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A cruise of the R/V Yaquina off Oregon during June and July of 1968 provided data for a study of the relationships of hydrographic and chemical parameters to estimates of biological activity. The emphasis was on carbon and nitrogen reservoirs. Phytoplankton pigments, nitrogen and C/N ratio were used along with AOU and the nitrate content of the water to estimate the distribution of phytoplankton production. Sigma-t, AOU, and nitrate were used to define the hydrographic and chemical conditions.

Upwelling was the major source of nitrate for the surface waters, and, consequently, phytoplankton production was most intense where upwelling was active. The Columbia River plume appeared to support a sizeable amount of phytoplankton production just south of the river mouth. Particulate nitrogen increased and particulate C/N ratio decreased as the water became more biologically

productive. Chlorophyll, particulate nitrogen, and C/N ratio showed the effects of upwelling and the Columbia River plume on biological production. A subsurface negative AOU core was clearly defined in areal extent and intensity. Its occurrence was explained by inshore phytoplankton production, oxygen exchange with the atmosphere, and possible in situ phytoplankton production.

Carbon and Nitrogen Reservoirs
off the Oregon Coast

by

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CARBON AND NITROGEN RESERVOIRS OFF THE OREGON COAST

INTRODUCTION

The Oregon coastal environment is unique during the summer. Northerly summer winds cause the surface currents to be predominantly southerly from April to October, and a moderate offshore component is present in June and July (Maugham, 1963). Copepod indicator species indicate the same southerly movement in summer (Cross and Small, 1967). The result of offshore movement of water is upwelling, which is a movement of water up towards the surface to replace surface water moved away by the winds. Upwelling can be identified by the sloping of the isopycnals up towards the coast. The 25.5 and 26.0 σ_t isolines describe the permanent pycnocline or upwelling front (Collins, 1964). Water movement under these upwelling conditions is shoreward below the permanent pycnocline and offshore above the permanent pycnocline (Smith, Pattulo, and Lane, 1966). Much of the upwelled water sinks beneath the seasonal pycnocline and moves offshore (Mooers, 1970).

In summer the Columbia River effluent or plume spreads south from the mouth of the river and forms a surface layer of low density water (Stefannson and Richards, 1963; Anderson, 1964; Park, 1966).

In the summer the surface waters are mostly depleted of nutrients except close to the coast where upwelling and the Columbia

River replenish the surface waters with nutrients (Stefannson and Richards, 1963). A subsurface oxygen maximum found during the summer months has been explained by loss of oxygen by diffusion (Pytkowicz, 1964) and by photosynthetic production (Stefannson and Richards, 1964; Anderson, 1969). Upwelling has been shown to be associated with the major areas of primary production off Oregon. Because of its supplying of nutrients to surface water, upwelling stimulates primary production (Stefannson and Richards, 1964). The Columbia River effluent also has been associated with primary production off Oregon (Anderson, 1964). Laurs (1967) suggested that low concentrations of nutrients limited phytoplankton growth off Oregon in summer except in the areas of upwelling next to the coast where abrupt changes in phosphate-phosphorus were related to changes in standing stocks of phytoplankton, herbivores, and primary carnivores.

Nitrogen is an element essential to phytoplankton. I will try to relate the changes in the carbon and nitrogen reservoirs to changes in phytoplankton pigments and nitrogen. A study of the changes of nitrogen from nutrient form to phytoplankton to zooplankton and further can tell us something of the processes and rates important in biological production. Upwelling has already been shown to stimulate production by bringing in nutrients. Nitrogen, specifically, will be studied here to see how upwelling will affect its distribution both in

nutrient form and in the biologically utilized forms. The distribution of the forms of nitrogen and the relative utilization of carbon and nitrogen can possibly be used to augment the phytoplankton pigment data and the changes in nitrate and oxygen content in the water in determining the extent and intensity of primary production.

The form of nitrogen we have examined in the water is nitrate, usually the most abundant dissolved inorganic nitrogen fraction available to phytoplankton. We also have examined nitrogen in particles on filter surfaces, which might serve as an index to the nitrogen which has been incorporated into living material. Chlorophyll a will be used as an index of the phytoplankton present in the particulate matter, and this, with particulate nitrogen and a carbon to nitrogen ratio, will be related to the nitrate reservoir. The Apparent Oxygen Utilization (AOU) will be used along with other measurements to estimate the extent and intensity of primary production.

METHODS

The data for this study were gathered during Cruise 6806-C of the R/V Yaquina off the Oregon coast from 24 June, 1968, to 3 July, 1968. Eighty-seven sampling stations were occupied in the waters north of Coos Bay ($43^{\circ}18'$ N. Lat. ; $124^{\circ}24'$ W. Long.) in order to cover the Columbia River plume, coastal waters in upwelling and non-upwelling areas, and offshore waters (Figure 1). The line of stations running to 40 miles off Depoe Bay was sampled three times during the cruise (on 24 June, 28 June, and 2 July).

At each station a hydrographic cast was made to furnish data on salinity, temperature, dissolved oxygen, and nitrate content of the water. The depths chosen for Nansen bottle placement were usually surface, 3, 6, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 125, 150, 200, 300, and 400 meters. If a temperature inversion was found by a preliminary bathythermograph cast, Nansen bottles were placed at five meter intervals around the temperature inversion. At each depth temperatures were read off standard reversing thermometers. The exact depth of each bottle was later computed from the temperature data. Salinity was analyzed on shipboard with a conductance salinometer. Nitrate concentrations were analyzed on shipboard with a Technicon Autoanalyzer. Oxygen samples were analyzed on shipboard by the Winkler titration method. The Apparent Oxygen

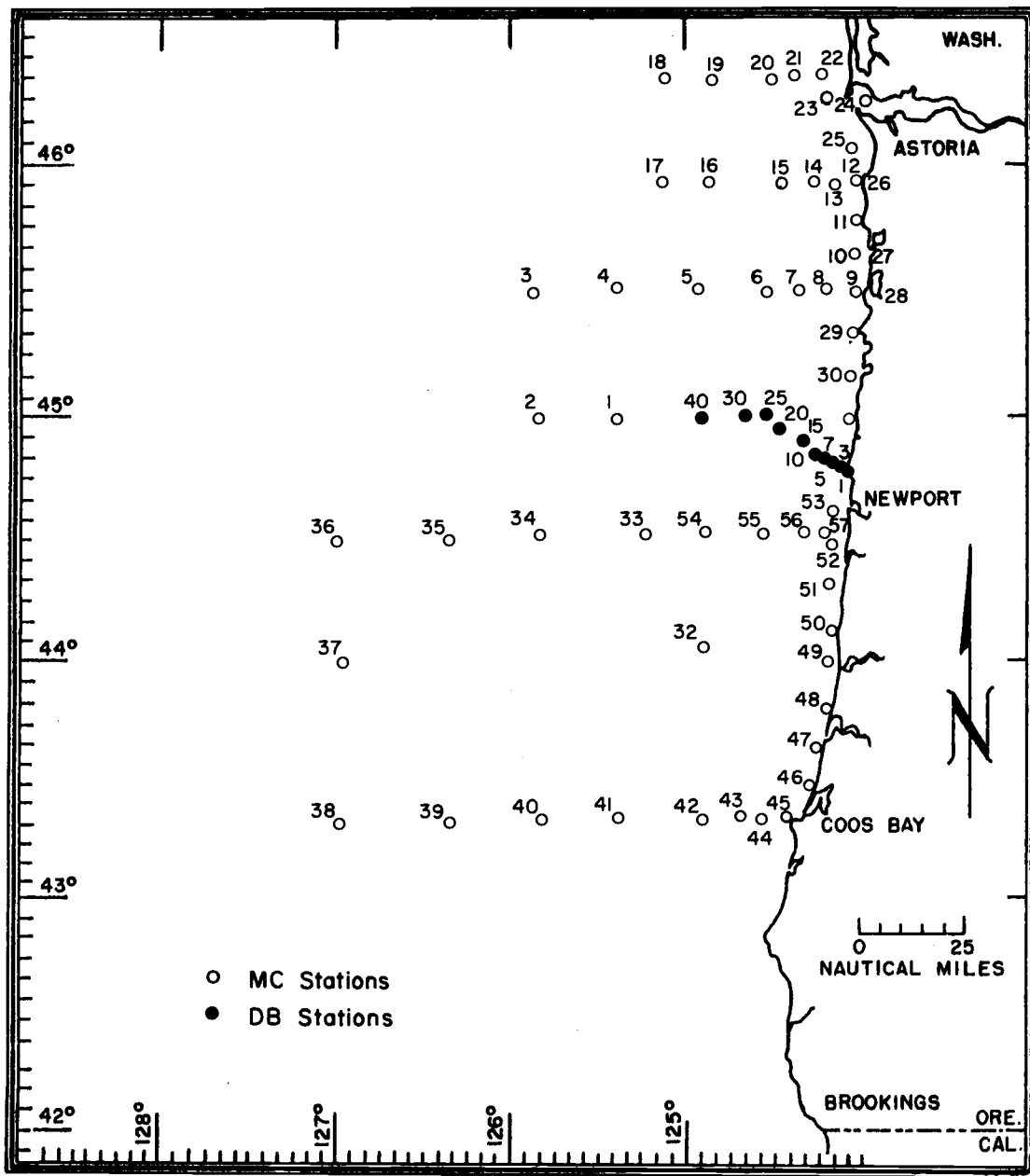


Figure 1. Locations of stations sampled during Cruise 6806-C.

Utilization (AOU) was taken as the difference between the oxygen content of the sample and the oxygen content of the sample which would be present if the sample were saturated with oxygen at that particular temperature and salinity (Redfield, 1942).

In addition to the Nansen bottle cast at each station, a Van Dorn bottle cast was made with bottles at depths of 10, 15, 25, and 50 meters. A surface sample of water was taken with a plastic bucket. A two liter subsample from each Van Dorn or bucket sample was filtered through a 0.8 μ pore size Millipore[®] filter for subsequent phytoplankton pigment analysis. Each filter was placed in a desiccator in the ship's freezer until termination of the cruise. Pigment concentration was determined in the shore laboratory by the method of Strickland and Parsons (1965).

A second subsample from each Van Dorn or bucket sample was taken for particulate carbon and nitrogen analysis. A variable amount of water was filtered through a Whatman GF/A glass fiber filter cut to fit in a Swinney adaptor mounted on a 150 ml syringe. Water was filtered until there was a sufficient amount on the filter for analysis; thus, the amount of water filtered varied with the abundance of particulate matter in the water. After filtration the filter was placed in a labeled fold of aluminum foil and placed in a desiccator in the ship's freezer. In the shore laboratory each glass fiber filter was dried in a 60°C oven for 24 hours. The material on the filter was analyzed

in a F & M Carbon-Hydrogen-Nitrogen Analyzer. This instrument combusts the sample at 1000°C in an oxygen atmosphere, converting the carbon, hydrogen, and nitrogen in the sample into carbon dioxide, water vapor, and nitrogen dioxide, respectively. The resultant gases are passed through cupric oxide absorption columns, and relative concentrations of each element are resolved as peaks on a recorder sheet. The glass fiber filter does not burn, although periodic blanks are run as a check. Absolute concentrations of carbon, hydrogen, and nitrogen can be obtained by comparing sample peak heights to an acetanilide calibration curve.

RESULTS

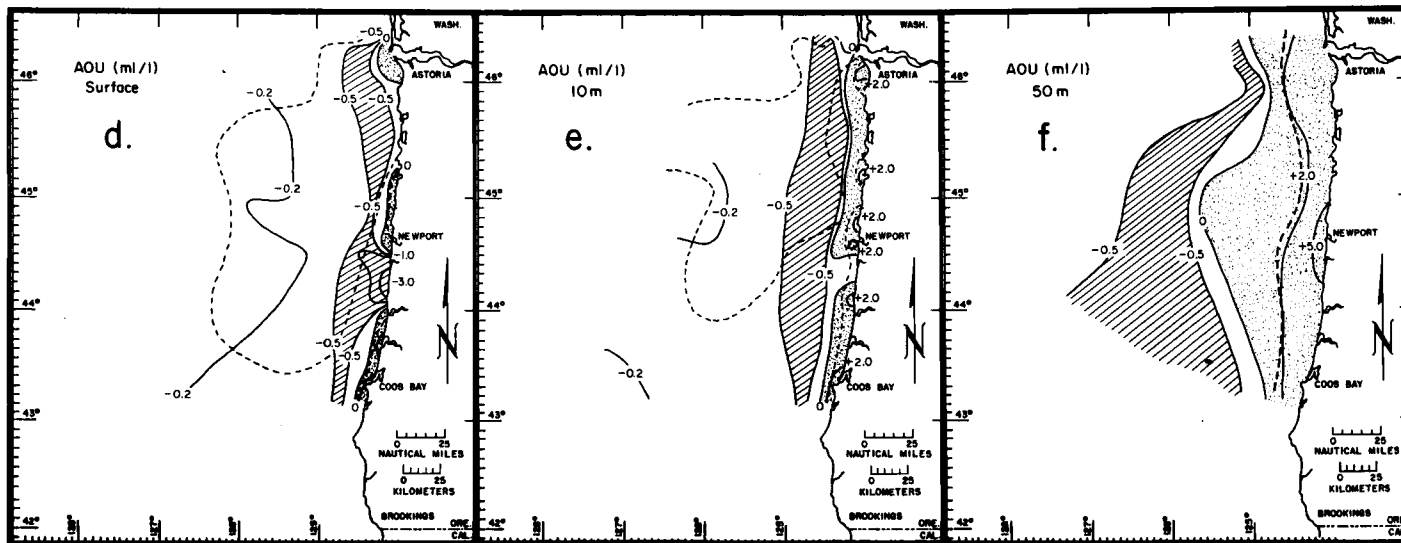
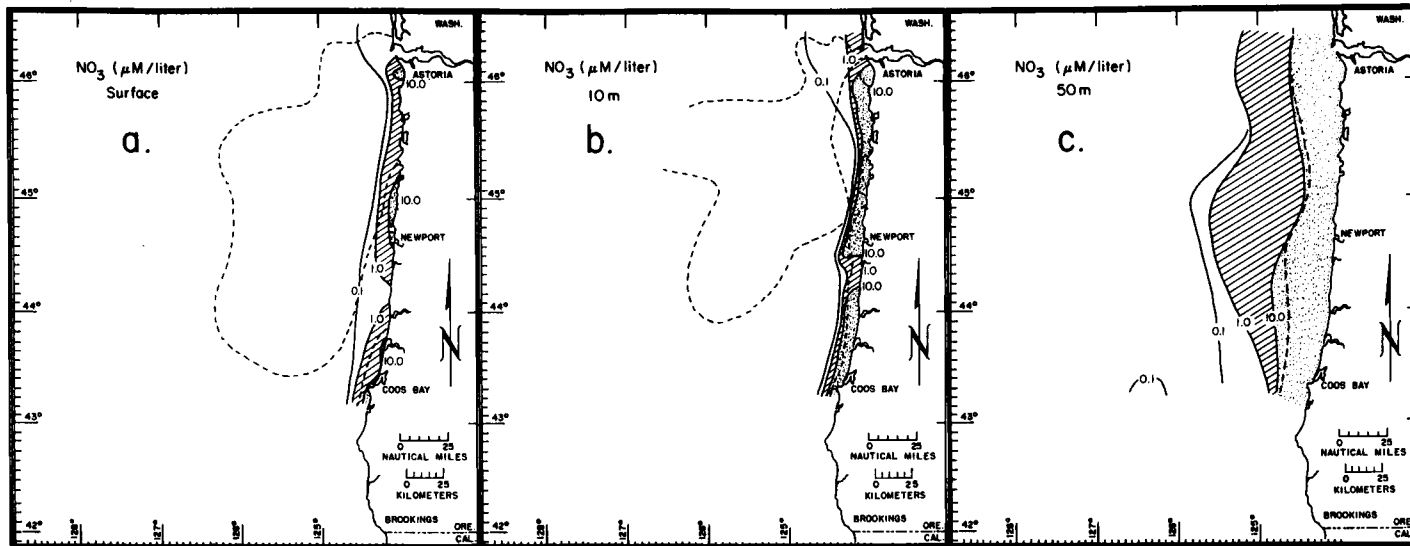
Horizontal Distributions

Density (σ_t)

At the sea surface, waters with σ_t values greater than 25.5 are confined to a few small areas close to the Oregon coast (Figure 2). The 25.5 σ_t contour has been used to define the seaward edge of the upwelling front (Collins, 1964). At ten meters the 25.5 σ_t line includes a larger area than at the surface, although it is still restricted to the southern half of the Oregon coast (Figure 2). The line is between 15 and 25 nautical miles offshore at 50 meters and roughly parallels the coastline (Figure 2). The distributions of σ_t at 15 and 25 meters are intermediate between the 10 and 50 meter distributions, and are not illustrated. These distributions of σ_t simply indicate the shoreward progression of the front as it moves towards the surface, and the patchy distribution of upwelled water at depths above ten meters.

The 23.5 σ_t contour has been chosen to define the edge of the Columbia River plume. This line is not congruent with the 32.5‰ salinity contour often used to define the plume at the surface (Anderson *et al.*, 1962), but follows more closely the 0.127 specific alkalinity contour, suggested as a definition of the edge of the plume by

Figure 2. Horizontal distributions of NO_3 and AOU found on Cruise 6806-C, 24 June, 1968, to 3 July, 1968. The dashed lines represent the 23.5 and 25.5 σ_t contour lines.



Park (1966). The $23.5 \sigma_t$ contour also closely follows the 32.0‰ salinity contour, particularly at the surface. The $23.5 \sigma_t$ contour is probably best considered as a conservative estimate of the plume boundary.

The area outlined by the $23.5 \sigma_t$ contour is greatest at the sea surface. At ten meters the area covered is less, and at 50 meters there is no water with a σ_t value of 23.5 or less. The 15 and 25 meter distributions of σ_t showed only a small area off the Columbia River mouth bounded by the $23.5 \sigma_t$ contour. The bottom edge of the plume is considered to be synonymous with the seasonal pycnocline off Oregon, although it is realized that surface heating and mixing with sea water become increasingly significant factors with increasing distance from the mouth of the river.

Nitrate

The horizontal distributions of nitrate indicate the source of supply of nitrate to the surface waters (Figure 2a, b, and c). At each of the three depths illustrated, the concentration of nitrate increases towards the coast. The $10 \mu\text{M NO}_3$ contour coincides remarkably well with the $25.5 \sigma_t$ contour at 50 meters, and fairly well at the other depths. This indicates that nitrate concentrations of $10 \mu\text{M}$ or greater are supplied to surface waters by upwelling. Columbia River plume water, on the other hand, always contained

less than $1\mu\text{M NO}_3$ except in the close proximity of the river mouth. In most instances water outside of upwelled water did not possess measurable nitrate concentrations.

AOU

The Apparent Oxygen Utilization (AOU) of a water sample depends on the past history of the water, including mixing processes and biological history. The greater the positive value of AOU, the greater the utilization of oxygen since the formation of the original water mass at the surface. Negative values might indicate biological production of oxygen; however, temperature changes might also cause supersaturation of oxygen in the water, and care must be exercised in interpreting negative values.

The areas of positive AOU at the surface (Figure 2d) are discontinuous along the coast. The positive AOU area off the mouth of the Columbia River probably indicates the low oxygen content of river runoff. The positive AOU areas farther south coincide with the $25.5 \sigma_t$ contour line, indicating a correlation with newly upwelled water.

An area of very negative AOU at the surface and ten meters along the coast south of Newport is coincident with an area of very great concentration of chlorophyll a and low nitrate levels. This was undoubtedly an area of intense photosynthetic activity during the period of sampling.

Along any transect from the Oregon coast seaward, at any selected depth there is usually a region of relatively high positive AOU which gives way to successively lower positive values and then goes through zero AOU to increasingly negative values up to a maximum negative region. Further offshore the values become less negative again. Thus, a negative AOU trough is formed at some distance offshore, the distance being increasingly farther from shore with increasing depth. The negative AOU trough can be defined by the -0.5 or -0.6 AOU contours (Figures 2d, e, and f). In surface water (Figure 2d) the trough contains the most negative values just south of the Columbia River mouth. The trough narrows perceptively just north of Newport, then broadens again in the south. The portion of the trough north of the narrow neck is contained within the $23.5 \sigma_t$ contour, suggesting a correlation with the Columbia River plume. The portion of the trough south of the neck apparently is caused, at least in part, by primary production in upwelled water, as much of the southern portion is not contained within the $23.5 \sigma_t$ contour line. Oxygen exchange with the atmosphere is also involved.

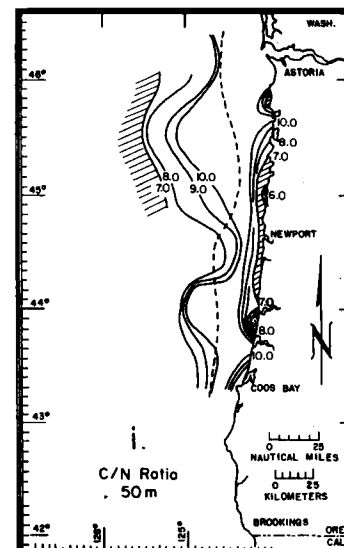
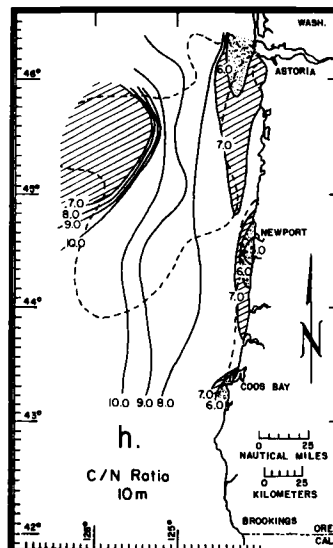
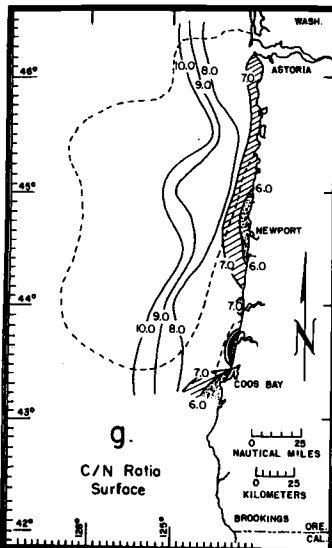
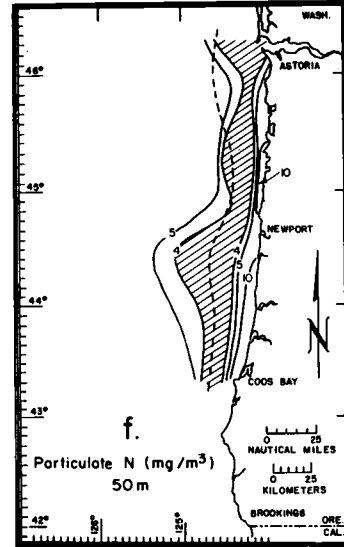
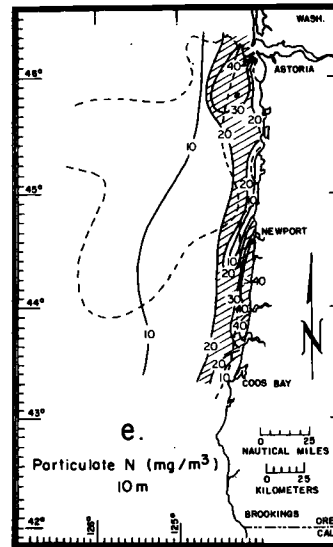
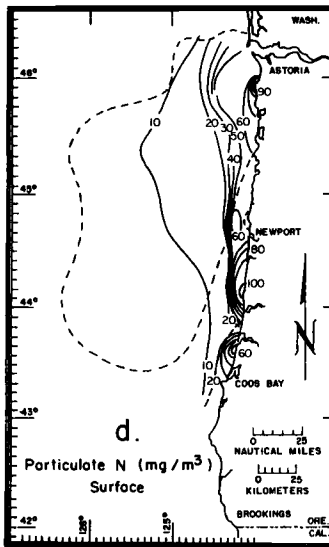
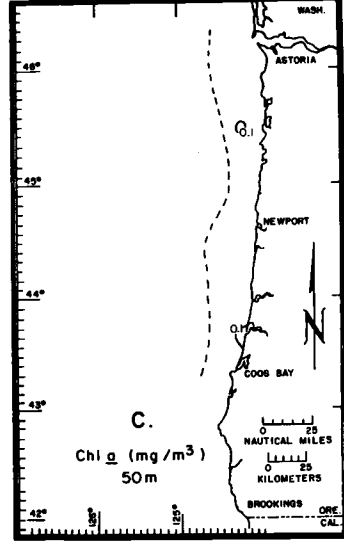
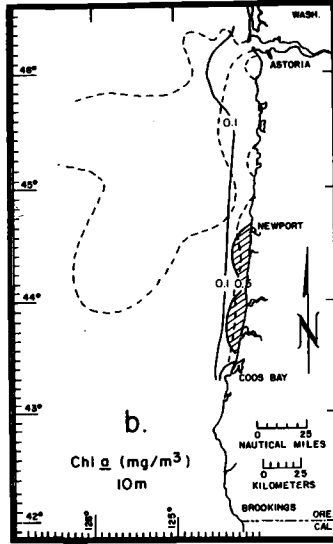
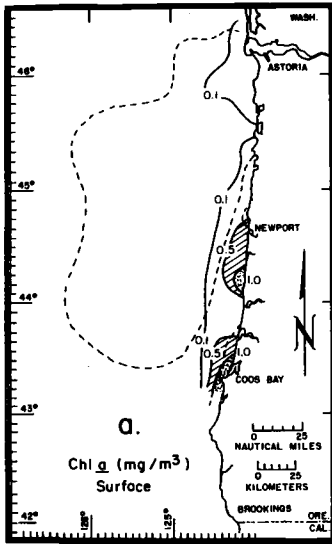
At ten meters the trough has gained in area and has moved offshore relative to the surface distribution (Figure 2e). It has also apparently shifted more extensively into the southern half of the coast. The distributions of AOU at 20 and 30 meters (not shown here) indicate that the AOU trough is located at successively greater distances

Figure 3. Horizontal distributions of chlorophyll a, particulate nitrogen, and C/N ratio found on Cruise 6806-C, 24 June, 1968, to 3 July, 1968. The dashed lines represent the 23.5 and 25.5 σ_t contour lines.

from shore, with no contour discontinuities or irregularities. At 50 meters the negative AOU zone is found even farther offshore (between 75 and 120 miles off Newport). At this distance from shore the negative AOU zone is not necessarily related to the negative AOU troughs found inshore at the surface and ten meters. The existence of negative AOU troughs at various distances from shore at various depths has implications bearing on the fate of upwelled water meeting Columbia River plume water, and on in situ primary production associated with the subsurface chlorophyll maximum described by Anderson (1969). These implications will be discussed later.

Chlorophyll a

The horizontal distributions of chlorophyll a at the surface, 10, and 50 meters are illustrated in Figures 3a, b, and c. The distributions at 15 and 25 meters were very similar to the distribution at ten meters. At 50 meters almost no chlorophyll a is detectable (Figure 3c). At both the surface and ten meters, measurable chlorophyll a is confined to narrow zones adjacent to the coast, with highest concentrations occurring along the southern half of the coast (Figures 3a and c). Except for the station inside the Columbia River mouth, all the chlorophyll a concentrations greater than 0.50 mg/m^3 lie inshore of the $23.5 \sigma_t$ contour. The bulges at the northern ends of the 0.10 mg/m^3 contour lines are a result of nutrient contributions from



the Columbia River. Similar bulges can be noted in the nitrate contours at the surface and ten meters (Figures 2a and b).

Chlorophyll a occurs in areas of both negative and positive AOU; however, most of the stations with very negative AOU values at the surface and ten meters have the largest concentrations of chlorophyll a. Two of the highest chlorophyll a concentrations are found at stations MC50 and MC51 (Figure 1), and these stations also have by far the most negative AOU values. The area of very negative AOU in the surface water just south of the Columbia River mouth is associated with appreciable amounts of chlorophyll a, although concentrations vary considerably in this area. Near the mouth of the Columbia River at ten meters, there are some offshore stations with more chlorophyll a than the nearest shore stations. These higher concentrations are possibly related to the offshore negative AOU trough, though data are too few in this area to be certain.

Particulate Nitrogen

At the surface the highest concentrations of particulate nitrogen occur next to the coast and decrease rather systematically with increasing distance from shore (Figure 3d). The bulge of higher values off the Columbia River mouth is evident at the surface and ten meters, and intense primary production south of Newport is easily distinguished in these data. At ten meters a ridge of relatively high

particulate nitrogen concentrations runs from the mouth of the Columbia River to slightly south of Newport, and picks up again off Coos Bay (Figure 3e). Values to either side of this ridge are lower than those in the ridge area. This ridge occurs in approximately the same area as the negative AOU trough. The far offshore areas all have relatively low concentrations of particulate nitrogen, usually in the range of 6-10 mg/m³.

At 50 meters a relatively wide particulate nitrogen trough extends the length of the coastline (Figure 3f). Inshore and offshore of the trough, concentrations are greater than 4 mg/m³. The trough is associated with "clean" upwelling water. The higher values inshore probably are the result of particles sinking from the very productive surface waters adjacent to the coast, while the somewhat higher values offshore of the trough probably represent some in situ production and sinking of surface particles from the Columbia River plume. It might be significant that the particulate nitrogen ridge at ten meters lies over the particulate nitrogen trough at 50 meters. Presumably, in situ production in effect "reaches down" to meet the nutrient rich upwelled water within the limits of the photic zone. The photic depth (depth of 1% incident radiation) is approximately 20 to 25 meters in the ridge-trough area.

C/N

The carbon to nitrogen ratio by weight (C/N) in healthy phytoplankton under conditions of nutrient sufficiency should theoretically be in the range of 6.0 to 7.0, despite slight species differences (Redfield, Ketchum, and Richards, 1963). Several investigators (Ketchum and Redfield, 1949; Parsons, Stephens, and Strickland, 1961) have found that both natural and laboratory cultures of various species of phytoplankton do, in fact, have C/N ratios around 6.0 to 7.0. Ketchum and Redfield (1949) showed that phytoplankton grown in a nitrogen deficient culture, however, had a C/N ratio of about 20. This high ratio resulted from a disproportionately large decrease in the amount of cellular nitrogen relative to carbon.

By inference from the above, a high C/N ratio in a natural phytoplankton population would indicate an unhealthy (probably nitrogen deficient) state. Care must be used in evaluating C/N ratios in material filtered from the sea, however. A high C/N ratio in particulate matter could be obtained either from unhealthy phytoplankton cells, from a large amount of non-living particulates with a high C/N ratio, or from a combination of the two. Other data, such as AOU, and perhaps chlorophyll determinations and cell counts, can be used to supplement the C/N data.

The distributions of the C/N ratio in particulate matter at the surface, ten meters, and 50 meters off Oregon are shown in Figures 3g, h, and i. In surface water almost all the C/N ratios less than 7.0 fall inshore of the $23.5 \sigma_t$ contour, indicating that the theoretical ratio holds only in a narrow band along the coast (Figure 3g). The Columbia River plume, with ratios higher than 8.0 (except near the river mouth), apparently restricts offshore movement of particles with low C/N ratios. The slight bulges of the 8.0 C/N contours off the mouth of the Columbia River and in the southern quarter of the sampling area suggest effects of Columbia River outfall and upwelling, respectively.

At ten meters C/N ratios below 7.0 are found inshore on the southern half of the coast, but along the northern half the situation is different (Figure 3h). In this region the C/N ratios less than 7.0 describe a wedge extending south from the Columbia River mouth, and are undoubtedly related to Columbia River discharge. The trough of low C/N ratios approximately overlaps the negative AOU trough, although the C/N trough is most prominent at ten meters and the AOU trough most prominent at the surface. Offshore from the C/N trough the ratios increase to above 10.0, then tend to decrease to below 7.0 again. The three far offshore stations with C/N ratios less than 7.0 are perhaps too few for drawing conclusions. The contours of ratios above 7.0 tend to conform to the axis of the Columbia River plume,

as would be expected, but the offshore area of low C/N ratios, if it is real, also falls within the $23.5 \sigma_t$ contour at ten meters.

In general, stations with an appreciable amount of chlorophyll a tend to have a low C/N ratio. Low C/N ratios also tend to be associated with large amounts of particulate nitrogen, indicating that nitrogen is the element responsible for fluctuations in C/N.

The distribution of C/N ratios at 50 meters (Figure 3i) is interesting in its relation to upwelling. There is a ridge of very high C/N ratios (greater than 13.0) 10 to 20 miles offshore and continuous along the coast from the Columbia River to Coos Bay. Inshore and offshore of this ridge the C/N ratios are lower. The distribution at 50 meters shows that this C/N ridge is roughly bisected by the $25.5 \sigma_t$ contour line; that is, the ridge overlaps the region where the freshly upwelled water is moving up into the upper 50 meters. It appears that freshly upwelled water brings up particles with high C/N ratios. The appearance of a particulate nitrogen trough over the same region at 50 meters (Figure 3f) indicates that the upwelled particles have a greatly reduced nitrogen content relative to carbon content. Inshore and offshore of the C/N trough at 50 meters the ratios are lower, probably because the particulate matter has recently sunk from the biologically active areas near the surface.

East-West Vertical Transects

Vertical distributions of several physical, chemical, and biological parameters were studied along four east-west transects off the coast of Oregon to get another perspective on the events occurring in this region. The distributions of the measured quantities showed similar characteristics in all four transects. Figures 4 and 5 refer to a representative transect off Depoe Bay, Oregon ($44^{\circ}48'$ N. Lat. ; $124^{\circ}04'$ W. Long.). This transect extends approximately 60 miles off the coast. The other three transects, not illustrated, were off Cape Arago ($43^{\circ}18'$ N. Lat. ; $124^{\circ}24'$ W. Long.) south of the Depoe Bay transect, and off Cape Mears ($45^{\circ}29'$ N. Lat. ; $123^{\circ}59'$ W. Long.) and Tillamook Head ($45^{\circ}57'$ N. Lat. ; $123^{\circ}59'$ W. Long.), both north of Depoe Bay. Figures 4 and 5 show the distributions on two separate days, 24 June and 28 June; therefore, changes of the distributions in time can be described in addition to the vertical distributions of the parameters.

Density (σ_t)

The permanent pycnocline defined by the 25.5 and 26.0 σ_t contours (Collins, 1964) slopes up towards the coast at Depoe Bay, indicating the presence of upwelling (Figure 4). The pycnocline centers at about 85 meters depth seaward of station DB30, and the 25.5 σ_t

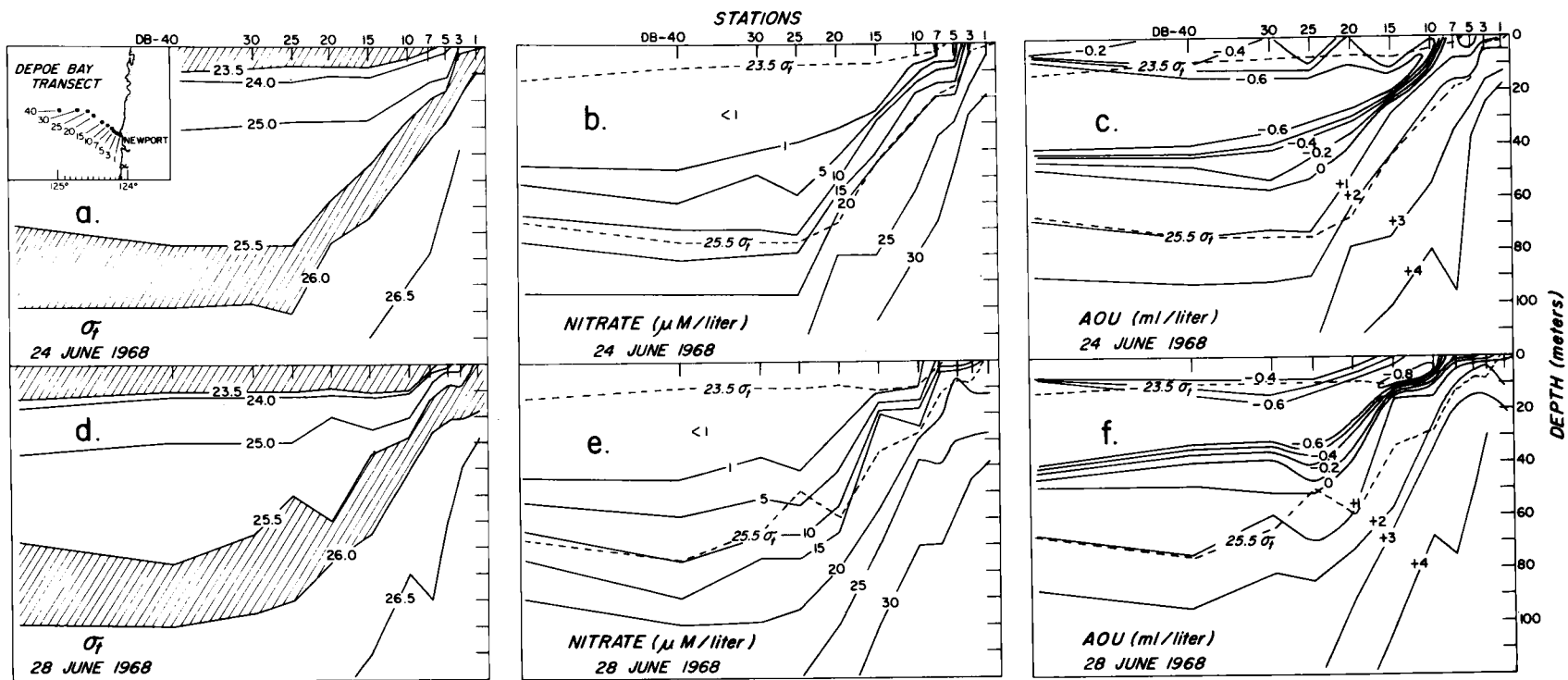


Figure 4. Vertical distributions of σ_t , NO_3 , and AOU along east-west transect.

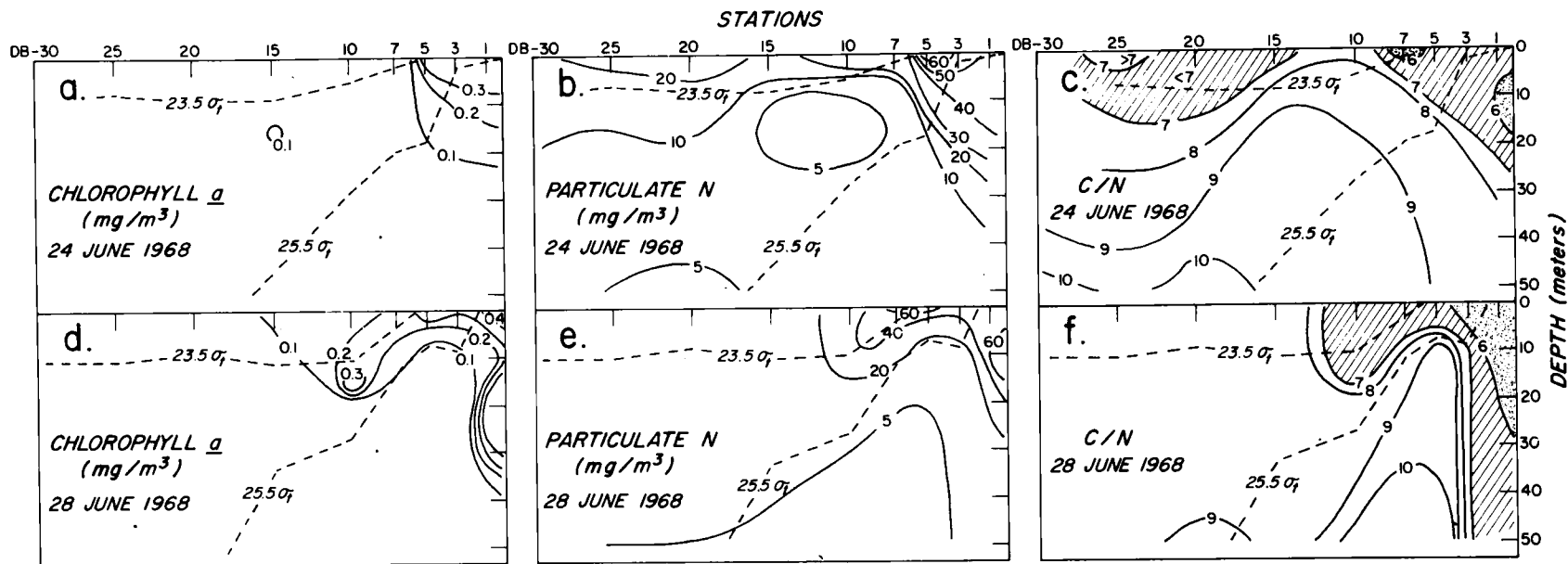


Figure 5. Vertical distributions of chlorophyll a, particulate nitrogen, and C/N ratio along east-west transect.

line breaks the sea surface about 1.5 miles offshore on 28 June (Figure 4). The intersection of the $25.5 \sigma_t$ line with the surface marks the seaward edge of the upwelling front off Oregon, for the purpose of this thesis. The situation is similar along the other transects with the exception that the upwelling front is found at different distances from shore. On the Cape Arago transect the $25.5 \sigma_t$ line breaks the surface about three miles offshore, while on the other transects north of Depoe Bay the line does not extend all the way up to the sea surface. These differences indicate the stronger effect of upwelling on the southern Oregon coast and possibly the masking of upwelling by Columbia River outfall in the north.

The $23.5 \sigma_t$ line has been chosen to delineate the boundary of the Columbia River plume and seasonal pycnocline. The sharp gradient between the 25.5 and $23.5 \sigma_t$ lines at the surface marks the zone of rapid density change between the upwelling front and the plume boundary.

The general appearances of the distributions of σ_t on 24 June and 28 June (Figure 4) are similar; however, there are significant differences in the depth of the $25.5 \sigma_t$ contour near shore. It moved towards the surface from 24 June to 28 June at stations DB1 and DB5 to DB15. It apparently sank, however, at DB3. At the rest of the stations it remained stationary. At DB5 the $25.5 \sigma_t$ line rose nine meters, giving a rate of approximately 3×10^{-3} cm/sec, which is

comparable to the rates found off Brookings, Oregon (Smith, Pattulo, and Lane, 1966). This rate represents a maximum for the Depoe Bay sections as DB5 to DB7 was the area of most rapid change in depth of the σ_t surfaces. The 26.0 σ_t line also rose at a comparable rate from 24 June to 28 June in the area between stations DB5 and DB10. It sank at stations DB1 and DB3. The 23.5 σ_t line appeared to sink slightly from 24 June to 28 June at stations DB10, DB15, and DB20, possibly as a result of the sharpening of the upwelling front from 24 June to 28 June.

Nitrate

The sloping nitrate isolines in general parallel the pycnocline (Figure 4). The 10 μ M NO₃ isoline at depth and the 15 and 20 μ M NO₃ isolines near the surface show a close correspondence to the 25.5 σ_t line. Offshore surface waters are devoid of measurable nitrate. Only close inshore does measurable nitrate appear in surface waters.

Between stations DB5 and DB15 from 24 June to 28 June, the 15 and 20 μ M isolines indicate the same rate of vertical movement towards the surface as the σ_t lines. Inshore of DB5 on 24 June the nitrate isolines angle up towards the surface. On 28 June they flatten out and deepen inshore of DB5. This feature indicates either sinking of water inshore or biological utilization of nitrate, or a combination of the two.

AOU

In general, the AOU isolines parallel the σ_t surfaces (Figure 4). The +1.0 AOU line closely corresponds to the 25.5 σ_t line offshore, but the 25.5 σ_t and +2.0 AOU lines are more closely associated from about DB10 to very near shore.

Conspicuous in the Depoe Bay transect is the negative AOU trough. In vertical section the trough is more easily visualized as a core which mainly lies under the 23.5 σ_t contour offshore and shoals inshore. The center of this core is at about 25 meters depth at a distance of 40 miles. On 24 June AOU values of -0.5 or less do not intersect the sea surface (Figure 4), but on 24 June the most shoreward -0.5 AOU isoline breaks the surface about nine miles offshore (Figure 4). Along the other transects the same general situation occurs.

The distribution of AOU shows a close correspondence to the distribution of nitrate. The bottom edge of the negative AOU core closely follows the $1\mu\text{M NO}_3$ isoline (Figure 4). The majority of the negative AOU water is thus water essentially devoid of nitrate. In general, the AOU distribution corresponds better to nitrate than to σ_t , especially in the surface waters. This is not unexpected in that phytoplankton metabolism is more directly affected by an essential nutrient than by a conservative property of sea water such as σ_t .

The inshore positive AOU contours rose towards the surface from 24 June to 28 June (Figure 4), indicating the same upward movement of water and the same apparent rate as given by the changes in distribution of σ_t and nitrate. At station DB1 the +2.0 and +3.0 AOU isolines were deeper on 28 June than on 24 June.

Chlorophyll a, Particulate Nitrogen, C/N

On 24 June the close inshore areas (out to DB7), particularly at the surface, had the highest concentrations of chlorophyll a and particulate nitrogen, and generally had the lowest C/N ratios for particulate matter (Figure 5). An area of low C/N ratios is also found in surface waters between DB15 and DB30. This area is associated with the patch of particulate nitrogen concentrations above 20 mg/m³ in the same area, but its origin is unknown. It is likely that it is an area broken off from the productive inshore area and moved offshore through a weakened gradient between the upwelling front and the Columbia River plume boundary.

On 28 June the distributions have changed markedly (Figure 5). A dome of upwelling water is present from DB3 to DB7. In the dome the chlorophyll a and particulate nitrogen concentrations are very low relative to concentrations seaward and shoreward, and the C/N ratios are high. The 25.5 σ_t line also shows a doming in this area. The nitrate concentrations of this water are high and the AOU values

positive.

In addition to the doming a thumb of rich water apparently moves offshore and downward between the 23.5 and 25.5 σ_t surfaces (Figure 5). This thumb of rich water lies in or at the bottom edge of the negative AOU core, and follows the 1 and 5 μM NO_3 contours. As high particulate nitrogen and chlorophyll a values make up the thumb, the thumb is probably new phytoplankton growth that has occurred between 24 June and 28 June.

Longshore Vertical Transects

Figures 6 and 7 show the distributions of σ_t , nitrate, AOU, chlorophyll a, particulate nitrogen, and C/N ratio in a north-south direction along the Oregon coast. The stations chosen to make up the longitudinal transect are all those which lie within one or two miles of the coast. Although the transect is a composite picture over seven days of sampling, and therefore has little fine detail, the large persisting features are evident.

The 25.5 σ_t line is shallower along the southern coast than along the northern coast (Figure 6); in fact, it breaks the surface only along the southern half of the coast and off Depoe Bay. Also, the 25.5 - 26.0 σ_t band is thicker along the southern half of the coast. These features reaffirm that, in general, upwelling is more intense along the southern half of the coast. However, two areas of doming

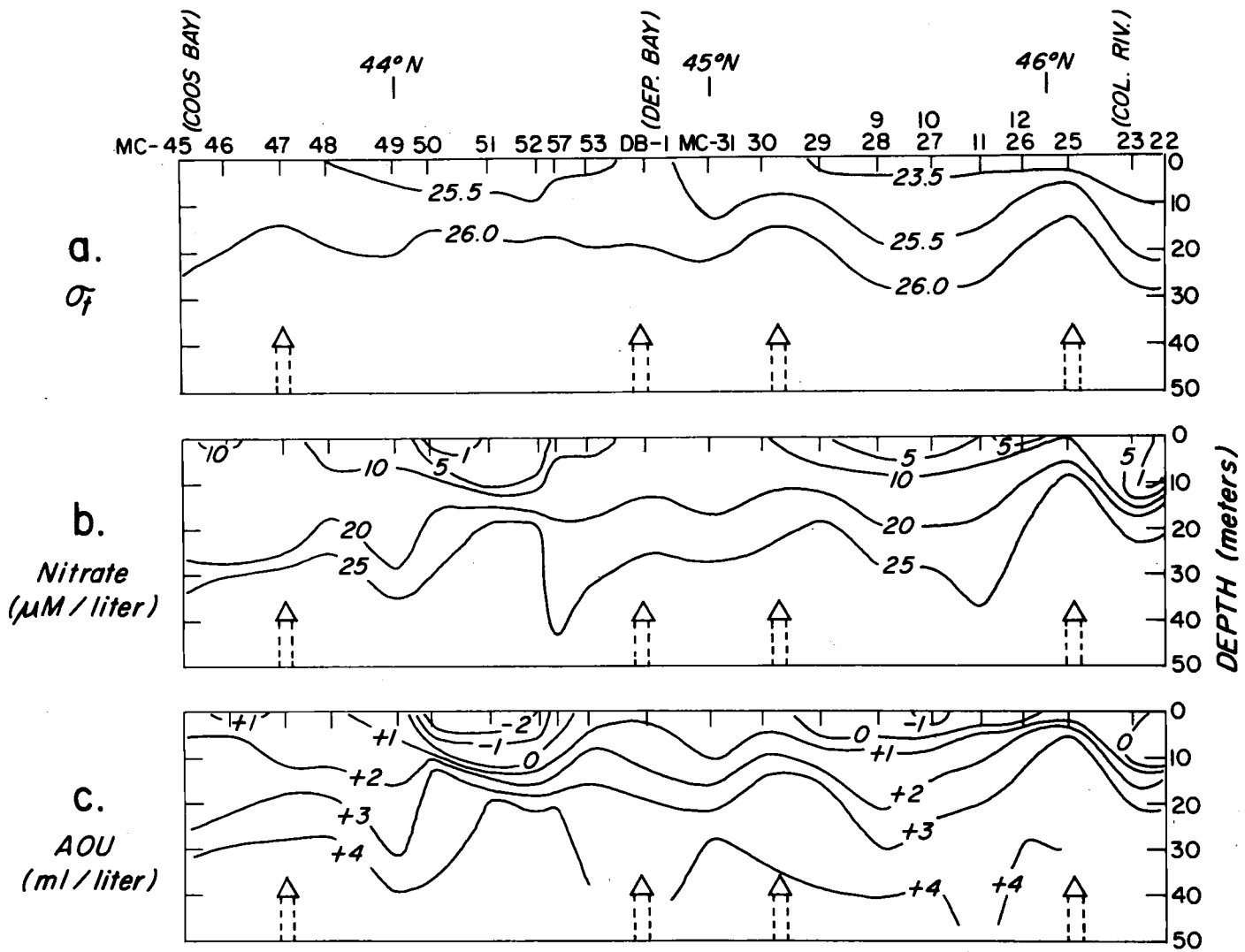


Figure 6. Vertical distributions of σ_t , NO_3 , and AOU along the longshore transect.

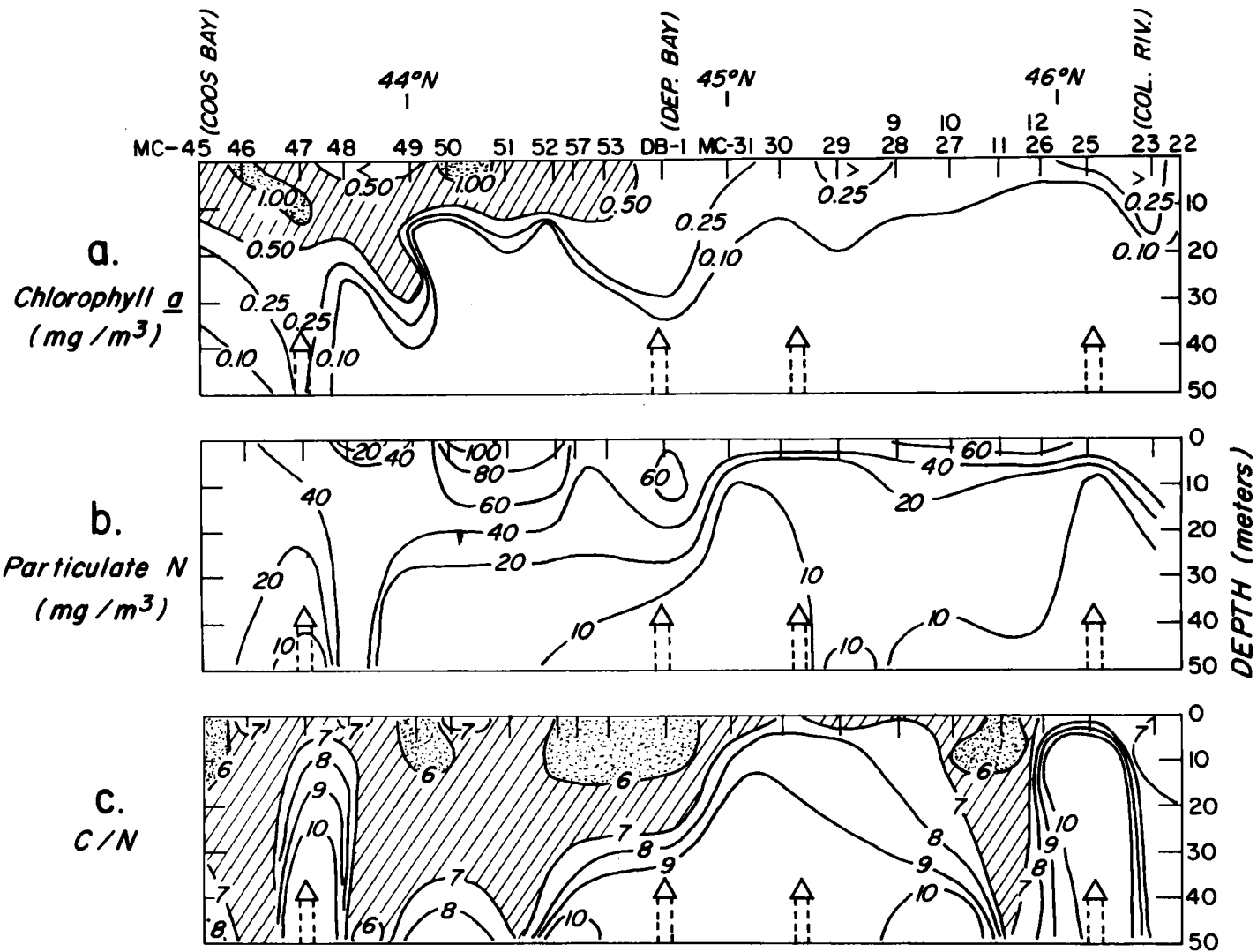


Figure 7. Vertical distributions of chlorophyll a , particulate nitrogen, and C/N ratio along the longshore transect.

of the isolines along the northern half of the coast also suggest upwelling. Possibly the $25.5 \sigma_t$ line does not appear at the surface in these areas because the Columbia River exerts a depressing effect. Areas of upwelling in Figures 6 and 7 are indicated by the large arrows.

The 15, 20, and $25 \mu\text{M}$ nitrate isolines also tend to be slightly deeper along the southern coast (Figure 6), and the doming effect is very similar to that of σ_t . The $10 \mu\text{M}$ nitrate isoline intersects the surface in the same locations as the $25.5 \sigma_t$ line. Water with a nitrate content less than $10 \mu\text{M}$ is found only in water less dense than $25.5 \sigma_t$. The low nitrate area at the surface between stations MC25 and MC29 is no doubt the result of utilization of the nutrient by phytoplankton in a portion of the Columbia River plume. However, the source of nitrate in this area probably is not the Columbia River, with relatively low surface concentrations at stations MC22 and MC23, but rather the upwelled water at MC25. The region MC50 to MC52 is one of very low nitrate content in surface waters, and, as indicated earlier, is a pocket of intense primary production between two areas of upwelling.

In all areas the AOU data correspond to the nitrate data (Figure 6). The upwelling domes, Columbia River wedge, and productive region between MC50 and MC52 are obvious. All the negative AOU values are found in water with less than $10 \mu\text{M}$ nitrate and with

densities less than $25.5 \sigma_t$.

The distribution of chlorophyll a shows significant differences along the coast (Figure 7). Concentrations of chlorophyll a were generally greater along the southern coast, with values above 0.50 mg/m^3 commonplace in the upper waters. A significant feature of the chlorophyll a profile is that in areas of upwelling in the southern half of the section chlorophyll a concentrations above 0.10 mg/m^3 extend to greater depths than in non-upwelling zones, while in the northern half the reverse seems to be true. For example, at MC25 and MC30 possible doming of the 0.10 mg/m^3 contour is observed. However, concentrations less than 0.25 mg/m^3 are also observed at the surface between MC28 and MC26, between two areas of upwelling. Chlorophyll a concentration is generally sparse in the northern part of the section, and perhaps gives little clue as to what processes are affecting it.

The tongue of relatively high chlorophyll a concentration extending from about 15 to 40 meters depth at MC49 apparently is a real feature, as it corresponds to downward extensions in the σ_t , nitrate, and AOU contours at MC49 (Figure 7). This feature appears to be the result of water sinking in the area of MC49. Possibly a circulation pattern is set up with upwelling at MC46 and MC47 and sinking at MC49. Some of the pigments from the region MC50 to MC53 might also be entrained into the region of apparent sinking at

MC49.

The deeper extensions of chlorophyll a concentrations into upwelling water in the southern section probably are the result of enhanced chlorophyll a production in such water. In effect, chlorophyll production "reaches down" to meet the nutrient-rich water coming up. Whether the increased chlorophyll is concomitant with an increase in the number of particles is not known.

Low particulate nitrogen concentrations tend to dome in the areas where high chlorophyll a concentrations extend deeper (Figure 7). Possibly contouring of the fewer particulate nitrogen data has given a false impression, and the question must be resolved with more data. The high productivity area centering around MC50 near the surface is distinguished by both high chlorophyll a and particulate nitrogen values. The particulate nitrogen contours in the northern coastal region tend to show the same features as the chlorophyll a contours, which suggest that the phenomena are not artifacts of contouring. Low particulate nitrogen concentrations tend to dome where low chlorophyll a concentrations tend to dome, for example. Not seen in the chlorophyll a profile, but observed in the particulate nitrogen profile, is the surface lens of higher concentrations between MC25 and MC29. This shallow region corresponds to the area of decreased nitrate and AOU values.

In general, C/N ratios lower than 7.0 are found in the southern half of the transect, corresponding to higher particulate nitrogen concentrations there, and higher C/N ratios in the northern half agree with lower particulate nitrogen concentrations (Figure 7). Two of the upwelling areas in particular show a pronounced doming of high (>10) C/N ratios. Also, the shallow productive area centering around MC11 is observed. The productive region between MC50 and MC52 is not strikingly evident in the C/N profile. Although values are generally below 7.0, and thus still within the theoretical ratio, two areas to the immediate north and south of the MC50 - MC52 region have ratios slightly below 6.0. Whether the ratios within and immediately outside the MC50 - MC52 region are significantly different is not known at this time.

There are not enough particulate nitrogen or C/N ratio data taken at MC49 to check correspondence with the tongue of high chlorophyll concentrations apparently sinking at MC49. At MC29 the particulate nitrogen contours, and, to a lesser degree, the C/N ratio contours suggest sinking adjacent to the upwelling area at MC30. Lack of precision in contouring might be involved, however, as the chlorophyll data do not show this feature.

Correlation Graphs

Data from the Depoe Bay transects sampled on 24 June and 28 June have been plotted in order to look for relationships among the different measured parameters. Cruise data outside of the Depoe Bay transect showed the same relationships as found for Depoe Bay data, and have not been included here.

As expected, the relationship between nitrate and σ_t greater than 25.5 is a straight line with high correlation (Figure 8). The majority of the points representing densities less than 25.5 σ_t correspond to measurable concentrations of nitrate lower than those predicted by extrapolation of the regression line for points in upwelled water. This condition indicates that either the nitrate is being biologically utilized, that upwelled water is being mixed with water of lower nitrate content, or both.

A strong relationship between σ_t and AOU is also observed (Figure 9). Most striking is the sharp break in the data. Waters with σ_t less than 24.75 all have similar AOU values because of mixing processes above the permanent pycnocline. The points corresponding to σ_t greater than 24.75 all have AOU values dependent mostly on their past origin.

The AOU - nitrate data (Figure 10) fairly closely fit a line predicted by the theoretical biochemical utilization of 138 molecules of

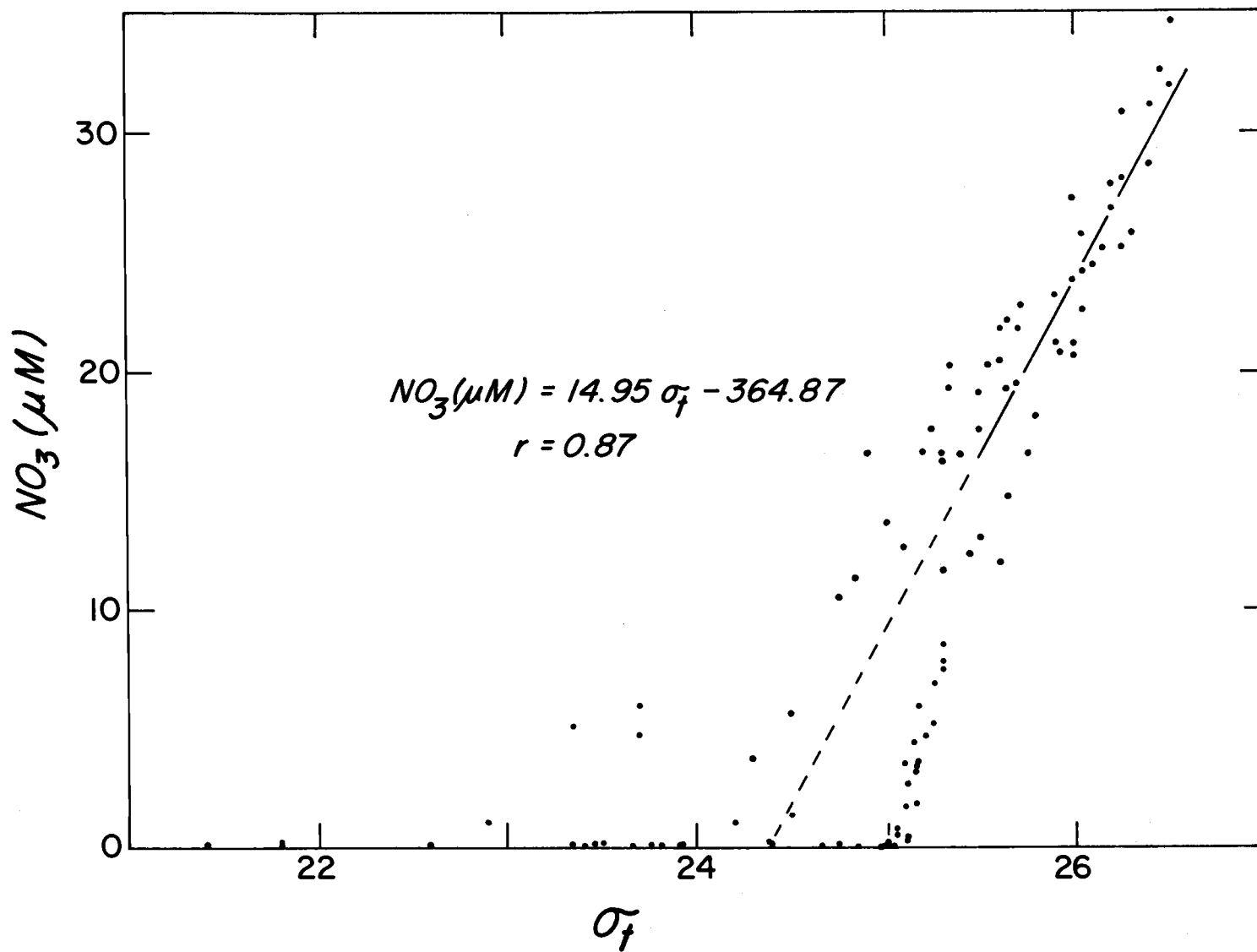


Figure 8. Nitrate vs σ_t .

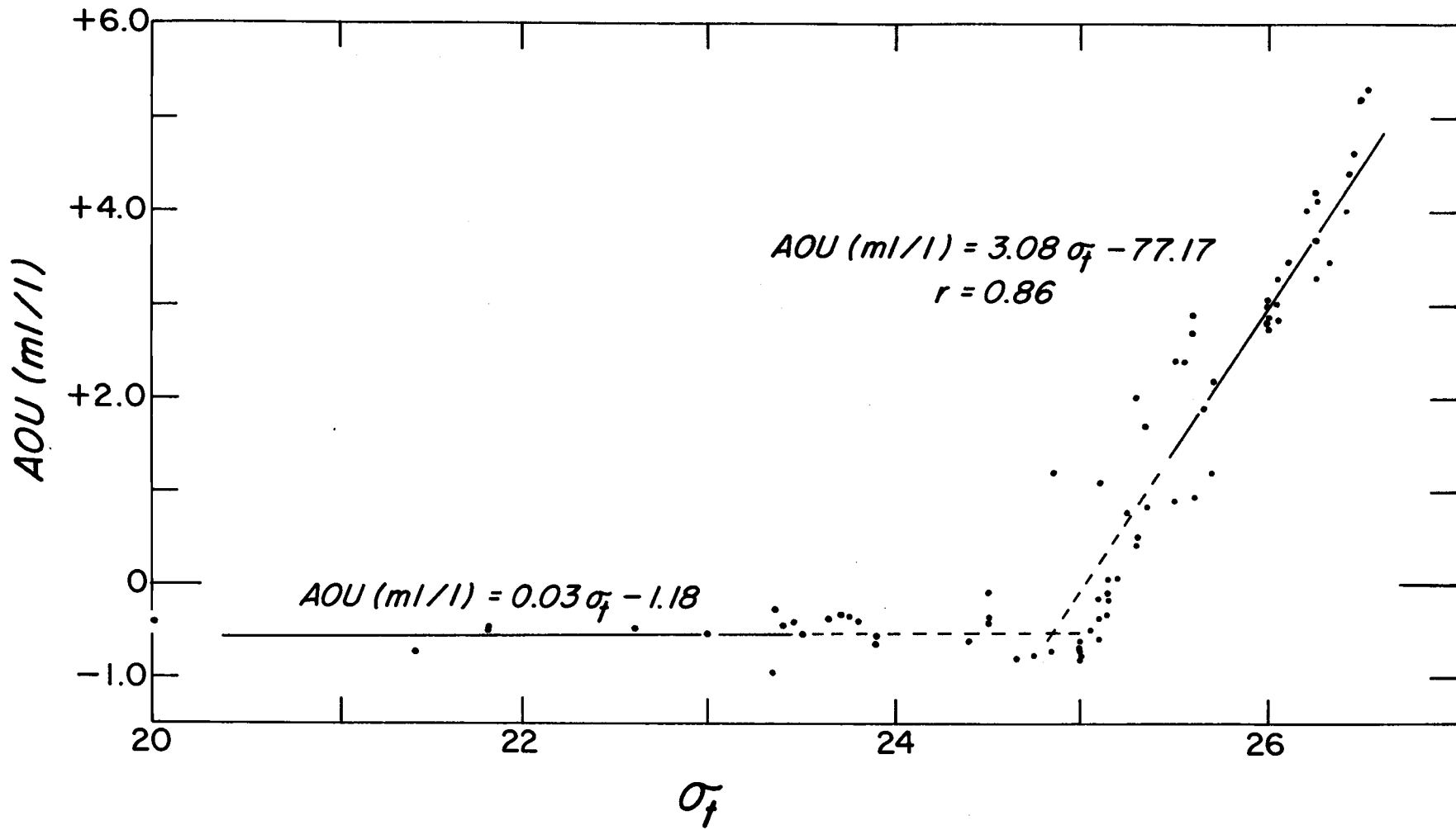


Figure 9. AOU vs σ_t .

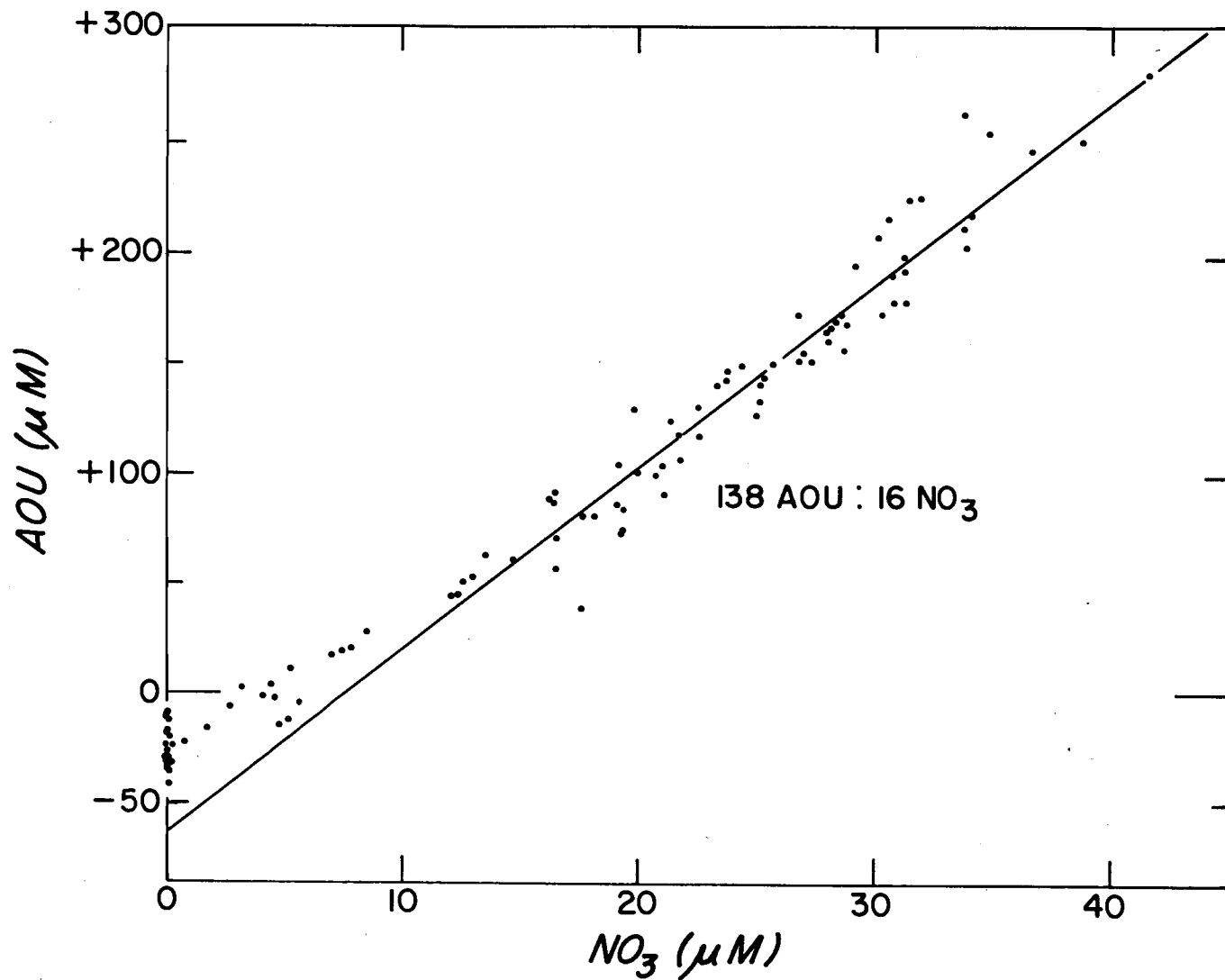
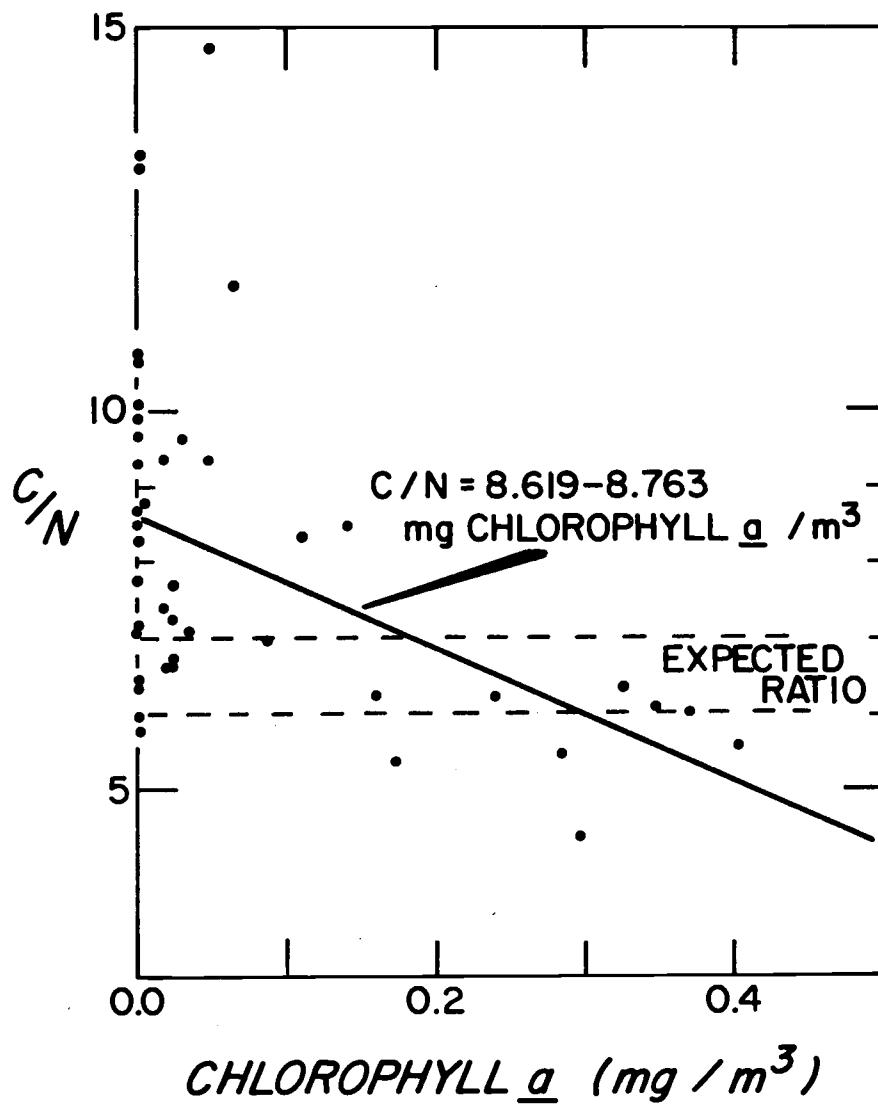


Figure 10. AOU vs nitrate.

oxygen produced for every 16 atoms of nitrogen utilized (Richards, 1965). The deviations of points from the line at low nitrate concentrations ($<10\mu\text{M}$) can be attributed to mixing of surface waters of different prehistories and possibly to effects of ammonia and other biologically useful nitrogenous compounds besides nitrate.

There is a fairly good linear correlation between C/N and chlorophyll a concentrations of about 0.10 mg/m^3 or greater (Figure 11). At chlorophyll a concentrations close to zero, there is a wide scatter of points as the C/N ratio is then more sensitive to other effects such as the amounts and types of detritus present. The majority of the data with a C/N ratio of 7.0 or less is associated with moderate to large amounts of chlorophyll a.

Figure 12 shows a graph of C/N ratio versus particulate nitrogen. The general trend is that the C/N ratio decreases with increasing particulate nitrogen to about 25 mg N/m^3 , showing the dependence of the ratio on the nitrogen concentration. At nitrogen concentrations greater than 25 mg N/m^3 the C/N ratio appears to stabilize around the expected range of 6.0 to 7.0.

Figure 11. C/N vs chlorophyll *a*.

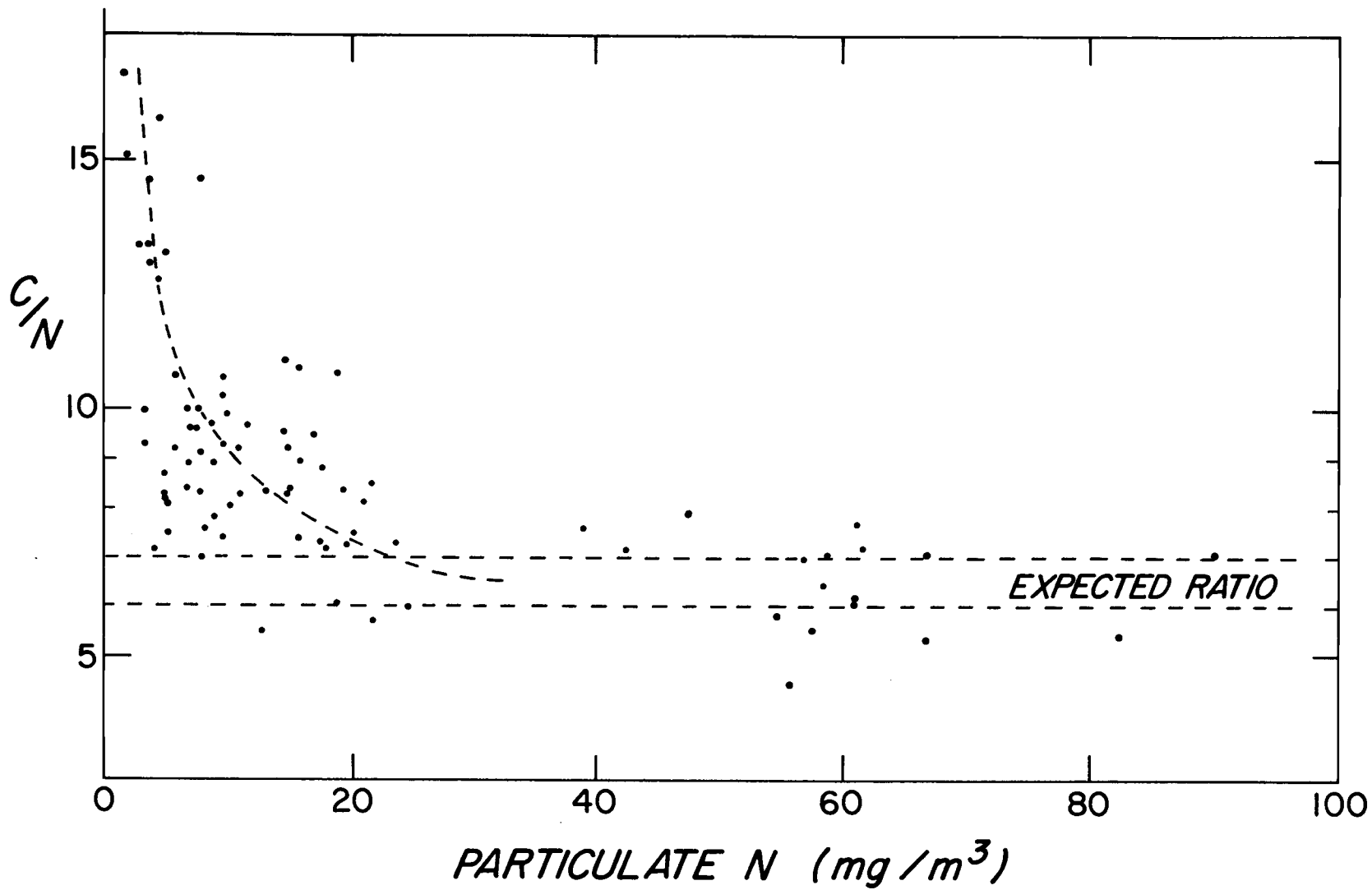


Figure 12. C/N vs particulate nitrogen.

DISCUSSION

The distribution of upwelled water determines to a large degree the areas of biological production off Oregon. Upwelling brings nitrate-enriched water into the upper 50 meters along the length of the coast; however, the intensity of the upwelling shows a patchy distribution and is characterized by upwelling "domes", localized both in time and space. The effect of upwelling apparently is depressed along the northern half of the Oregon coast by the Columbia River plume. Water movement inferred from changes in σ_t distributions is upward and shoreward along the permanent pycnocline, similar to the model proposed by Mooers (1970). Currents parallel to the coastline are superimposed on this water movement.

The data clearly show that the major source of nitrate is upwelling water. The Columbia River apparently adds a small amount of nitrate to the area immediately south of the Columbia River mouth. Outside of the upwelling areas little measurable nitrate is found in the upper 50 meters, indicating that the nitrate brought up by upwelling is rapidly utilized by the phytoplankton.

The biologically productive areas can be defined by the high standing stocks of chlorophyll a and by the apparent production of oxygen and utilization of nitrate. The relationships of chlorophyll a to the values of AOU or nitrate concentration are not clear because

of time lags, ocean currents, and the continual influx of nitrate and water of low oxygen content. More significant would be the relationship of chlorophyll a to the rate of change of nitrate and AOU, and time series data are needed for this. Despite these effects, water with negative AOU values and no measurable nitrate usually is found in areas with large standing stocks of chlorophyll.

High particulate nitrogen values and low C/N values are generally associated with high chlorophyll a concentrations, but for the same reasons mentioned above do not show clear-cut relationships to AOU and nitrate concentration. The C/N ratio is determined by the concentration of particulate nitrogen, which in turn must be dependent on the utilization of nitrate by phytoplankton. However, my data do not clearly relate nitrate and particulate nitrogen, for the same reasons of time lags, currents, etc. mentioned before.

Much of the variation in the C/N ratios probably is a result of varying amounts and types of detritus which is taken as particulate matter along with the phytoplankton. Holm-Hansen, Strickland, and Williams (1966) found particulate nitrogen concentrations of 3 to 5 mg N/m³ and C/N ratios of 9.0 or greater in waters below 75 meters off California. These values are comparable to my values found in the upwelling domes. In the upper 75 meters they found an average C/N ratio of 5.56. Dal Pont and Newell (1963) found low C/N ratios (3.0 to 5.0), and moderately high concentrations of particulate

nitrogen, in the upper 150 meters of an oceanic station several hundred miles offshore. However, they indicated that the C/N ratio decreased with depth and concluded that nitrogen was more refractory than carbon, contrary to what my data suggest.

Phytoplankton production depends directly on the supply of nitrogen that is available in the photic zone; consequently, the areas of highest productivity, as inferred from chlorophyll a standing stocks and AOU values, are located where upwelling is most active close to the coastline. In some areas the chlorophyll production extends deeper when over an upwelling dome, as if it were "reaching down" to meet the upwelling nutrients. The expansion and movement of the productive areas depends on the currents and the rate of supply of nutrients. The Columbia River plume appears to be a partial barrier to seaward spreading, causing the productive water to either flow seaward under the plume or to move north or south from its origin. The southerly longshore movement of surface waters in the summer off Oregon has been demonstrated by direct current movement (Collins et al., In press). Smith, Pattulo, and Lane (1966) found that the offshore velocity of surface water is about 4 cm/sec off Brookings, Oregon, during the summer, but longitudinal movement predominates; this feature might be seen in my longshore transects (Figures 6 and 7) as southerly extensions of productive waters from the upwelling domes.

The Columbia River plume appears to support a productive phytoplankton population just south of the river mouth. Waters inside the mouth contain high concentrations of chlorophyll a but relatively little nitrate. Probably the phytoplankton population carried out by the plume is stimulated towards rapid growth by the nitrate brought up to the plume by upwelling. Anderson (1964) found similar conditions of high productivity south of the Columbia River mouth during the summer months.

The areal extent and distribution of the negative AOU core is very similar to that of the oxygen maximum described by Stefannson and Richards (1964) for waters off Oregon and Washington. Lack of measurable nitrate, moderate to low amounts of particulate nitrogen (5 to 20 mg N/m³), varying C/N ratios, and scattered low amounts of chlorophyll a characterize the offshore portion of the negative AOU core. When the core appears inshore near the surface, it is often associated with productive water with high concentrations of chlorophyll a and particulate nitrogen, and low C/N ratios.

The inshore portion of the negative AOU core is probably formed by a combination of oxygen diffusion in from the atmosphere and photosynthesis. Upwelling brings undersaturated water to the surface, where oxygen diffusion serves to increase the oxygen content and decrease the AOU. Phytoplankton populations begin to proliferate as the nutrient-rich water moves into the photic zone, and

add to the total oxygenation. As both processes are occurring near the surface the water is moved offshore and ultimately under the seasonal pycnocline. As the water moves between the seasonal and permanent pycnoclines, oxygen exchange with the atmosphere becomes a lesser effect and photosynthetic oxygenation becomes relatively more important. The negative AOU trough or core is formed as a result of greater oxygen concentration in these waters relative to that in waters above or below the two pycnoclines. Even though photosynthesis apparently has a greater effect than diffusion in the trough, over the total photic zone throughout the summer oxygen exchange has the greater effect. Pytkowicz (1964) has shown that atmospheric exchange almost doubles photosynthetic input from April to September off Oregon.

Where the seaward limit of the negative AOU trough is, and where the beginning of the in situ subsurface chlorophyll and productivity maximum (Anderson, 1969) lies, is not known. Undoubtedly there are no clear-cut boundaries. My data shows some scattered amounts of chlorophyll at the bottom edge of the negative AOU core; however, my sampling was not detailed enough and might have missed the chlorophyll maximum of Anderson (1969).

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