Oceanic stratified euphotic zone as elucidated by 
\(^{234}\text{Th}:^{238}\text{U}\) disequilibria

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Abstract

Profiles of dissolved and particulate \(^{234}\text{Th}\) were determined at the VERTEX 2 and 3 stations off Manzanillo, Mexico, and at the VERTEX 4 station about 900 km north of Hawaii. By modeling the disequilibria between \(^{234}\text{Th}\) and \(^{238}\text{U}\) in the dissolved and particulate form, estimates of scavenging rates for \(\text{Th}\) from the dissolved to particulate phases, particle residence times, and the flux of \(\text{Th}\) via particle removal can be obtained. \(^{234}\text{Th}:^{238}\text{U}\) activity ratio profiles indicate that the euphotic zone can be separated into two layers: An upper oligotrophic layer characterized by low new production values, low net scavenging, and long dissolved \(^{234}\text{Th}\) residence times; and a subsurface eutrophic layer with higher new production values, more intense scavenging, and shorter dissolved \(^{234}\text{Th}\) residence times.

New production, rather than total primary production may determine net scavenging rates of reactive elements from oceanic surface waters. These results contribute to the emerging descriptions of the layered structure of oligotrophic euphotic zones and support the notion that this may be a general and ubiquitous feature of global stratified oligotrophic regimes. These layered systems can be structured not only in biological and nutrient parameters, but also in terms of the rates of chemical scavenging and elemental transport.

The layered structure of biological processes within stratified oceanic euphotic zones has been recognized for quite some time. Since Steele and Yentsch’s (1960) paper on the vertical distribution of chlorophyll, the subsurface chlorophyll maximum has received a great deal of attention and is now a well known oceanographic feature. Dugdale (1967) proposed a two-layer model, for oceanic euphotic zones, in which nutrient-limited phytoplankton populations overlie light-limited populations. Venrick (1982) reported two distinct floral assemblages associated with each of these layers, which also seem to be differentiated ecologically in terms of competition and predation. Herbland et al. (1985) showed a strong stratification in size classes of photosynthetic organisms (especially <1 \(\mu\)m) of the equatorial Atlantic, with the major shift in size spectra occurring at or near the base of the mixed layer. Recently, the presence of stratified systems in meso- and oligotrophic regimes has been further interpreted in terms of the concepts of Dugdale and Goe ring (1967) and Eppley and Peterson (1979) regarding “new” and “regenerated” production (Harrison et al. 1983; Knauer et al. 1984; Jenkins and Goldman 1985). Such a stratified euphotic zone can be visualized as an oligotrophic layer overlying a eutrophic layer which decays with depth to a classical middepth aphotic system. After winter mixing, the euphotic zone becomes stratified in terms of temperature, salinity, and oxidized nutrients. The upper wind-mixed layer is well lit and tightly coupled with respect to nutrient cycling. By this we mean that practically all production within this layer is thought to be maintained by recycling. In this layer, new production is very low (about 5% of total production: Eppley and Peterson 1979), and nutrients supplied through winter mixing are depleted through the sinking of large particles such as marine snow and fecal pellets. In contrast, nutrient cycling in that portion of the euphotic zone below the mixed layer is less tightly coupled. There is a greater supply of oxidized nutrients by vertical mixing, and new production is much higher in this region (about 30% of total production). Consequently the flux of particulate organic carbon (POC) from this layer is much greater.

This stratified scenario, as proposed by Knauer et al. (1984) and Small and Knauer (pers. comm.), is based primarily on measurements of primary production, zoo-

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1 This research was supported by National Science Foundation grants OCE 79-23322, OCE 79-19928, and OCE 82-16672.
plankton grazing, fecal pellet production, and sediment trap data. Evidence emerging from these studies suggests that, although the majority of the primary production generally occurs in the surface mixed layer of oligotrophic waters, the POC flux is negligible immediately below this layer.

In contrast, the euphotic zone below the mixed layer has lower primary production; however, it appears to have substantial new production as evidenced by the POC flux at the base of this zone. Thus the euphotic zone during this time of year seems to be structured inversely with respect to new and total primary production.

Previous studies in which $^{234}\text{Th} : ^{238}\text{U}$ disequilibria have been used to calculate residence times for dissolved and particulate $^{234}\text{Th}$ have shown dramatic differences in scavenging intensity and particle transport processes between oligotrophic and eutrophic regimes. A natural extension of this disequilibrium approach is to the study of scavenging intensity and particle transport processes within a stratified system.

Numerous investigators have taken advantage of $^{234}\text{Th} : ^{238}\text{U}$ disequilibria to study scavenging processes. Pioneering work with total $^{234}\text{Th} : ^{238}\text{U}$ ratios was done by Bhat et al. (1969) and others (Matsumoto 1975; Knauss et al. 1978; Kaufman et al. 1981). Subsequent investigators have determined Th:U ratios in both dissolved and particulate forms (McKee et al. 1984; Santachi et al. 1979; Bacon and Anderson 1982). More recently Coale and Bruland (1985) have also demonstrated the utility of $^{234}\text{Th} : ^{238}\text{U}$ disequilibria for the eutrophic California Current system, an area of minimal abiogenic particle input. Using dissolved and particulate fractions, they showed that the scavenging of Th from dissolved to particulate form varies as a function of primary production. They also suggested that the rate of particle removal was determined by the types and abundances of grazing zooplankton present. In a similar manner Bruland and Coale (in press) used $^{234}\text{Th} : ^{238}\text{U}$ disequilibria to determine variations in scavenging rate (dissolved to particulate) in surface waters throughout a variety of oceanographic regimes. These results indicate more rapid scavenging of dissolved Th in areas of higher mixed-layer productivity (coastal and equatorial divergence stations) and much less intense scavenging in oligotrophic and mesotrophic regimes.

Whereas Coale and Bruland (1985) observed that the scavenging intensity of $^{234}\text{Th}$ was proportional to total primary production within the California Current, Bruland and Coale (in press) emphasized the dependence of scavenging intensity on particulate organic carbon flux or new production (rather than total production). However, vertical profiles in the oligotrophic regimes, composed of relatively few samples from the euphotic zone, failed to resolve any significant structure in scavenging rate within the upper 100 m. Within the California Current system the euphotic zone is contained within the mixed layer and $^{234}\text{Th} : ^{238}\text{U}$ disequilibria, as driven by primary production or particle flux, are relatively uniform. These $^{234}\text{Th} : ^{238}\text{U}$ ratios increase toward equilibrium at depths just below the mixed layer. New production is thought to vary as a function of total production and in similar ratios throughout this regime (new production/total production = 20–30%; Eppley and Peterson 1979; Knauer and Martin 1981). Because total primary production and new production covary in the California Current, $^{234}\text{Th}$ scavenging could not be unequivocally related to either one of these variables in this region. In contrast, in mesotrophic or oligotrophic systems the euphotic zone may extend below the mixed layer, dividing the euphotic zone into a well-lit upper layer where nutrients and carbon are efficiently recycled and a lower layer more characteristic of a coastal eutrophic regime. A system that is structured with respect to total and new production and particle flux gives us a unique opportunity to evaluate the dependence of scavenging rate on these parameters.

For simplicity we have chosen to treat our stations as two-layered systems. If the scavenging rate is proportional to new production, which we will treat as being quantitatively equivalent to particle flux (over sufficiently long time intervals), then the region of most intense scavenging, as determined by $^{234}\text{Th} : ^{238}\text{U}$ disequilibria, will occur within the lower layer. On the other hand,
if scavenging rate is proportional to total production (rather than new production), then the region of most intense scavenging will occur within the upper layer.

In this paper we present profiles of $^{234}\text{Th}$ : $^{238}\text{U}$ ratios determined for both the dissolved and particulate fractions on VERTEX 2 and VERTEX 3 cruises off Manzanillo, Mexico, and VERTEX 4 in the central North Pacific. In an attempt to more fully characterize the areas of high biological particle production in terms of scavenging and particle transport and their relation to new and total production, we sampled the oligotrophic euphotic zone in more detail. Sampling the upper water column on VERTEX 2 gave us our first indication of increased scavenging immediately below the mixed layer. On VERTEX 3 and 4, we obtained more detailed profiles of the upper water column.

We thank the crew and officers of the RV Wecoma and Cayuse, G. Smith for assistance in VERTEX 4 sample collection, D. Beals for assistance in radiochemical processing and analysis of VERTEX 4 samples, and G. Gill for comments on this manuscript.

**Sampling and analysis**

Seawater samples for this study were collected on three occasions from the VERTEX 2 and VERTEX 3 stations about 480 km west-southwest and 720 km southwest of Manzanillo, Mexico, in the eastern tropical North Pacific and from the VERTEX 4 station about 900 km north of Hawaii (Fig. 1). Shipboard sample processing was used for $^{234}\text{Th}$ to minimize in-growth and decay corrections. Collections were made with 30-liter, Teflon-coated Go-Flo samplers (General Oceanics, Inc.). The Go-Flo bottles were pressurized with filtered nitrogen gas, and the seawater was passed via Teflon tubing through a 145-mm (diam), 0.3-μm pore-size Nuclepore membrane filters supported in a Teflon filter sandwich. Dissolved samples were collected in 20-liter Cubitainers and acidified with 50 ml of concentrated HCl. Filters for particulate analysis were stored frozen until processed.

For analysis, dissolved samples are spiked with a $^{230}\text{Th}$ yield tracer, equilibrated, and coprecipitated with Fe(OH)$_3$. The Fe(OH)$_3$ fraction is collected by filtration on glass-fiber filters and dissolved in HCl. Thorium isotopes are separated and purified with a series of anion exchange columns. Particulate samples are spiked with tracer and processed with bomb digestion (Eggimann and Betzer 1976) and subsequent anion exchange procedures similar to those used for the dissolved samples. Final Th fractions are electroplated on platinum disks. Thorium activities are determined by alpha-counting with calibrated, silicon surface barrier detectors used to determine yield, followed by beta-counting with calibrated, low background, gas flow detectors operated in anticoincidence with a common guard. Uranium activities, collectively a conservative property of seawater (Turekian and Chan 1971), are not determined directly but are calculated for each sample with the empirical relationship

$$^{238}\text{U} \text{dpm liter}^{-1} = 0.07081 \times \text{salinity}$$

as determined by Ku et al. (1977). Using these techniques, our analysis of four samples of deep water from the central North Pacific, stored acidified for 1 yr, yielded a mean $^{234}\text{Th} : ^{238}\text{U}$ activity ratio of 1.008±0.013. This is in excellent agreement with the expected equilibrium value.

**Scavenging model**

Due to the relatively short half-life of $^{7}\text{H} \text{Th}$, its high particle reactivity, and its ubiquitous production by the alpha decay of its conservative parent $^{238}\text{U}$, $^{234}\text{Th} : ^{238}\text{U}$
disequilibrium has been shown to be an ideal tracer to quantify rates of particle scavenging and transport processes. The $^{234}$Th half-life of 24.1 d and the analytical error associated with current beta-counting techniques limit the utility of this tracer to processes with time scales between 1 and 300 d.

The $^{234}$Th:$^{238}$U scavenging model of Coale and Bruland (1985) can be used to calculate dissolved and particulate residence times and the particulate flux for Th in oceanic euphotic zones. Briefly, we exploit the fact that the particle reactive daughter, $^{234}$Th, is produced in nearly uniform quantities throughout the water column by the alpha decay of its nonparticle reactive, conservative parent, $^{238}$U. We assume advection and diffusion of $^{234}$Th to be negligible with respect to vertical transport of $^{234}$Th via sinking particles and that the activity of $^{234}$Th is not changing significantly over the course of our observations (steady state). A mass balance for Th in the dissolved form can then be written:

$$J_{Th} = A_U \lambda_{Th} - A_{d,Th} \lambda_{Th}. \quad (1)$$

$A_U$ is the activity of $^{238}$U, $\lambda_{Th}$ is the decay constant for $^{234}$Th, and $A_U \lambda_{Th}$ is therefore the rate of production of $^{234}$Th by the decay of $^{238}$U. $A_{d,Th}$ is the activity of dissolved $^{234}$Th, $A_{d,Th} \lambda_{Th}$ is then the rate at which dissolved $^{234}$Th is lost due to radioactive decay. $J_{Th}$ represents the scavenging, or flux, of dissolved $^{234}$Th to the particles. For particulate $^{234}$Th a similar mass balance can be written:

$$P_{Th} = J_{Th} - A_{p,Th} \lambda_{Th}. \quad (2)$$

$J_{Th}$ (from Eq. 1) is the source of particulate $^{234}$Th; $A_{p,Th}$ is the activity of particulate $^{234}$Th, $A_{p,Th} \lambda_{Th}$ is the rate at which particulate $^{234}$Th is lost due to radioactive decay and $P_{Th}$ is the rate at which particulate $^{234}$Th is lost via sinking or grazed particulates. Since $J_{Th}$ and $P_{Th}$ represent the non-radioactive removal rates for both dissolved ($A_{d,Th}$) and particulate ($A_{p,Th}$) $^{234}$Th reservoirs, the mean residence times for $^{234}$Th can be defined for both the dissolved ($\tau_d$) and particulate ($\tau_p$) phases:

$$\tau_d = A_{d,Th}/J_{Th}, \quad \tau_p = A_{p,Th}/P_{Th}. \quad (3)$$

By assuming that the scavenging from the dissolved to particulate form follows first-order kinetics, we can define a scavenging rate constant $\Psi_d$, where

$$J_{Th} = A_{d,Th} \Psi_d. \quad (5)$$

Similarly, for particulate removal, we define a suspended particulate removal rate constant, $\Psi_p$.

$$P_{Th} = A_{p,Th} \Psi_p. \quad (6)$$

**Results**

The locations of VERTEX 2, 3, and 4 stations are shown in Fig. 1; vertical profiles for temperature, nitrate, plant pigments, and dissolved, particulate, and total $^{234}$Th:$^{238}$U activity ratios for the upper 300 m of the water columns are presented in Fig. 2. The $^{234}$Th and $^{238}$U profiles for the upper 300 m of the water column are presented in Table 1 together with the model-derived parameters $A_{d,Th}$,$A_U$, $A_{p,Th}$,$A_{U}$, $A_{d,Th}$,$A_{U}$, $\tau_d$, $\Psi_d$, $\tau_p$, $\Psi_p$, $J_{Th}$, and $P_{Th}$. Occasionally, $^{234}$Th activities exceed $^{238}$U activities. In some cases this produced rather unusual (negative) values for $\tau_d$, $\Psi_d$, $\tau_p$, $\Psi_p$, $J_{Th}$, and $P_{Th}$. With respect to our model, negative values would imply a supply of $^{234}$Th other than from the decay of $^{238}$U. Such values may indicate sinking and remineralization of particles carrying $^{234}$Th in a region close to secular equilibrium, thereby increasing total $^{234}$Th activities above the activity of $^{238}$U. It is our opinion that in most cases these negative values are artifacts reflecting the analytical uncertainty in attempting to discriminate a system that is very close to equilibrium. The errors, given in Table 1 and depicted in Fig. 2 represent $\pm 1$ SD from the mean where replicate values (from samples or analyses) were available. For single determinations, analytical uncertainty was obtained by propagation of alpha- and beta-counting errors and the corresponding uncertainties in background, detector blanks, and efficiencies as well as errors in all pipet deliveries, yield tracer calibrations, volumes, and time intervals used in calculating final $^{234}$Th activities.
Stratified Th : U disequilibria

Fig. 2. Vertical profiles of temperature, nitrate, pigments, and $^{234}\text{Th} : ^{238}\text{U}$ ratios for VERTEX 2, 3, and 4. For each station, upper horizontal lines delineate the base of the mixed layer and lower horizontal lines delineate the base of the euphotic zone. The vertical line at $^{234}\text{Th} : ^{238}\text{U} = 1$ represents radioactive equilibrium. The hatched area represents total $^{234}\text{Th}$ deficiency with respect to its parent $^{238}\text{U}$. 
Table 1. This table presents the measured, calculated, and model-derived parameters. The units are as follows: Depth (m); $A_U$, $A_{Th}$, $A_{Pb}$ (dpm liter$^{-1}$); the activity ratios are unitless; $A_{Th}$ represents total (dissolved + particulate) $^{234}$Th; $r_o$, $r_p$ (d); $\psi_o$, $\psi_p$ (d$^{-1}$); $J_{Th}$, $P_{Th}$ (dpm 1,000 liter$^{-1}$ d$^{-1}$). For this model $\Psi_o$ and $\Psi_p$ represent pseudo first-order scavenging rate constants and are described in the text. Units are d$^{-1}$.

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<th>Depth (m)</th>
<th>$A_U$</th>
<th>$A_{Th}$</th>
<th>$A_{Pb}$</th>
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<th>$\frac{J_{Th}}{A_{Th}}$</th>
<th>$\frac{J_{Th}}{A_{Pb}}$</th>
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Table 1. Continued.

| Depth (m) | $A_0$ | $\Delta A_{\text{in}}$ | $\Delta A_{\text{out}}$ | $\Delta A_{\text{in}}$ | $\Delta A_{\text{out}}$ | $\Delta A_{\text{in}}$ | $\Delta A_{\text{out}}$ | $\Delta A_{\text{in}}$ | $\Delta A_{\text{out}}$ | $\Delta A_{\text{in}}$ | $\Delta A_{\text{out}}$ | $\Delta A_{\text{in}}$ | $\Delta A_{\text{out}}$ |
|-----------|-------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 25        | 2.50  | 2.51±0.04     | 0.18±0.04     | 1.00±0.02    | 0.072±0.017  | 1.07±0.02    | -8.741       | -0.001       | -33          | -0.030       | -0.29         | -5.5          | VERTEX 4       |
| 40        | 2.49  | 2.31±0.11     | 0.17±0.01     | 0.93±0.04   | 0.067±0.004  | 0.99±0.04   | 447          | 0.002       | 412          | 0.002       | 5.2           | 0.40          |
| 50        | 2.49  | 2.04±0.07     | 0.70±0.01     | 0.82±0.03   | 0.082±0.004  | 0.90±0.03   | 158          | 0.006       | 29           | 0.035       | 13            | 7             |
| 60        | 2.48  | 1.36±0.05     | 0.38±0.01     | 0.55±0.02   | 0.154±0.005  | 0.70±0.02   | 42           | 0.024       | 18           | 0.055       | 32            | 21            |
| 75        | 2.48  | 1.60±0.04     | 0.47±0.01     | 0.64±0.02   | 0.192±0.005  | 0.84±0.02   | 63           | 0.016       | 41           | 0.025       | 25            | 12            |
| 90        | 2.47  | 1.74±0.02     | 0.33±0.01     | 0.71±0.01   | 0.132±0.004  | 0.84±0.02   | 83           | 0.012       | 28           | 0.035       | 21            | 12            |
| 100       | 2.47  | 1.68±0.03     | 0.33±0.01     | 0.68±0.01   | 0.134±0.008  | 0.81±0.03   | 74           | 0.014       | 25           | 0.040       | 23            | 13            |
| 125       | 2.46  | 2.28±0.00     | 0.20±0.01     | 0.93±0.00   | 0.083±0.003  | 1.01±0.00   | 440          | 0.002       | -307         | -0.003      | 5.2           | -0.66         |
| 150       | 2.46  | 2.17±0.10     | 0.26±0.01     | 0.88±0.04   | 0.105±0.005  | 0.99±0.04   | 263          | 0.004       | 298          | 0.003       | 8.3           | 0.86          |
| 175       | 2.45  | 2.51±0.10     | 0.17±0.01     | 1.03±0.04   | 0.068±0.004  | 1.09±0.10   | -1.409       | -0.001      | -25          | -0.040      | -1.8          | -6.6          |
| 200       | 2.45  | 2.30±0.10     | 0.13±0.01     | 0.94±0.04   | 0.053±0.003  | 1.00±0.04   | 568          | 0.002       | 374          | 0.003       | 4.1           | 0.34          |
| 250       | 2.43  | 2.28±0.19     | 0.08±0.00     | 0.94±0.08   | 0.033±0.001  | 0.97±0.08   | 335          | 0.002       | 42           | 0.024       | 4.3           | 1.9           |
| 500       | 2.41  | 2.36±0.07     | 0.09±0.01     | 0.98±0.03   | 0.036±0.002  | 1.02±0.03   | 1.710        | 0.001       | 78           | -0.013      | 1.4           | -1.1          |
| 1,000     | 2.44  | 2.49±0.08     | 0.11±0.01     | 1.02±0.04   | 0.044±0.002  | 1.07±0.04   | -1.663       | -0.001      | 23           | 0.043       | 1.5           | 4.5           |
| 1,500     | 2.45  | 2.04±0.07     | 0.11±0.01     | 0.83±0.03   | 0.047±0.002  | 0.88±0.03   | 175          | 0.006       | 14           | 0.073       | 12            | 8.4           |
In our estimates of $^{238}$U activities, we assigned an error of the order of 1% (1 SD) to the salinity determination (in which we have much greater confidence) and propagated it along with all other errors. This error is small with respect to the final uncertainties in our determinations. The average analytical errors (SD) for VERTEX 2 dissolved and particulate $^{234}$Th analyses were 6.7 and 7.5%. For VERTEX 3, they averaged 3.5 and 3.4%. For VERTEX 4, they averaged 4.6 and 5.9%. The time scales over which $^{234}$Th:$^{238}$U disequilibria can be used is limited by the accuracy and precision with which the $^{234}$Th:$^{238}$U activity ratio can be determined. As an example, Fig. 3 depicts dissolved residence time, $\tau_d$, as a function of the dissolved $^{234}$Th:$^{238}$U activity ratio: a 3.5% error (VERTEX 3) is incorporated in this calculation. This error has been used to construct error estimates about $\tau_d$ and is depicted as the hatched area in Fig. 3. As can be seen from this figure, the closer the system is to equilibrium, the more difficult it becomes to evaluate residence times reliably. For example a dissolved $^{234}$Th:$^{238}$U activity ratio of $0.90 \pm 0.03$ yields $\tau_d = 313$ d, but a range (±1 SD) of 223–462 d.

Measurements of light transmission using deck and submarine photometers at VERTEX 2, 3, and 4 indicate mixed-layer thicknesses for these stations of 40, 45, and 25 m (Fig. 2). The shallow VERTEX 4 mixed layer of 25 m is typical of summer stratification, whereas the deeper mixed layers at VERTEX 2 and 3 are characteristic of autumn. In all cases, the euphotic zone extended deeper than the mixed layer, allowing slight illumination of nutrient-rich waters below.

Primary production at VERTEX 2, 3, and 4 is relatively uniform throughout the mixed layer and, in general, decreases monotonically with depth (Knauer et al. 1984). In sediment trap collections from the 0- to 40-m layer, no resolvable detrital flux was observed. However, a significant flux was observed in sediment traps beneath the euphotic zone for all stations. New production as a percentage of the 40–100-m primary production at the VERTEX 2 site, for example, was 15% in terms of carbon—a percentage slightly less than those in eutrophic regions (Knauer et al. 1984; Small and Knauer pers. comm.). Furthermore, Small and Knauer (pers. comm.) found that fecal pellets from the more abundant, large (200–2,000 μm) microcrustaceans in the lower layer at the VERTEX 2 location represented slightly over 4% of the primary carbon production in the lower layer, but 30% of the trap-estimated carbon flux from this layer. Because the total particulate carbon flux out of the 0–40-m layer was immeasurably small and no fecal pellets were seen in the 30-m trap, the fraction due to fecal pellet flux was undefined. Those pellets released by zooplankton of any size in the upper layer must have been fragmented and recycled there.

Discussion

Important conclusions and hypotheses can be drawn from these observations. First, the upper layer is tightly coupled. Essentially all carbon and nitrogen fixed in this layer is consumed and recycled within it. Second, new production is a prominent component of primary production in the lower layer. Third, due to the sharp nutri-
Stratified Th : U disequilibria

Our $^{234}$Th:$^{238}$U data, in general, are consistent with these observations and can be used to further expand the concept of stratified euphotic systems with respect to elemental scavenging.

Dissolved scavenging — $^{234}$Th : $^{238}$U disequilibria integrated over the depth of the mixed layer yield dissolved $^{234}$Th residence times of 52, 62, and $>320$ d for VERTEX 2, 3, and 4. These observations are consistent with other calculations of oligotrophic mixed-layer residence times (Bruland and Coale in press). However, in the region immediately below the mixed layer, residence times for dissolved $^{234}$Th drop precipitously to minima of 8, 25, and 42 d for VERTEX 2, 3, and 4. These correspond to scavenging rate constants $\Psi_q$ of 0.13, 0.040, and 0.024 d$^{-1}$, which are characteristic of the coastal and eutrophic scavenging rate constants associated with high production regimes (Coale and Bruland 1985). Moreover, these results indicate that net scavenging rates are more closely related to new production rather than to total production.

It is important to make a distinction here between net and gross scavenging. The combination of high productivity and negligible particle flux for the mixed layer implies a high degree of in situ recycling within this layer. Recycling processes are a result of metazoan and microbial oxidative decomposition and dissolution of particulate phases. It is possible, and even likely, that gross scavenging of $^{234}$Th in the upper layer is considerably higher than in the lower layer, but metazoan and microbial particle destruction effectively recycles this particulate Th back into solution so that a low net removal is observed.

The net flux of $^{234}$Th from the dissolved to particulate phase ($J_{Th}$) is higher in the lower euphotic layer than in the upper layer, giving rise, in every case, to the pronounced minimum in dissolved phase $^{234}$Th : $^{238}$U ratios in the lower layer (Fig. 2). This minimum coincides with greater particle abundance in the lower layer, greater total particle flux out of the lower layer, and greater partitioning of the particle flux of the lower layer into fecal pellet flux.

Within the mixed layer, all parameters except light are relatively uniform and evenly distributed about a depth-integrated mean. However in the lower layer there are gradients of nitrate, light, temperature, and density so that an integrated mean of $^{234}$Th is no longer representative of scavenging throughout this layer. The lower layer is highly stratified. Complex ecological and biogeochemical processes are structured over this gradient. The processes that control $^{234}$Th scavenging within this region are complex and can lead to large variations in scavenging rate (Table 1). In every case the minimum in dissolved $^{234}$Th activities, the minimum in dissolved $^{234}$Th residence time, and the maximum in scavenging rate and flux for the conversion of dissolved to particulate phases corresponds closely with the depth of the subsurface pigment maximum (Fig. 2). A subsurface pigment maximum in the euphotic zone is a well documented and prominent feature of both Pacific and Atlantic oligotrophic regimes (e.g. Hayward and McGowan 1985; Takahashi and Hori 1984; Anderson 1969; Platt et al. 1983). We believe that the bulk of the new production and elemental scavenging are fundamentally linked in some way to this pigment maximum.

Particle removal — In every case we observe greater integrated removal of particulate $^{234}$Th ($P_{Th}$) in the lower layer than in the upper layer (Table 1). This finding is also consistent with the observations that particulate flux out of the euphotic zone occurs principally from the lower layer (Knauer et al. 1984; Small and Knauer pers. comm.). With the exception of VERTEX 4, particulate $^{234}$Th residence times are longer in the lower layer. These longer particle residence times in the lower layer during VERTEX 2 and 3 seem contrary to the fact that particulate flux is greater from the lower layer than from the upper layer. However, particulate residence time is a function of removal rate ($P_{Th}$) as well as the activity, or
Table 2. Sediment trap and model-derived estimates of $^{234}$Th flux (dpm m$^{-2}$ d$^{-1}$).

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<tr>
<th>MLML* trap sample or depth integral</th>
<th>Particulate $^{234}$Th flux</th>
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<tr>
<td>VERTEX 2</td>
<td></td>
</tr>
<tr>
<td>MLML 30-m trap</td>
<td>835±45†</td>
</tr>
<tr>
<td>30-m integrated $P_{Th}$</td>
<td>570</td>
</tr>
<tr>
<td>MLML 120-m trap</td>
<td>1,878±48</td>
</tr>
<tr>
<td>120-m integrated $P_{Th}$</td>
<td>1,222</td>
</tr>
<tr>
<td>VERTEX 3</td>
<td></td>
</tr>
<tr>
<td>MLML 80-m trap</td>
<td>1,505±50†</td>
</tr>
<tr>
<td>80-m integrated $P_{Th}$</td>
<td>1,500</td>
</tr>
<tr>
<td>MLML 120-m trap</td>
<td>730±14</td>
</tr>
<tr>
<td>120-m integrated $P_{Th}$</td>
<td>1,861</td>
</tr>
<tr>
<td>VERTEX 4</td>
<td></td>
</tr>
<tr>
<td>MLML 150-m trap</td>
<td>671</td>
</tr>
<tr>
<td>150-m integrated $P_{Th}$</td>
<td>630</td>
</tr>
</tbody>
</table>

* Moss Landing Marine Laboratories.
† Samples in which large numbers of killed zooplankton were not completely removed before analysis; therefore they are thought to be artificially high in $^{234}$Th. Trap deployment depths do not necessarily correspond to depths of upper and lower euphotic zones for these stations.

size, of the particulate reservoir. Coale and Bruland (1985) suggested that particulate removal is controlled by the types and abundances of grazing zooplankton present. At the VERTEX 2 and 3 sites, Small and Knauer (pers. comm.) observed greater numbers of large zooplankton in the lower euphotic layers than in the upper layers. These observations suggest that particulate $^{234}$Th residence times should be shorter in the lower layer, not longer. Particulate $^{234}$Th residence times at the VERTEX 2 and 3 stations seem to vary mainly as a function of the size of the particulate $^{234}$Th reservoir. In all cases the activity of particulate $^{234}$Th is greater in the lower layer and coincident with a large pigment maximum; this is also a region in which greater suspended particulate concentrations were observed.

The POC maximum was not necessarily coincident with the pigment maximum at the stations for which we have POC data (VERTEX 2 and 4). For VERTEX 2, integrated mixed-layer and lower-layer POC values were 44 and 45 µg C liter$^{-1}$, respectively, with a maximum of 64 µg C liter$^{-1}$ at 60 m. For VERTEX 4, integrated mixed- and lower-layer POC values were 30 and 29 µg C liter$^{-1}$, respectively, with a maximum of 53 µg C liter$^{-1}$ at 50 m (G. Knauer et al. pers. comm.). Pigment maxima for VERTEX 2 and 4 occurred at 50 and 90 m. In both cases the $^{234}$Th scavenging rate is greatest in or near the pigment maximum and is not necessarily associated with the particle maximum.

The VERTEX 2 and 3 stations both show a lower, but significant, flux of $^{234}$Th from the upper layer via particle removal ($P_{Th}$). This finding is somewhat contrary to the sediment trap and fecal pellet observations of Knauer et al. (1984) and the fact that some type of upper-layer particle removal process is required to both establish the two-layer system initially and to maintain $P_{Th}$ as observed with water-column $^{234}$Th disequilibria. This apparent discrepancy needs to be reconciled. Knauer et al. (1984) and Small and Knauer (pers. comm.) could resolve no fecal pellet flux from the 0- to 40-m depth interval; however, a large number of dead zooplankton (swimmers, killed by the trap preservative) were observed in the traps. Killed zooplankton were not quantitatively removed in samples from particle interceptor traps (PITS) analyzed for $^{234}$Th; thus, the $^{234}$Th flux values could have been artificial. Sediment trap results and model-derived estimates of $^{234}$Th flux for VERTEX 2, 3, and 4 are given in Table 2. During VERTEX 3, the shallowest trap (80 m) was set 35 m below the mixed layer so we have no direct evidence to account for the apparent discrepancy in water-column-derived $P_{Th}$ and trap-measured $P_{Th}$. We can suggest, however, that particulate $^{234}$Th may be transported out of this layer by large, vertically migrating zooplankton. The latter scenario would serve to short-circuit particle transport from this layer.

Some evidence supports this active transport scenario. The pelagic red crab *Pleuroncodes planipes* was a dominant component of the meroplankton during VERTEX 2, having been observed in net tows in the mixed layer and the lower euphotic zone. *Pleuroncodes planipes* is known to inhabit waters in this area from the surface to 300 m. The fecal pellets of this organism were conspicuous components of the trap flux at 120 m but were absent from the 30-m trap. If micronectonic organisms such as *P. plani-
zones appear to structure elemental scavenging and particle transport and may be a feature of oligotrophic euphotic zones in general. Data for this study reflect only summer and autumn conditions. Due to the seasonally variable nature of stratification, we would expect to see seasonally variable scavenging and particle flux from these layers as well.

Conclusions

$^{234}$Th : $^{238}$U disequilibrium data can be used to elucidate and support the concept of stratified oceanic euphotic zones. Moreover, $^{234}$Th : $^{238}$U disequilibria can be used to describe oceanic elemental scavenging and particle transport rates within these stratified systems. Disequilibrium data indicate that net rates of particle reactive elemental transfer from the dissolved to particulate phase are low in the oligotrophic mixed layer. Scavenging and particle transport rates are highest in or near the pigment maximum associated with the lower euphotic layer of the two-layer system. The rates then generally decrease to aphotic midwater values. Gross rates of elemental scavenging have yet to be assessed. Differences in scavenging between upper and lower layers suggest that net rates of elemental scavenging vary as a function of new production rather than total production. Stratified euphotic zones appear to structure elemental scavenging and particle transport and may be a feature of oligotrophic euphotic zones in general. Data for this study reflect only summer and autumn conditions. Due to the seasonally variable nature of stratification, we would expect to see seasonally variable scavenging and particle flux from these layers as well.

References


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Submitted: 4 September 1985
Accepted: 5 August 1986