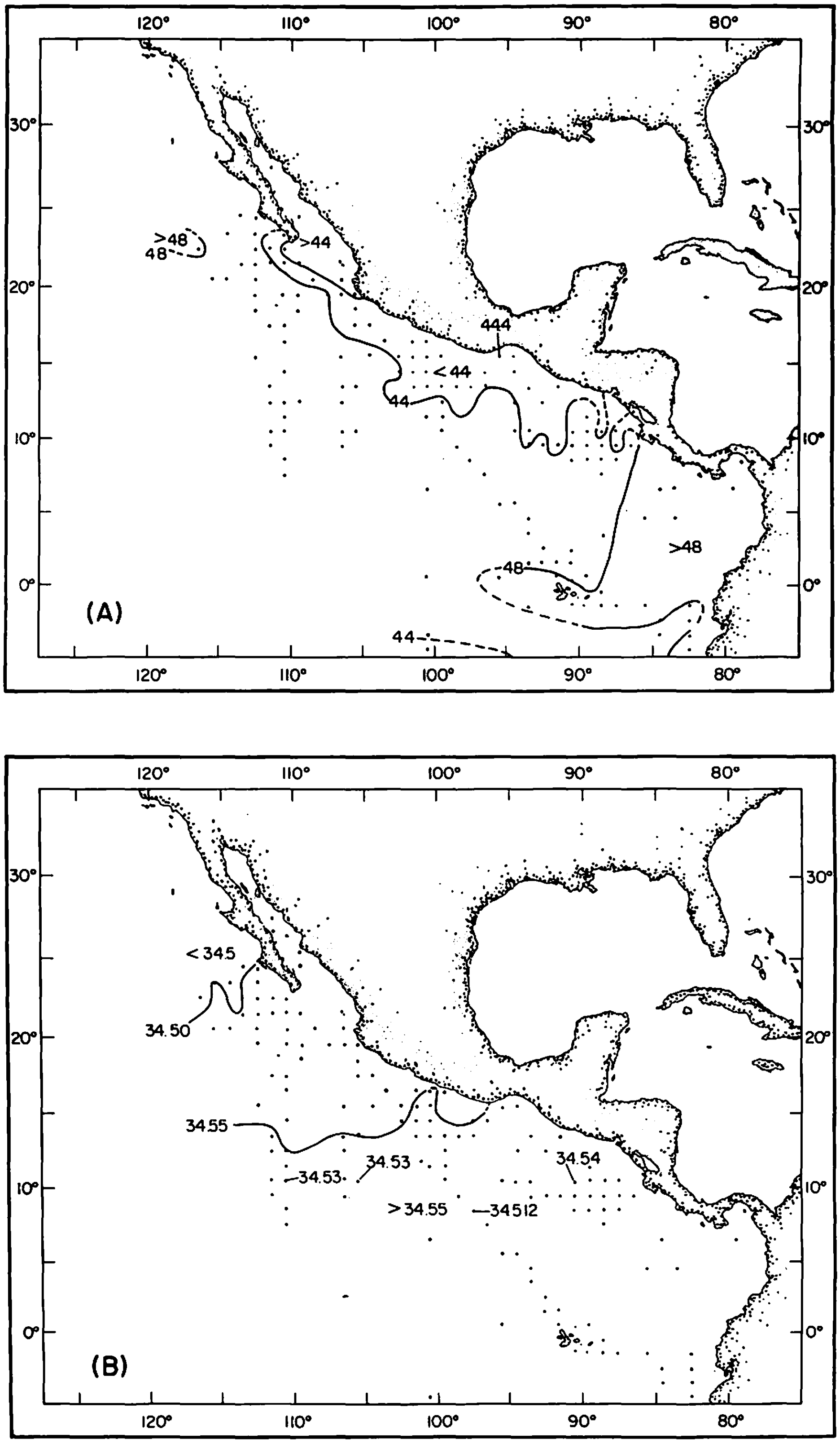


Figure 25. Equivalent nitrate in μg-atoms/liter (A) and salinity in °/₀₀ (B) on the 27.3 σ_T surface. Expected nitrate on this surface is 48.6 μg-atoms/liter.

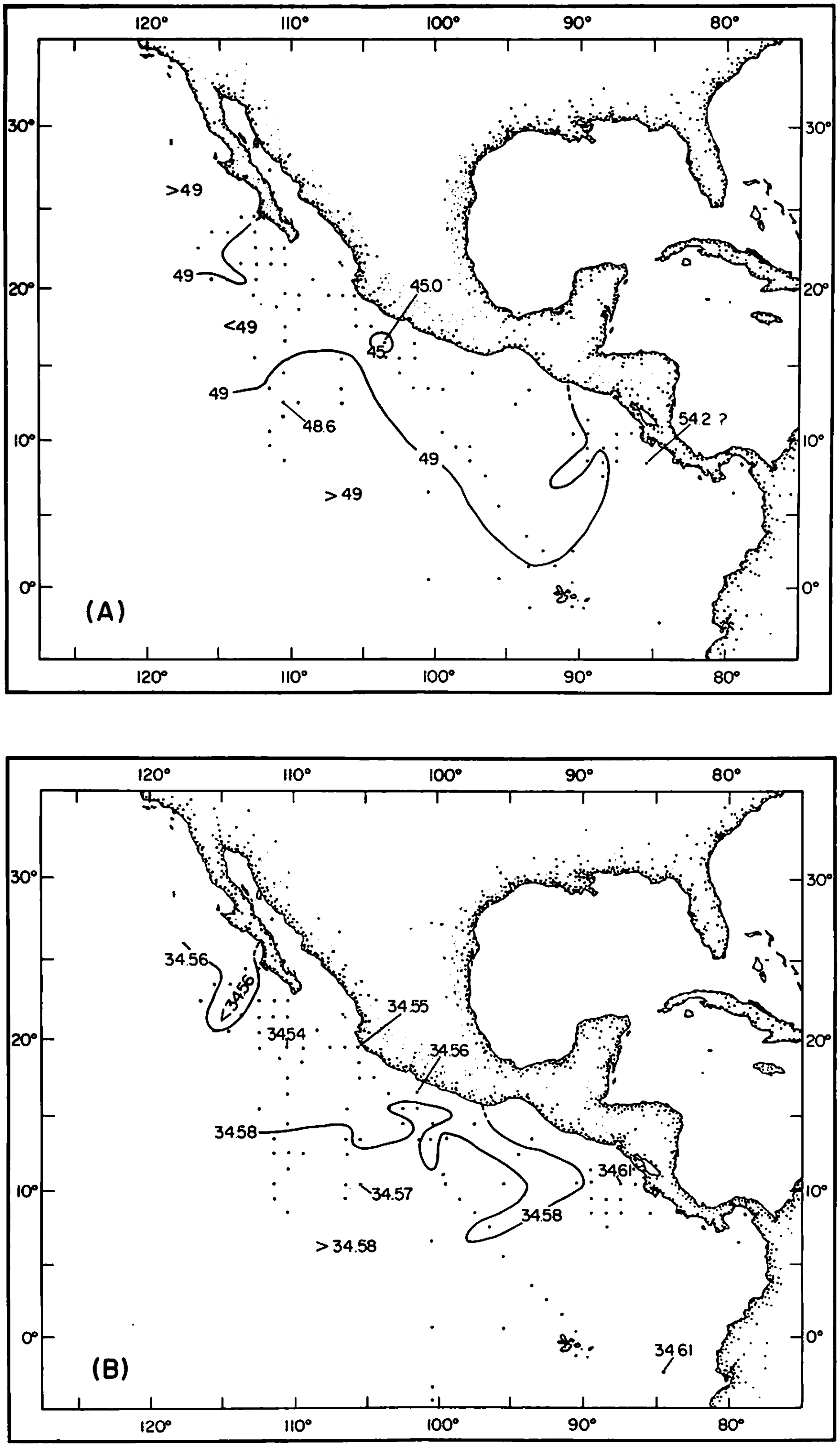


Figure 26. Equivalent nitrate in µg-atoms/liter (A) and salinity in $^{\circ}/_{\circ\circ}$ (B) on the 27.5 σ_T surface. Expected nitrate on this surface is 50.7 µg-atoms/liter.

NITRATE DEFICITS

By averaging equivalent nitrate values in the source waters for the oxygen deficient strata a term called expected nitrate ($NO^-_{3_{EXP}}$) was determined. Nitrate deficits ($NO_{3_{ANOM\ II}}$),[3] as shown above (Fig. 11), are then calculated as follows:

$$NO^-_{3_{ANOM}} = NO^-_{3_{EXP}} - NO^-_{3_{EQUIV}}, \text{ and} \tag{2}$$

$$NO^-_{3_{ANOM\ II}} = NO^-_{3_{ANOM}} \times 1.094. \tag{3}$$

A more detailed discussion of the development, the reliability and the rational behind the method for computing nitrate deficits is given in Codispoti (1973). Here it is sufficient to note that the above equations used in combination with the expected nitrate values given in the figure captions (Figs. 17-26) will yield useful nitrate deficit estimates for the study region. However, the reader should be aware that the method for calculating nitrate deficits may be slightly modified when published in its final form (Codispoti and Richards, in prep.).

Figures 27 and 28 give some idea of the agreement between the above method and the method of Cline and Richards (1972). These comparisons were made using the same data employed for developing Cline and Richards' method. One disadvantage of their method is that it requires reactive phosphorus data and is sensitive to errors and systematic differences in these data.

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[3] As mentioned on page 15, nitrate deficits provide a measure of the amount of nitrate converted to free nitrogen during denitrification.

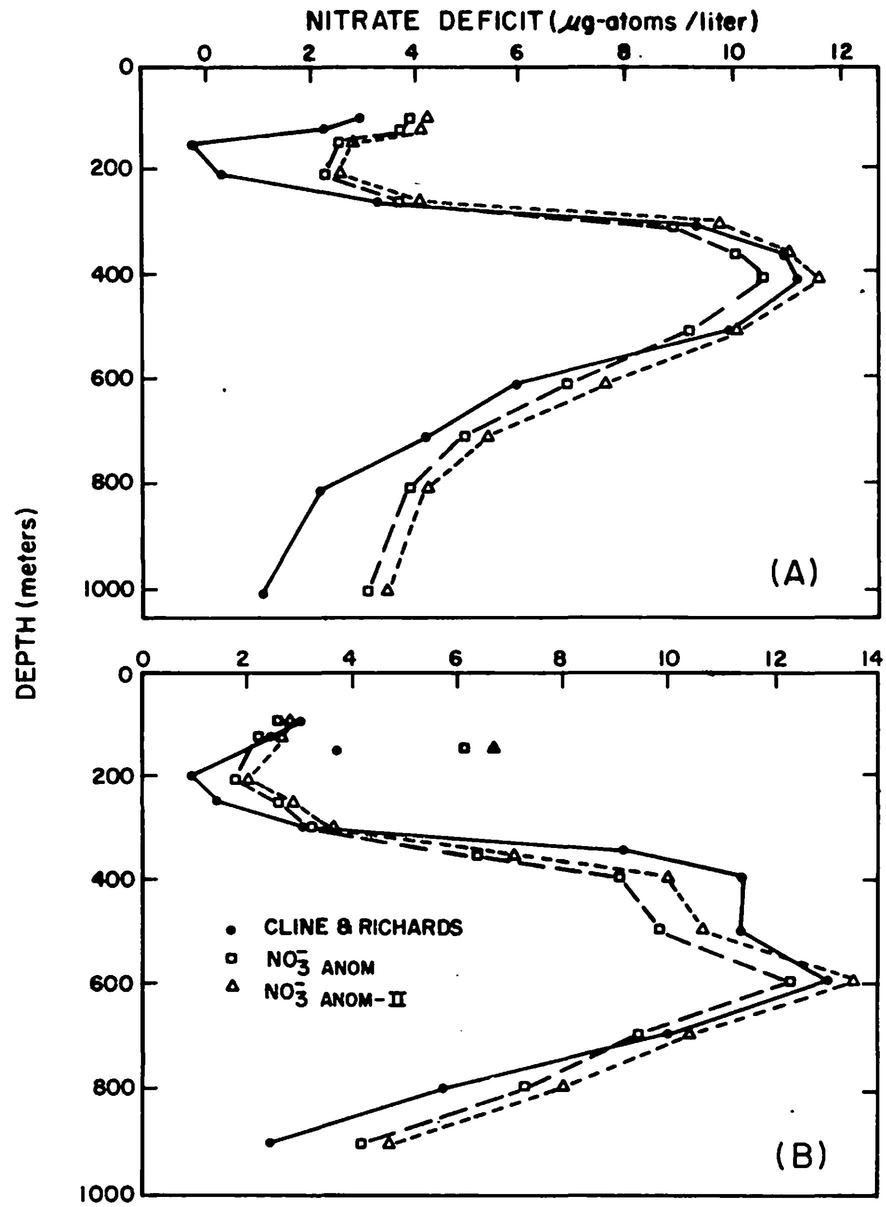
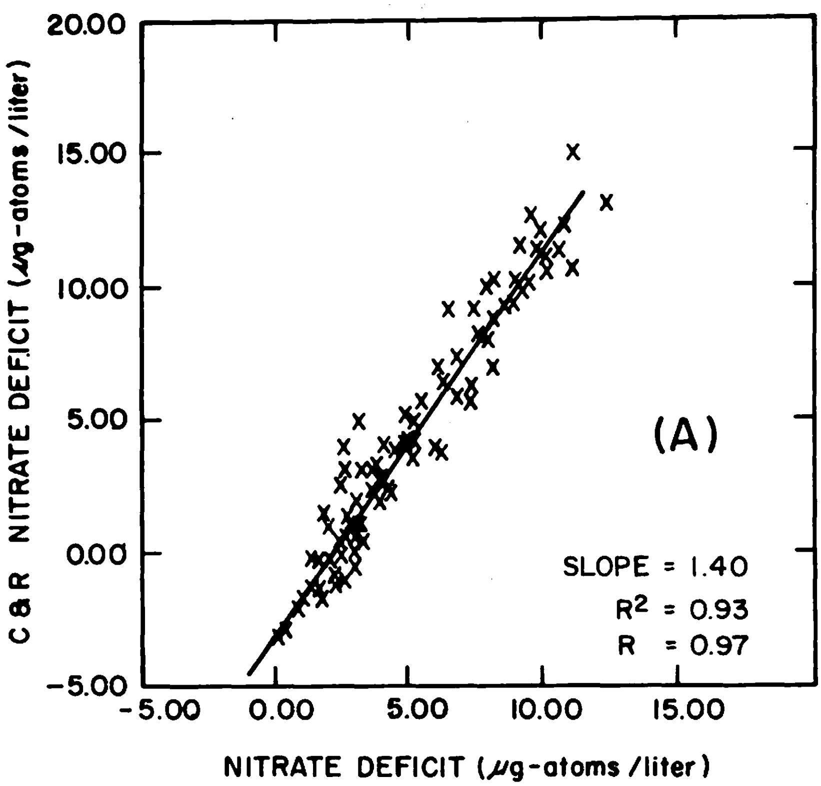


Figure 27. NO_3^- ANOM, NO_3^- ANOM II and Cline and Richards' (1972) nitrate deficits versus depth at two selected stations.



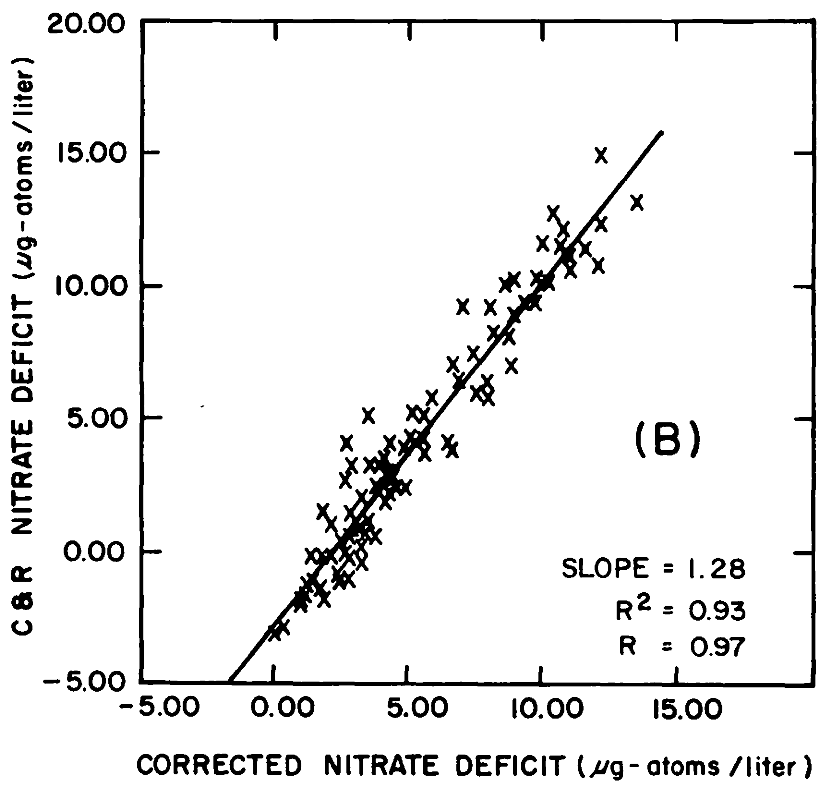


Figure 28. $NO_{3\ ANOM}^{-}$ versus Cline and Richards' (1972) nitrate deficits (A) and $NO_{3\ ANOM\ II}^{-}$ versus Cline and Richards' nitrate deficits (B).

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report No. 289	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SOME CHEMICAL AND PHYSICAL PROPERTIES OF THE EASTERN TROPICAL NORTH PACIFIC WITH EMPHASIS ON THE OXYGEN MINIMUM LAYER		5. TYPE OF REPORT & PERIOD COVERED INTERIM 1959-1972 6. PERFORMING ORG. REPORT NUMBER M73-64
7. AUTHOR(s) Louis A. Codispoti		8. CONTRACT OR GRANT NUMBER(s) Contract Nonr-477(37) and N-00014-67-A-0103-0014
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Washington Department of Oceanography Seattle, Washington 98195		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project NR 083 012
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research La Jolla, California		12. REPORT DATE October 1973 13. NUMBER OF PAGES 38
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release: distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Oceanographic data
Physical oceanographic data
Chemical oceanographic data
Oxygen minimum layer
Thomas G. Thompson cruises
Other agencies cruises
Eastern tropical North Pacific

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is basically an atlas presenting diagrams and charts of temperature, salinity, oxygen, nutrient, and relative baroclinic current data for the eastern tropical North Pacific. Special emphasis is on the oxygen deficient layer in this region and a number of the charts constitute an isentropic study of this layer. Two of the included properties, nitrate deficits and equivalent nitrate, are particularly appropriate for investigations dealing with denitrification in these waters, and the methods for calculating them are described.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. (Continued)

A temperature-salinity, temperature-oxygen diagram presents evidence for significant respiration at depths of about 800 m.

FOR UNCLASSIFIED TECHNICAL REPORTS, REPRINTS, & FINAL REPORTS
PUBLISHED BY OCEANOGRAPHIC CONTRACTORS
OF THE OCEAN SCIENCE & TECHNOLOGY DIVISION
OF THE OFFICE OF NAVAL RESEARCH
(REVISED SEPTEMBER, 1973)

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