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## Particulate carbon and nitrogen fluxes and compositions in the central equatorial Pacific

Peter J. Hernes<sup>a,\*</sup>, Michael L. Peterson<sup>a</sup>, James W. Murray<sup>a</sup>, Stuart G. Wakeham<sup>b</sup>,  
Cindy Lee<sup>c</sup>, John I. Hedges<sup>a</sup>

<sup>a</sup>*School of Oceanography, University of Washington, Box 357940, Seattle, WA 98195-7940, USA*

<sup>b</sup>*Skidaway Institute of Oceanography, 10 Ocean Science Circle, Savannah, GA 31411, USA*

<sup>c</sup>*Marine Sciences Research Center, State University of New York, Stony Brook, NY 11794, USA*

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### Abstract

Mass, carbon, and nitrogen fluxes and carbon and nitrogen compositions were determined for particulate samples from plankton net tows, shallow floating sediment traps, intermediate and deep moored sediment traps, and sediment cores collected along 140°W in the central equatorial Pacific Ocean during the US JGOFS EqPac program. Mass, particulate organic carbon (POC), and particulate inorganic carbon (PIC) fluxes measured by the floating sediment traps during the Survey I (El Niño) and Survey II (non-El Niño) cruises follow essentially the same pattern as primary production: high near the equator and decreasing poleward. POC fluxes caught in free-floating traps were compared with alternative estimates of export fluxes, including <sup>234</sup>Th models, new production, and other sediment trap studies, resulting in widely differing estimates. Applying <sup>234</sup>Th corrections to the trap-based fluxes yielded more consistent results relative to primary production and new production. Despite factors of five differences in measured fluxes between different trap types, POC:<sup>234</sup>Th ratios of trap material were generally within a factor of two and provided a robust means of converting modeled <sup>234</sup>Th export fluxes to POC export fluxes. All measured fluxes decrease with depth. Trap compositional data suggest that mineral “ballasting” may be a prerequisite for POC settling. POC remineralization is most pronounced in the epipelagic zone and at the sediment–water interface, with two orders of magnitude loss at each level. Despite seawater supersaturation with respect to calcium carbonate in the upper ocean, 80% of PIC is dissolved in the epipelagic zone. Given the time-scale differences of processes throughout the water column, the contrasting environments, and the fact that only 0.01% of primary production is buried, sedimentary organic carbon accumulation rates along the transect

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\* Corresponding author. Present address: Baruch Institute, The University of South Carolina, Columbia, SC 29208, USA. Tel.: + 1-803-777-1017; fax: + 1-803-777-3935.

E-mail address: pjhernes@biol.sc.edu (P.J. Hernes).

are remarkably well correlated to primary production in the overlying surface waters. POC to particulate total nitrogen (PTN) ratios for all samples are close to Redfield values, indicating that POC and PTN are non-selectively remineralized. This constancy is somewhat surprising given conventional wisdom and previous equatorial Pacific results suggesting that particulate nitrogen is lost preferentially to organic carbon. © 2001 Elsevier Science Ltd. All rights reserved.

*Keywords:* Geochemistry; Organic carbon; Inorganic carbon; Sediment traps; Carbonate;  $^{234}\text{Th}$ ; Central equatorial Pacific

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## 1. Introduction

Prior to the US JGOFS Equatorial Pacific (EqPac) Process Study, little was known about the organic biogeochemistry of the central equatorial Pacific, despite the global significance of carbon and nitrogen fluxes in the equatorial Pacific as a whole (Chavez and Barber, 1987). In addition to high fluxes, the central equatorial Pacific is characterized by meridional gradients in primary production (up to fourfold higher near the equator compared to the oligotrophic regions poleward of  $12^{\circ}\text{S}$  and  $12^{\circ}\text{N}$ ; Barber et al., 1996) and phytoplankton biomass due to equatorial upwelling (Chavez, 1989; Peña et al., 1990). Because of these unique characteristics of the region, we endeavored to study organic geochemical features throughout the entire water column and into the sediment.

In these studies, we sought both elemental- and molecular-level characterizations of particulate organic material (POM) sinking throughout the water column and into the sediment in order to study the dynamics and efficiency of carbon transfer. We also wanted to elucidate the processes in the interior of the ocean that affect preservation and ultimate burial of POM. Particles were intercepted at several levels, including plankton net tows near the sea surface, floating sediment traps at 105 m, moored sediment traps at  $\sim 1000$  and  $\sim 4000$  m, and sediment cores. The suite of analyses included elemental compositions, reported here, and molecular-level characterizations of carbohydrates (Hernes et al., 1996), lipids (Wakeham et al., 1997a), and pigments and amino acids (Lee et al., 2000) (see Wakeham et al. (1997b, 1999) for overviews of the molecular data). Carbon and nitrogen characterization of organic material (OM) serves as a powerful tool for placing constraints on, and identifying trends in OM processing and preservation (Reuter and Perdue, 1984). These trends can be further studied at the molecular level, which often reveals patterns not seen in the elemental data.

A major objective of the EqPac Process Study was to determine export fluxes from the epipelagic zone (Murray et al., 1992). In addition to the flux estimates presented here, a number of different estimates of export flux were made by other investigators, including a second set of floating sediment traps, several  $^{234}\text{Th}$  studies to measure and calculate particulate fluxes, multiple dissolved organic carbon (DOC) studies to determine DOC fluxes, and measurements of new production (NP) to determine net export fluxes. In an ideal steady-state system, particulate organic carbon (POC) export plus DOC export from the euphotic zone should equal NP. The use of so many techniques to quantify export flux offers the unique opportunity to compare these techniques (see also Quay, 1997).

## 2. Methods

### 2.1. Sample collection

Samples were collected on four cruises during the US JGOFS EqPac program. Ten drifting sediment trap samples were collected at 105 m depth from each of two survey cruises, Survey I (TT007: February–March 1992, El Niño conditions) and Survey II (TT011: August–September 1992, non-El Niño conditions), ranging from 5°S to 12°N latitude along 140°W longitude and a station at 12°S, 135°W. The floating indented rotating sphere (IRS) traps (Peterson et al., 1993, Fig. 1C) consisted of modified 0.68 m ID cylinders that had straight walls for 0.47 m which tapered down to 0.15 m ID at the collection chamber. The total height of the collection chamber was 1.32 m. In order to minimize water current “cells” or eddies within the collection chamber, each trap was equipped with four evenly spaced baffles (~2 cm tall consisting of ~1 cm squares) placed in the top cylindrical portion of the trap. This particular baffle arrangement was chosen after field testing of multiple configurations in Puget Sound, Washington (unpublished data). All traps were equipped with IRS valves in order to eliminate washout of particulate and dissolved samples, retain poison biocide treatments, and minimize contamination by swimmers (e.g. Lee et al., 1988; Coale, 1990; Michaels et al., 1990; Peterson and Dam, 1990). The floating array consisted of a single frame containing four such sediment traps giving a combined surface area of ~1.5 m<sup>2</sup>.

Prior to deployment, a 0.51 solution containing 50 mg l<sup>-1</sup> HgCl<sub>2</sub> and 50 g l<sup>-1</sup> NaCl in seawater was introduced into the bottom of the trap collection chamber (0.3 m high, 0.15 m ID). Approximately 10 ml of the initial brine was saved to measure initial concentrations of DOC so that leaching of organic carbon (OC) from collected particulate material could be assessed. Deployments were 1.5–3 d in length. The brine layer remained largely intact throughout deployment and retrieval (i.e. mixing was confined to ~1 cm above the initial brine layer), as confirmed by measuring centimeter-scale salinity profiles with a refraction salinometer. Upon retrieval, all traps were drained to the brine layer. The four collections were combined and passed through an 850-μm-mesh stainless steel sieve. No further attempts were made to remove zooplankton. Approximately 10 ml of Hg-treated supernatant from the combined sample was removed and filtered through a GF/F filter for comparison with initial concentrations of DOC, thus quantifying OC leaching from the particulate material. Both initial and final DOC samples were refrigerated and brought back to the laboratory for analysis. Particulate samples were split for multiple analyses. No attempts were made to determine the forms of carbonate minerals. The carbohydrate/CHN split was centrifuged in a tared centrifuge tube and the supernatant was discarded after measuring its salinity for salt correction. A wet weight of the tube and pellet was taken, and the pellet was freeze-dried. After reweighing the tube and dried pellet for determination of mass flux, the pellet was ground to pass through a 351-μm-mesh sieve. A salt correction was made from the measured supernatant salinity and the difference between the wet and dry weights of the pellet.

Plankton samples were collected with oblique vertical tows (generally between 0900 and 1600 h) of a 26-μm-mesh net from 0 to 100 m at most stations where floating sediment traps were deployed. In all cases, collected material was passed through an 850-μm-mesh stainless steel sieve. All plankton tow material was split as above and collected on 90 mm GF/A filters, from which material was scraped, freeze-dried, and ground to pass a 351-μm-mesh sieve. All plankton samples were

corrected for 3 wt% sea salt based on an average surface seawater salinity and a 50:50 water/particle content of the filtered material.

Yearlong trap deployments were made at 0°, 5°N, and 9°N from January 1992 (deployment cruise W9201B) through February 1993 (recovery cruise TT015) with moored IRS (~1000 m depth) and no valve control (NVC) (~1000 and ~4000 m depth) sediment traps equipped with single collection chambers (Peterson et al., 1993, Figs. 1A and B). Both the IRS and NVC traps consisted of cylinders 0.15 m in diameter and contained baffles at the top of the trap similar to the drifting traps. The height:diameter aspect ratio of the NVC trap was 11.0:1, while the aspect ratio above the IRS trap was 5.4:1. The IRS traps contained one poison diffuser (high-density polyethylene bottle with polypropylene closure) with ~400 g NaCl, ~400 mg HgCl<sub>2</sub>, and ~400 mg HgO. Sparingly soluble HgO was added as a buffer for long-term deployments, but had been entirely solubilized upon retrieval. The NVC traps contained two diffusers, each with ~400 g NaCl, ~400 mg HgCl<sub>2</sub>, and ~400 mg HgO, and a funnel secured at the bottom that enabled particles to pass through to the brine layer while minimizing resuspension and washout during retrieval. Upon retrieval, brine layers were confirmed by measuring a salinity profile. All samples were then handled as described above for floating sediment traps. IRS traps from ~1000 m ended collection prematurely, whereas those deployed at ~4000 m failed mechanically.

Sediment samples were collected at 9°N, 5°N, 2°N, 0°, 2°S, 5°S, and 12°S on the benthic cruise (TT013) using a multi-corer (Barnett et al., 1984). Sediment cores from each station were sectioned, with corresponding depth horizons from multiple cores being combined, homogenized, and frozen. At a later date, combined samples from the sediment surface, 0–0.5 cm, and 10–12 cm horizons were thawed and split for multiple analyses.

## 2.2. Analytical methods

DOC concentrations were determined with a Shimadzu TOC-5000 analyzer. All samples were first acidified to pH ~1 with 6 N HCl and sparged with N<sub>2</sub> to remove DIC. Leached DOC was calculated by multiplying final DOC concentrations less initial concentrations times the volume of brine solution in the composite 105 m trap samples before splitting.

Calcium and magnesium concentrations were determined by ICP-MS (Elan 5000, Perkin-Elmer, Norwalk, CT) using standard addition and internal standardization. Calcium carbonate dissolution (or “precipitation” in many cases) was measured from changes in calcium concentrations in the initial and final brine solutions as back calculated from Ca:Mg ratios. Evaporation of samples during long-term storage precluded direct calcium comparisons.

Percent OC, total nitrogen (TN), total carbon (TC), and inorganic carbon (IC) (by difference) were determined in duplicate on all solid samples with a Carlo Erba CHN analyzer after the methods of Hedges and Stern (1984). OC was determined by vapor-phase acidification for all plankton tow and sediment trap samples. In-vial acidification was used for all sediment core samples. The precision for elemental analyses was ± 2% of the measured value, except for sediment OC and shallow trap IC (both ± 6%), and plankton IC (± 22%).

All <sup>234</sup>Th analyses on 105 m trap samples were carried out as outlined in Murray et al. (1996). <sup>234</sup>Th correction factors were based on the calculated <sup>234</sup>Th fluxes of Murray et al. (1996), which were determined by measuring the <sup>234</sup>Th deficiency in the upper water column at each station

relative to  $^{238}\text{U}$ .  $^{234}\text{Th}$  correction factors are simply the predicted  $^{234}\text{Th}$  flux divided by the measured  $^{234}\text{Th}$  flux.

### 3. Results

All results are listed in Tables 1–3.

Leaching of organic matter (OM) from collected trap material into the overlying water in traps is known to occur (e.g. Knauer et al., 1990; Hansell and Newton, 1994; Murray et al., 1996) and will lead to underestimates of POC flux unless taken into account. In the 105 m traps, more OC was leached (measured as excess DOC in the final brine water) during Survey II than Survey I (Table 1). Across the entire transect, OC leachate accounts for an average 11% of POC + OC<sub>leached</sub> during Survey I and 30% during Survey II. Since excess DOC measured in the traps undoubtedly entered as particulate material, measured POC plus leached OC yields our best estimate of total POC export flux, and all references to POC flux in the 105 m traps can be assumed to include the OC leachate.

Similar to OM leaching, particulate inorganic carbon (PIC) dissolution in sediment traps is also a concern (Thunell et al., 1983; Bé et al., 1985). Given the magnitude of the PIC collected in our traps, any significant dissolution should be measurable as decreased Mg:Ca ratios in the brine solutions. However, there were no systematic differences seen between the initial and final brine solutions (data not shown). The variability in the measured Mg:Ca ratios corresponds to a variability in the PIC flux of  $\pm 0.20 \text{ mmol PIC m}^{-2} \text{ d}^{-1}$ . Thus, no corrections were made to the PIC data.

$^{14}\text{C}$  primary production rates (from Barber et al., 1996) as well as mass, POC, and PIC fluxes of the floating traps all show similar qualitative patterns across the transect (Fig. 1), with higher fluxes (or rates) just north and south of the equator, and lower fluxes toward the ends of the transect. In both survey cruises, a local minimum occurred at the equator that was more pronounced during Survey II. Fluxes measured in the traps during Survey II were similar to or lower than during Survey I.

$^{234}\text{Th}$  correction factors for the 105 m IRS floating traps range from 0.26 to 30.9 with the highest values generally at the ends of the transect (Table 2). Correction factors less than one theoretically indicate overtrapping of  $^{234}\text{Th}$  while those greater than one indicate undertrapping (Buesseler, 1991; Murray et al., 1996).

There are pronounced decreases of particulate carbon fluxes with depth (Fig. 2). Our moored trap POC fluxes compare very well with those of Honjo et al. (1995) — our 9°N and 5°N fluxes at  $\sim 1000$  and  $\sim 4000$  m essentially bracket theirs at  $\sim 2200$  m (0.23 and 0.08 versus 0.11  $\text{mmol m}^{-2} \text{ d}^{-1}$  at 9°N; 0.61 and 0.30 versus 0.33  $\text{mmol m}^{-2} \text{ d}^{-1}$  at 5°N). The POC flux measured in their equatorial trap at  $\sim 3600$  m is slightly less than ours at  $\sim 3450$  m (0.36 versus 0.45  $\text{mmol m}^{-2} \text{ d}^{-1}$ ) and both are lower than the 1.34  $\text{mmol m}^{-2} \text{ d}^{-1}$  measured in our equatorial  $\sim 1000$  m trap.

The floating traps contained 5–38% POC, generally with higher values toward the ends of the transect and lower values near the equator (Table 1). Percent particulate total nitrogen (PTN) values parallel %POC, ranging from 0.5 to 7.4. %PIC, on the other hand, is higher near the equator than at the ends of the transect during Survey I and generally increases from north to south

Table 1

Bulk and elemental fluxes and compositions of particulate material from sediment traps and cores<sup>a</sup>

Sample location, depth	Particle flux <sup>b</sup>		Particle composition							Atomic ratio	
	Bulk	OM + CaCO <sub>3</sub>	OC	IC	TN	OC leached	OC	IC	TN	OC:TN	IC:OC
	(mg m <sup>-2</sup> d <sup>-1</sup> )		(mmol m <sup>-2</sup> d <sup>-1</sup> )			(wt%)					
<b>Shallow floating traps, all 105 m</b>											
<i>Survey I</i>											
12°N	37	30	1.46	0.12	0.08	49	24.1	3.97	3.21	8.72	0.16
7°N	51	54	0.58	0.43	0.05	22	10.7	10.2	1.65	9.27	0.95
5°N	193	193	2.11	1.51	0.19	18	10.8	9.41	1.78	9.02	0.87
2°N	610	661	4.13	5.73	0.42	11	7.22	11.3	1.32	8.73	1.56
1°N	736	656	4.53	5.51	0.50	4	7.08	9.00	0.67	8.61	1.27
0°N	558	562	2.50	5.02	0.27	0	5.38	10.9	0.62	9.09	2.03
1°S	560	579	3.74	4.93	0.46	5	7.57	10.6	1.17	7.79	1.40
2°S	115	123	1.05	0.99	0.12	7	10.3	10.4	1.75	8.31	1.01
5°S	56	57	1.09	0.35	0.13	16	20.0	7.58	3.58	6.92	0.38
12°S	37	36	0.76	0.21	0.08	22	19.2	6.92	3.22	7.16	0.36
<i>Survey II</i>											
12°N	37	46	1.39	0.18	0.17	16	37.6	5.75	7.40	6.70	0.15
9°N	28	25	1.79	0.07	0.11	58	32.5	2.87	6.14	7.07	0.09
5°N	169	135	3.56	0.67	0.37	20	20.3	4.73	2.92	7.65	0.23
2°N	234	202	4.83	1.43	0.30	49	12.8	7.32	2.23	8.28	0.57
1°N	105	83	2.01	0.50	0.18	33	15.4	5.79	2.36	7.53	0.38
0°N	85	79	0.67	0.65	0.07	10	8.47	9.21	1.18	8.89	1.09
2°S	167	144	2.62	1.00	0.26	29	13.4	7.16	2.33	7.21	0.54
3°S	245	211	3.37	1.48	0.33	22	13.0	7.23	2.17	7.98	0.56
5°S	174	145	2.15	1.02	0.23	16	12.5	7.03	1.81	7.93	0.56
12°S	98	92	1.14	0.69	0.11	16	11.7	8.42	2.17	8.67	0.72
<b>Moored sediment traps</b>											
<i>IRS traps</i>											
9°N, 1070 m	18	10	0.17	0.06	0.01	ND	11.2	4.18	1.15	11.33	0.37
5°N, 1020 m	51	32	0.51	0.19	0.06	ND	12.2	4.61	1.79	7.85	0.38
0°N, 955 m	136	91	0.98	0.67	0.10	ND	8.71	5.93	1.02	9.85	0.68
<i>NVC traps</i>											
9°N, 1070 m	27	17	0.23	0.11	0.03	ND	10.5	5.10	1.35	9.01	0.49
9°N, 4200 m	27	8	0.08	0.06	0.01	ND	3.60	2.70	0.38	10.97	0.75
5°N, 1020 m	84	58	0.61	0.43	0.08	ND	8.63	6.16	1.33	7.52	0.71
5°N, 3600 m	77	42	0.30	0.35	0.03	ND	4.74	5.39	0.48	11.42	1.14
0°N, 955 m	164	105	1.35	0.72	0.11	ND	9.89	5.26	1.31	8.72	0.53
0°N, 3459 m	85	55	0.45	0.44	0.04	ND	6.43	6.31	0.65	11.52	0.98

Table 1 (continued)

Sample location, depth	Particle flux <sup>b</sup>		Particle composition							Atomic ratio	
	Bulk	OM + CaCO <sub>3</sub>	OC	IC	TN	OC leached	OC	IC	TN	OC:TN	IC:OC
	(mg m <sup>-2</sup> d <sup>-1</sup> )		(mmol m <sup>-2</sup> d <sup>-1</sup> )				(wt%)				
<i>Sediment cores</i>											
9°N, 0–0.5 cm	3.56	ND	0.0020	0.000	0.0003	ND	0.677	0.01	0.110	7.19	0.02
9°N, 10–12 cm	ND	ND	ND	ND	ND	ND	0.409	0.00	0.070	6.85	0.00
5°N, 0–0.5 cm	34.8	ND	0.0063	0.324	0.0006	ND	0.217	11.2	0.026	9.69	51.5
5°N, 10–12 cm	ND	ND	ND	ND	ND	ND	0.081	10.8	0.011	8.21	134
2°N, 0–0.5 cm	36.2	ND	0.0099	0.307	0.0012	ND	0.330	10.2	0.045	8.49	30.9
0°N, 0–0.5 cm	41.1	ND	0.0081	0.350	0.0012	ND	0.238	10.2	0.042	6.65	43.1
0°N, 10–12 cm	ND	ND	ND	ND	ND	ND	0.122	10.3	0.017	8.42	84.7
2°S, surface	ND	ND	ND	ND	ND	ND	0.300	9.90	0.051	6.82	33.0
2°S, 0–0.5 cm	49.9	ND	0.0092	0.434	0.0014	ND	0.222	10.4	0.040	6.51	47.1
5°S, 0–0.5 cm	37.3	ND	0.0040	0.348	0.0005	ND	0.129	11.2	0.019	8.11	86.9
12°S, surface	ND	ND	ND	ND	ND	ND	0.190	6.86	0.037	5.93	36.2
12°S, 0–0.5 cm	12.6	ND	0.0023	0.060	0.0003	ND	0.218	5.73	0.028	9.13	26.3

<sup>a</sup>OM, organic material; OC, organic carbon; IC, inorganic carbon; TN, total nitrogen; IC, inorganic carbon; ND, not determined; DOC, dissolved organic carbon; CaCO<sub>3</sub>, calcium carbonate; (OC:TN)<sub>a</sub>, atomic organic carbon to total nitrogen ratio; IC:OC, inorganic carbon to organic carbon ratio.

<sup>b</sup>Bulk sediment accumulation rates are from DeMaster et al. (unpublished).

during Survey II. %PIC values range from 4 to 11.3, with 12% indicating pure CaCO<sub>3</sub>. In the moored traps, %POC and %PTN both decrease from the ~1000 m traps to the ~4000 m traps, going from 8.6–12.2% POC to 3.6–6.4% and 1.0–1.8% PTN to 0.38–0.65%. %PIC for all the moored traps varies from 2.7 to 6.3, with no consistent depth trends. In the sediment, %POC and %PTN are much lower than for the trap samples, ranging from 0.08 to 0.68% POC and 0.01 to 0.11% PTN. %PIC, on the other hand, is > 10 from 5°N to 5°S, about half that at 12°S, and negligible at 9°N.

(OC:TN)<sub>a</sub> ratios for all particulate samples range from 4.2 to 11.5 with most values between 6.5 and 9.0 (Tables 1 and 3). The lowest ratios were obtained from the plankton net tow samples, and the highest from the moored traps. IC:OC ratios for all particulate samples vary from 0 (9°N sediments) to 87 (5°S sediments). IC:OC ratios in the plankton net tows are all < 0.2. The floating trap samples range from 0.1 to 2.1, with higher ratios near the equator. IC:OC ratios in the moored traps vary from 0.4 to 1.1. Other than at 9°N, all sediment samples exhibit high IC:OC, reflecting the predominance of CaCO<sub>3</sub> preservation over POM preservation (Broecker and Peng, 1982).

Table 2  
Comparison of POC and  $^{234}\text{Th}$  fluxes and compositions for IRS (105 m) and PIT (100 m) trap material relative to new production<sup>a,b</sup>

	Uncorrected POC flux		$^{234}\text{Th}$ correction factor <sup>c</sup>		$^{234}\text{Th}$ -corrected POC flux		POC: $^{234}\text{Th}$ of trap material		New production <sup>d</sup> (mmol $\text{C m}^{-2} \text{d}^{-1}$ )	
	IRS	PIT	IRS	PIT	IRS	PIT	IRS	PIT		
	(mmol $\text{m}^{-2} \text{d}^{-1}$ )				(mmol $\text{m}^{-2} \text{d}^{-1}$ )		( $\mu\text{mol dpm}^{-1}$ )			
<i>Survey I</i>										
12°N	1.46	6.48	(12.5)	0.319	(18.3)	2.07	(29.1)	3.30	7.9	
9°N		6.87		0.373		2.56		2.15	3.8	
7°N	0.58	9.25	0.63	0.350	0.37	3.24	0.40	3.59	3.2	
5°N	2.11	14.6	(14.5)	0.265	(30.6)	3.86	(17.5)	2.21	5.1	
2°N	4.13	35.9		0.038	4.13	1.36		1.23	7.9	
1°N	4.53	14.9	0.26	0.172	1.18	2.56	0.82	1.79	3.0	
0°N	2.50		1.17		2.92		1.25		3.6	
1°S	3.74	12.0		0.192	3.74	2.30		1.21	4.8	
2°S	1.05	12.8	1.01	0.242	1.06	3.08	1.25	3.63	9.2	
5°S	1.09	3.40	2.21	0.488	2.41	1.66	2.86	1.98	6.6	
12°S	0.76	5.40	(30.9)	0.621	(23.5)	3.35	(25.4)	3.62	7.9	
Mean $\pm$ 1 SD	2.2 $\pm$ 1.5	12.2 $\pm$ 9.3	1.1 $\pm$ 0.7	0.3 $\pm$ 0.2	2.3 $\pm$ 1.4	2.6 $\pm$ 0.8	1.3 $\pm$ 0.9	2.5 $\pm$ 1.0	5.7 $\pm$ 2.2	
<i>Survey II</i>										
12°N	1.39	7.14	(13.3)	0.758	(18.5)	5.39	(17.3)	5.05		
9°N	1.79	8.79	4.6	0.629	8.22	5.51	5.61	3.75	5.3	
7°N		5.46		0.885		4.85		2.94	6.6	
5°N	3.56	15.1	3.5	0.568	12.5	8.56	5.41	3.72	6.6	
3°N		14.4		0.334		4.82		2.50	4.7	
2°N	4.84	33.4		0.625	4.84	21.9	7.84	7.84	33.0	
1°N	2.01	28.7	7.0	0.474	14.1	13.6	5.19	5.02	23.1	
0°N	0.67	6.38	(26.2)	1.02	(17.6)	6.49	(5.57)	2.06	19.1	
1°S		8.28				8.28		2.54	9.2	
2°S	2.62	14.6	3.2	0.339	8.39	4.95	4.74	2.80	13.9	
3°S	3.37	20.5		0.510	3.37	10.5		5.43	17.8	
5°S	2.15	29.0		0.505	2.15	14.7		5.79	7.9	
12°S	1.14	4.04	4.9	0.833	5.56	3.38	4.02	2.43	1.8	
Mean $\pm$ 1 SD	2.4 $\pm$ 1.3	15.1 $\pm$ 9.9	4.6 $\pm$ 1.5	0.6 $\pm$ 0.2	7.4 $\pm$ 4.2	8.7 $\pm$ 5.3	5.0 $\pm$ 0.7	4.0 $\pm$ 1.7	12.4 $\pm$ 9.2	

<sup>a</sup>Data in parentheses were not included in calculation of means — see text.

<sup>b</sup>IRS, indented rotating sphere; PIT, particle interceptor trap; POC, particulate organic carbon.

<sup>c</sup>The cylindrical PIT traps were deployed simultaneously with our traps, but on different arrays and have an area of 0.0039 m<sup>2</sup> and an aspect ratio of 8.0:1 (Murray et al., 1996).

<sup>d</sup>McCarthy et al. (1996).

Table 3  
Elemental compositions of plankton caught in net tows<sup>a</sup>

Location	Size fraction ( $\mu\text{m}$ )	OC	TN	IC	(OC:TN) <sub>a</sub>	IC:OC
		(wt%)				
<i>Survey I</i>						
5°N	26–850	30.5	5.77	2.19	6.64	0.07
2°N	26–850	31.7	7.02	0.80	4.88	0.03
0°N	64–300	24.8	5.65	1.50	4.87	0.06
0°N	300–850	30.2	7.49	3.62	4.23	0.12
2°S	26–850	19.6	3.67	1.12	5.93	0.06
<i>Survey II</i>						
9°N	26–850	36.3	7.91	4.03	4.84	0.11
5°N	26–850	32.2	6.06	3.06	7.13	0.10
2°N	26–850	16.7	2.36	1.18	6.90	0.07
0°N	26–850	22.4	4.12	3.73	6.98	0.17
2°S	26–850	20.2	3.20	2.08	7.07	0.10
5°S	26–850	23.0	4.10	2.90	6.30	0.13

<sup>a</sup>OC, organic carbon; TN, total nitrogen; IC, inorganic carbon; (OC:TN)<sub>a</sub>, atomic organic carbon to total nitrogen ratio; IC:OC, inorganic carbon to organic carbon ratio.

## 4. Discussion

### 4.1. Fluxes

#### 4.1.1. Meridional trends in fluxes

Comparisons across the north–south transect between <sup>14</sup>C primary production (PP) (Barber et al., 1996), calcification rates (Balch and Kilpatrick, 1996), particulate carbon fluxes as measured by sediment traps, and carbon accumulation in the sediment reflect a number of processes occurring in the water column (POC in Fig. 3 and PIC in Fig. 4). In this comparison we include data from the 105 m traps from this study and the corresponding 17 d collections from the ~3000 m traps of Honjo et al. (1995). The latter are used in place of ours because coverage along the transect by our moored traps is incomplete and fluxes for the two types of moored traps are in excellent agreement. This comparison shows a dip in PP near the equator that is reflected in the fluxes throughout the water column and into the sediment, with the single exception of the fluxes measured at ~3000 m simultaneously with the Survey I cruise (Fig. 3). If sediments are, in general, reflective of the overlying water column, then sediment accumulation rates may act as a proxy for the combined effects of POC and DOC fluxes measured during the survey cruises. With that possibility in mind, it is striking that the major features in PP are so well preserved at each depth along the transect in spite of the effects of horizontal transport seen in DOC profiles (Murray et al., 1994; Peltzer and Hayward, 1996) and predicted by models (Toggweiler, 1990; Feely et al., 1995).

In contrast to PP and POC fluxes, biogenic calcification rates (available only for Survey II) and PIC fluxes suggest more distortion of the surface signal (Fig. 4). The large PIC “spike” between 2°N

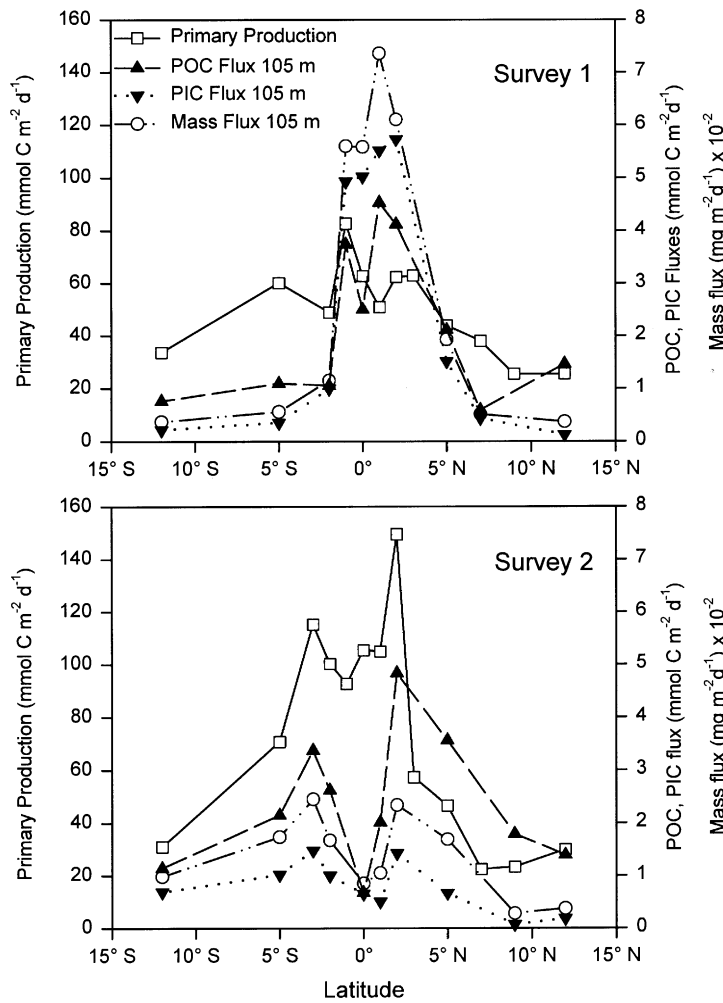


Fig. 1. Primary production (Barber et al., 1996) and measured fluxes of mass, POC, and PIC collected by drifting sediment traps at 105 m depth versus latitude.

and 2°S measured at 105 m during Survey I is also evident at ~3000 m, but is spread out between 5°N and 5°S in the sediment. The large dip near the equator in calcification rates and 105 m trap PIC fluxes during Survey II, however, is barely reflected at ~3000 m, and not at all in the sediment. In one sense, it is counterintuitive that there should be more distortion in PIC profiles than POC profiles since higher density PIC has the potential to sink faster than POC and if so, would be subject to less horizontal transport. Calcite dissolution is likely a factor. However, considering that POC losses in the 105–3000 m interval and 3000 m–sediment interval are as large or larger than PIC losses, the greater poleward spread in the PIC profiles is puzzling. Although time-scale differences in sampling could also be invoked, the tight coupling between the 17 d trap measurements at ~3000 m and the sediment suggests that the 3 d measurements at 105 m during the same period are also reasonably representative.

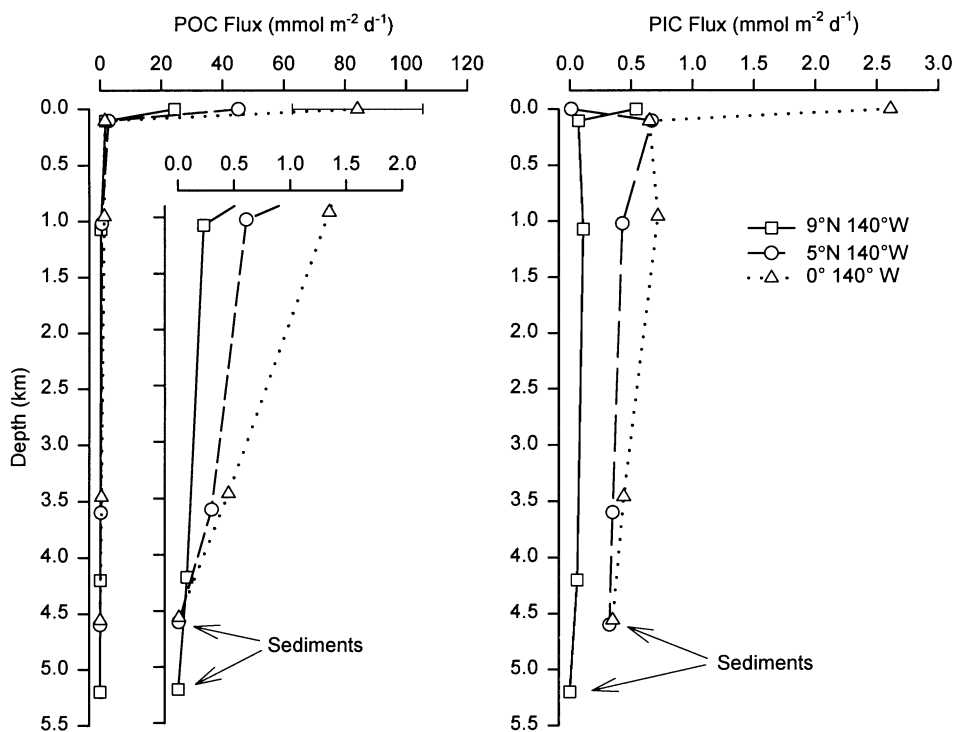


Fig. 2. Carbon fluxes versus depth at 0°, 5°N, and 9°N. Surface values are primary production from Barber et al. (1996) or calcification rates from Balch and Kilpatrick (1996). Deepest data points represent OC and IC accumulation rates in the sediments calculated from sediment accumulation rates of DeMaster (unpublished).

In contrast to PP estimates, the 105 m traps did not reflect the same increase in POC flux along the transect during Survey II relative to Survey I. Instead, POC fluxes for our two cruises are comparable. Honjo et al. (1995) also report that their moored traps from 5°N to 5°S collected similar amounts of material during both El Niño and post-El Niño periods in spite of the measured increase in PP during the latter. One explanation for the offset from PP is that currents (and therefore likely the lateral shear since the traps were drogued at the surface) at 105 m during Survey II were considerably higher than during Survey I (Kessler and McPhaden, 1995), thereby increasing the hydrodynamic biases of the trap collections. For instance, during Survey I, the equatorial undercurrent (EUC) was at 160 m — well below the IRS traps — and averaged about  $20 \text{ cm s}^{-1}$  (Murray et al., 1995). During Survey II, the EUC rose to 110 m depth and averaged about  $80 \text{ cm s}^{-1}$ . Thus, the 105 m traps during Survey II at times were likely experiencing currents more than four times those of Survey I. Coincidentally,  $^{234}\text{Th}$  correction factors (discussed below) for the 105 m traps during Survey II were a factor of four greater than Survey I (Table 2).

#### 4.1.2. Comparison to new production, $^{234}\text{Th}$ -modeled fluxes, other sediment traps

Quantification of new production and export fluxes of carbon from the euphotic zone is critically important to the EqPac study (Murray et al., 1992). Sediment traps are currently the only tool for

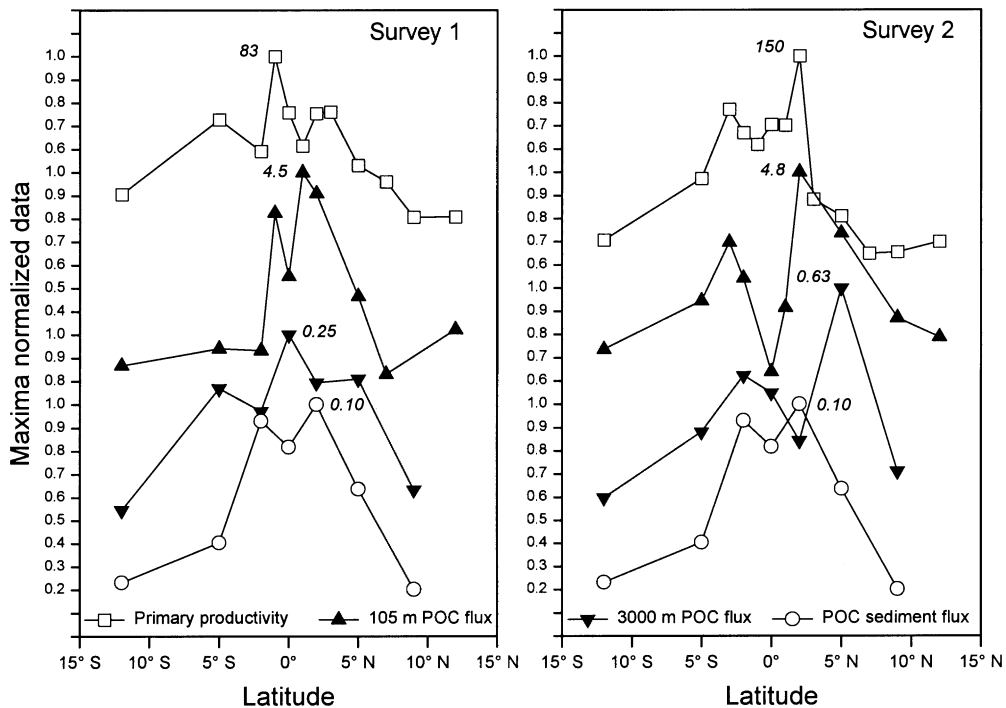


Fig. 3. Relative primary production (Barber et al., 1996), POC fluxes at 105 and  $\sim 3000$  m (Honjo et al., 1995), and POC accumulation rates calculated from sediment accumulation rates of DeMaster et al. (unpublished) versus latitude. Data are normalized to the maximum value in each transect. Ordinate scale is reset to 1.0 at each maximum, and the absolute magnitude ( $\text{mmol C m}^{-2} \text{d}^{-1}$ ) of each parameter is given next to its maximum.

direct collection and measurement of export flux, although sediment trap measurements are subject to several biases and artifacts (e.g. Butman, 1986; Buesseler, 1991; Gust et al., 1992). Therefore it is important to compare sediment trap-measured fluxes with indirect determinations, such as new production and  $^{234}\text{Th}$ -based export models.

In addition to the IRS floating traps at 105 m, other estimates of export fluxes conducted on the same or similar cruises included a set of floating particle interceptor traps (PIT) (Murray et al., 1996), new production integrated to the 0.1% light level ( $\sim 120$  m) (McCarthy et al., 1996; Murray et al., 1996), and two  $^{234}\text{Th}$ -based export calculations (Buesseler et al., 1995; Murray et al., 1996). The five different flux estimates showed a considerable range, varying by up to a factor of 10 (Fig. 5). In general, the IRS trap POC fluxes (uncorrected for  $^{234}\text{Th}$ ) and the  $^{234}\text{Th}$ -based POC flux calculations of Buesseler et al. (1995) track fairly closely and provide a lower estimate for POC export. In contrast, the new production measurements and PIT POC fluxes (uncorrected for  $^{234}\text{Th}$ ) of Murray et al. (1996) provide an upper estimate. This large range of fluxes, even when obtained by similar techniques, points out the difficulties in establishing accurate carbon flux measurements either directly with sediment traps or indirectly by other means. Further, an inherent problem with comparing these estimates is that time scales are much different — 1.5–3 d for floating traps, 24 h

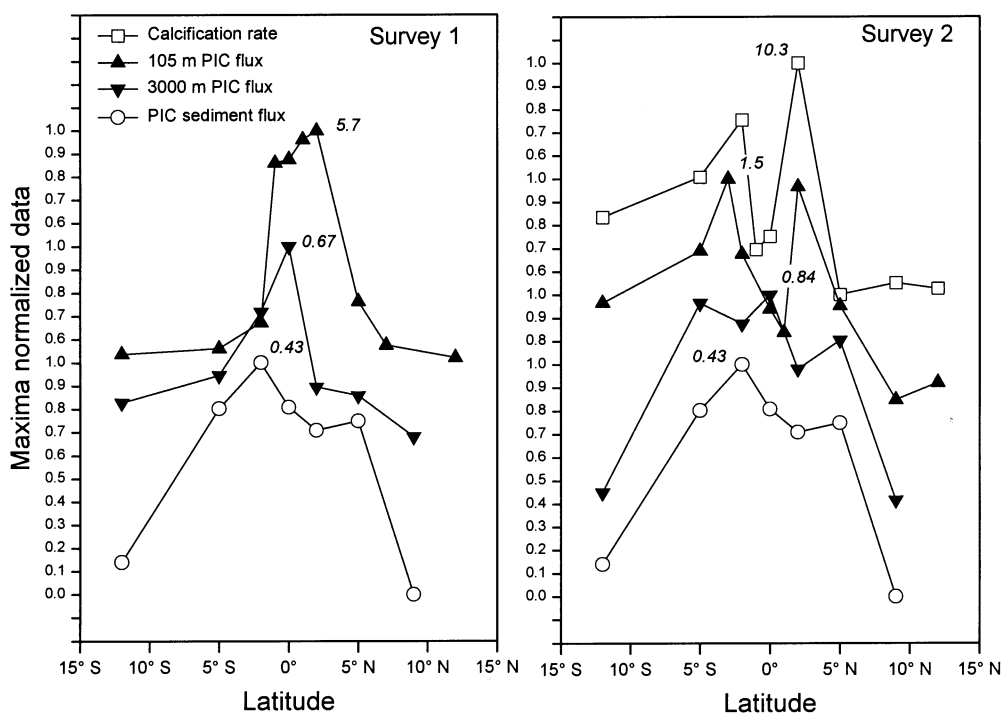


Fig. 4. Relative calcification rates (Survey 2 only; Balch and Kilpatrick, 1996), PIC fluxes at 105 and  $\sim 3000$  m (Honjo et al., 1995), and sediment PIC accumulation rates calculated from sediment accumulation rates of DeMaster et al. (unpublished) versus latitude. Data are normalized to the maximum value in each transect. Ordinate scale is reset to 1.0 at each maximum, and the absolute magnitude ( $\text{mmol C m}^{-2} \text{d}^{-1}$ ) of each parameter is given next to its maximum.

for new production, and 15–20 d for  $^{234}\text{Th}$ -based models. In general, however, if horizontal transport of DOC away from the equator was a significant export term in new production, then POC export measurements made by sediment traps and  $^{234}\text{Th}$ -based models should be consistently lower than new production estimates. For instance, Toggweiler (1990), Feely et al. (1995), and Peltzer et al. (1996) all suggested that more than half of new production is exported as DOC, while Murray et al. (1996), Hansell et al. (1997), Zhang and Quay (1997), and Quay (1997) concluded that DOC export is less than half of new production. The scatter in fluxes shown in Fig. 5 is sufficient to support either of these scenarios, including one of no DOC export.

The different approaches for estimating export flux have contrasting concerns. The debate surrounding  $^{234}\text{Th}$ -based estimates of POC export focuses largely on the POC: $^{234}\text{Th}$  ratios used to convert  $^{234}\text{Th}$  fluxes to POC fluxes, while controversy over sediment trap estimates generally centers on swimmers and the hydrodynamics of various trap designs in different current regimes. To address the latter, Eppley (1989) suggested the use of  $^{234}\text{Th}$  to calibrate sediment trap measurements. Murray et al. (1996) suggested that the ratio of the predicted  $^{234}\text{Th}$  flux to the  $^{234}\text{Th}$  flux measured by sediment traps could be used as a correction factor for any component of sediment trap material that showed proportionality with  $^{234}\text{Th}$ . On the surface, these floating

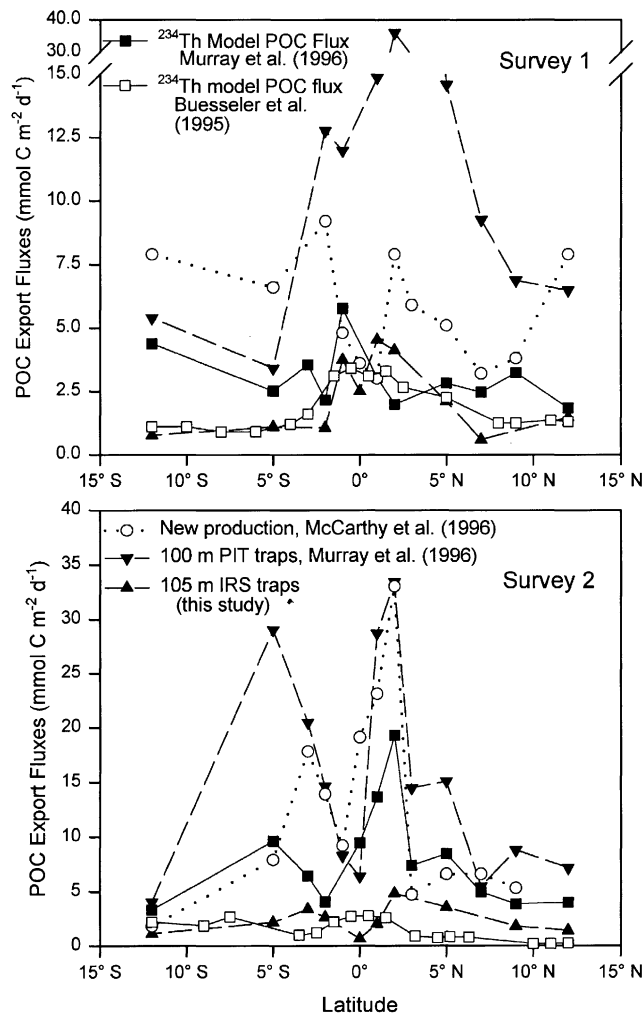


Fig. 5. POC fluxes collected in PIT traps at 100 m depth (Murray et al., 1996) and IRS traps at 105 m depth,  $^{234}\text{Th}$ -modeled POC export fluxes from Murray et al. (1996) and Buesseler et al. (1995), and new production (converted to  $\text{mmol C m}^{-2} \text{d}^{-1}$  using Redfield ratios) from McCarthy et al. (1996) versus latitude.

sediment traps might seem to be poor candidates for  $^{234}\text{Th}$  calibration, given the time-scale differences. However, the mathematical contribution of the traps to POC flux calculations is a POC: $^{234}\text{Th}$  ratio integrated over 1.5–3 d, which is actually a closer match to the 15–20 d for the  $^{234}\text{Th}$ -based models than the 1–5 h over which particles are typically filtered to obtain these ratios.

We are now in a position to conduct a more thorough comparison of the IRS and PIT design traps, with and without  $^{234}\text{Th}$  calibration. IRS and PIT traps deployments were simultaneous and originated from the same location, although the free-floating arrays often drifted in different directions. The IRS traps were deployed only at 105 m. The PIT traps were deployed at multiple depths from 50 to 250 m, but only the 100 m traps are used for this comparison. Fluxes are given for

each station during Surveys I and II, as well as average fluxes for each survey (Table 2). The uncorrected fluxes of POC varied greatly. The average PIT fluxes were about six times higher than corresponding IRS fluxes. Because zooplankton swimmers were removed from both samples and solubilization of DOC was accounted for, these differences are likely due to hydrodynamic effects. The  $^{234}\text{Th}$  correction factors in Table 2 suggest that, with respect to  $^{234}\text{Th}$ , PIT traps on average overcollected by two to three times while the IRS traps on average undercollected by up to a factor of five. Five IRS samples had very low  $^{234}\text{Th}$  values and were left out of this analysis. The reason these samples had low  $^{234}\text{Th}$  is unclear, but we have never seen such high correction factors before on natural samples and suspect that there was a problem with the thorium analyses.

We used the  $^{234}\text{Th}$  correction factors in Table 2 to correct the POC fluxes for both the PIT and IRS traps. This calculation assumes that  $^{234}\text{Th}$  and POC are contained in the same particles and is supported by the correlation between POC and  $^{234}\text{Th}$  shown by Murray et al. (1996). As a result of this correction, the fluxes measured by the PIT traps were generally decreased, while fluxes measured by the IRS traps were increased (Table 2). Even though the uncorrected POC fluxes differed greatly, the  $^{234}\text{Th}$ -corrected POC fluxes for these two different trap designs agreed well, generally within a factor of two at each station. For Survey I, the IRS and PIT fluxes averaged  $2.3 \pm 1.3$  and  $2.6 \pm 0.7$  respectively, and for Survey II  $7.4 \pm 4.0$  and  $8.7 \pm 5.1$ . These mean fluxes agreed within 15% of each other for each survey. Corrected data for both trap designs indicate that POC fluxes were about three times higher for Survey II than Survey I. Ratios of POC export to new production averaged about 0.50 for the El Niño conditions of Survey I and 0.75 for the cold-tongue conditions of Survey II. The  $^{234}\text{Th}$ -corrected POC fluxes are consistent with the hypothesis that about 25–50% of new production is exported as DOC (Murray et al., 1996; Hansell et al., 1997; Zhang and Quay, 1997; Quay, 1997).

Even though the uncorrected carbon fluxes of these traps differed, their mean POC: $^{234}\text{Th}$  ratios were in fairly good agreement (Table 2). The values for the PIT traps were higher than for the IRS traps during Survey I ( $2.5 \pm 1.0$  versus  $1.3 \pm 0.9$ ), but lower during Survey II ( $4.0 \pm 1.7$  versus  $5.0 \pm 0.7$ ). The implication is that by using the average POC: $^{234}\text{Th}$  directly measured for each surface trap sample to represent all sinking particles at that location, similar POC fluxes are calculated with either type of trap (when based on the integrated  $^{234}\text{Th}$  deficit of the overlying water; Buesseler et al., 1995). Both trap designs yield a POC: $^{234}\text{Th}$  ratio that is a factor of two to five larger than that sampled by Buesseler et al. (1995) using relatively coarse particles collected on 53  $\mu\text{m}$  Nyltex screens. Even within different sediment trap collections from the EqPac study there is still a factor of 10 variability in the individual POC: $^{234}\text{Th}$  ratios whose origins remain unknown. Nevertheless, the consistency between samples from both trap designs supports the assertion of Quay (1997) that a carbon balance in Survey II is possible only with  $^{234}\text{Th}$ -modeled POC fluxes based on POC: $^{234}\text{Th}$  ratios from sediment traps. This finding highlights the importance of both  $^{234}\text{Th}$  and sediment trap techniques for determining POC fluxes. While models for  $^{234}\text{Th}$  fluxes may presently be more robust than sediment trap measurements for determining carbon export fluxes in the dynamic surface ocean, there may be no substitute for directly measuring POC: $^{234}\text{Th}$  on settling particles collected via sediment traps. This approach, however, requires that sediment trap samples be collected and counted within a short time relative to the half-life of  $^{234}\text{Th}$  (24.1 d).

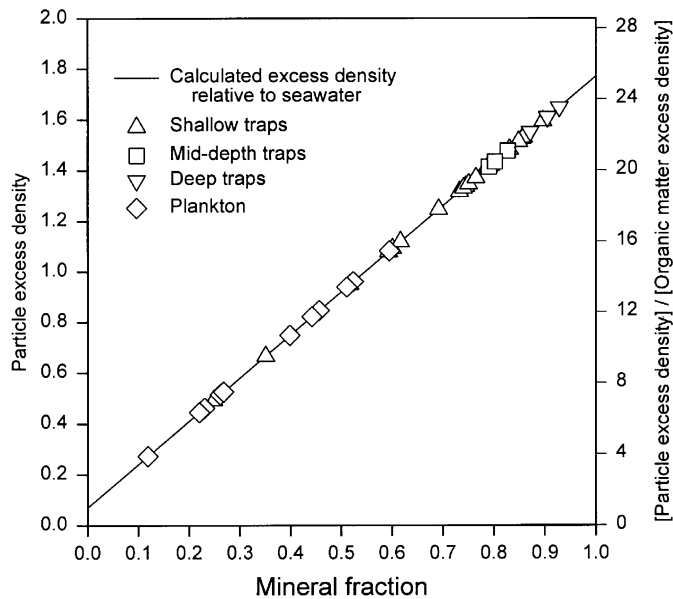


Fig. 6. Calculated relationship between particle excess density relative to seawater ( $\rho_{\text{particle}} - \rho_{\text{seawater}}$ , where  $\rho_{\text{seawater}} = 1.03 \text{ g cm}^{-3}$ ) and the fraction of mineral material. Pure organic matter ( $\rho \cong 1.1 \text{ g cm}^{-3}$ ) is on the left and pure mineral ( $\rho \cong 2.8 \text{ g cm}^{-3}$ ) on the right. Plotted sediment trap and plankton data show the observed range in composite sample excess densities. Organic and mineral compositions of samples were determined from carbon data by assuming  $\text{POM} = 2\text{POC}$ , and  $\text{CaCO}_3 = 8.33\text{PIC}$ . The right-hand scale demonstrates the factor by which the excess densities for particulate material exceed those of pure POM.

#### 4.1.3. Differential particle collection in traps

In general, hydrodynamic biases in sediment trap samples should affect the collection of less dense particles (i.e. rich in organics) differently than more dense particles (i.e. rich in minerals). For instance, whereas uncorrected POC fluxes in the PIT traps are higher by as much as a factor of 10 versus the IRS traps (Table 2), uncorrected PIC fluxes in PIT traps (data not shown) are similar to or lower than for IRS traps. Differential collection of POC and PIC due to hydrodynamics brings up two important factors to consider in all measurements and calculations involving particle dynamics in the ocean water column, namely particle size and density. Both characteristics have long been recognized for their role in the flux of settling particles (i.e. McCave, 1975; Bishop et al., 1977), and both factors have important implications for  $^{234}\text{Th}$  modeling. Because of its higher density, PIC trapping efficiency appears to be more equivalent in different trap designs than that of POC. Any  $^{234}\text{Th}$  scavenged by PIC will lead to lower POC: $^{234}\text{Th}$  ratios in trap material. For instance, POC: $^{234}\text{Th}$  ratios for the Survey II IRS traps are on average nearly four times those of Survey I (5.0 versus  $1.3 \mu\text{mol dpm}^{-1}$ , Table 2), while %PIC for Survey II IRS traps is on average only 60% that of Survey I (5.8 versus 9.6%, Table 1). During both surveys, POC: $^{234}\text{Th}$  ratios consistently decrease as %PIC increases. As with density, size likely plays a role in trapping efficiency, with larger particles less susceptible to hydrodynamic biases than smaller particles (e.g. Gust et al., 1996). Since POC: $^{234}\text{Th}$  ratios are known to differ with particle size, generally increasing with decreasing size (e.g. Buesseler et al., 1995; Murray et al., 1996), it is important to

know the size distribution of sinking material in a study locale in order to evaluate the potential impact of hydrodynamic biases.

Of the two factors, size and density, density tends to get less attention, despite differences of almost a factor of three between organic and inorganic materials. More importantly, however, density differences between organic and mineral matter lead to variations in particle excess density in seawater ( $\rho_{\text{particle}} - \rho_{\text{seawater}}$ ) of up to a factor of 25. Fig. 6 illustrates how drastically the excess density of a particle — in this case particles from our EqPac study — can change depending on composition, with pure organic matter ( $\rho \cong 1.1 \text{ g cm}^{-3}$ ) and pure mineral ( $\rho \cong 2.8 \text{ g cm}^{-3}$ ) as end members. For example, the composite excess densities of the particulate material collected at any single station by our 105 m traps (plotted along the mixing line in Fig. 6) vary from 0.5 to 1.6. Sinking rates theoretically should be proportionately variable (Stokes' Law), although particle shape likely plays a role as well. Significantly, no collected sediment trap mixture ever contained less than 25 wt% mineral material, and hence never had an average excess density less than five times that of pure organic matter. Given the near-neutral buoyancy of pure organic matter, its association with mineral “ballast” in a test or aggregate must be a prerequisite for effective transport by sinking. In the Arabian Sea, Ittekkot et al. (1992) suggest that continental minerals via aeolian input play a key role in the sedimentation of marine organic matter due to their high density. We suggest biogenic ballast to be as important. Surprisingly, this fundamental variable in the Stokes equation is seldom taken into account in vertical flux models and discussions.

#### 4.1.4. Flux variation with depth

As in other open ocean environments (Seuss, 1980; Martin et al., 1987; Wakeham and Lee, 1989; Honjo, 1996), POC fluxes through the water column decrease sharply with depth in the equatorial Pacific (Survey I, Figs. 2 and 4), such that on average for the EqPac study  $\sim 0.1\text{--}1\%$  of PP reaches the sea floor and only  $\sim 0.01\%$  actually accumulates in the sediment. On an absolute basis, most remineralization of total PP occurs in and just below the epipelagic zone ( $\sim 95\%$  by 105 m), where extensive release of nutrients fuels PP (Najjar et al., 1992; Toggweiler and Carson, 1995). Given zooplankton digestion efficiencies of 65–85% (e.g. Landry et al., 1984; Downs and Lorenzen, 1985; Cowie and Hedges, 1996),  $> 95\%$  remineralization in the epipelagic zone would require, on average, that POM pass through the equivalent of 2–3 heterotrophic cycles before exiting to the interior of the ocean. On a relative basis, the sediment–water interface is also a region of extensive degradation, with two orders of magnitude loss of sedimenting POC.

As mentioned previously, our moored trap POC fluxes at  $\sim 1000$  and  $\sim 4000$  m essentially bracket those of Honjo et al. (1995) at  $\sim 3000$  m. Considering the difference in trap design (large cones versus the tall cylinders in this study), this agreement suggests that hydrodynamic biases are much less important in the interior of the ocean than near the surface. Lee et al. (1998) also report excellent agreement for different trap types deployed at depths  $> 1000$  m in the Arabian Sea. In contrast to the epipelagic zone and sediment–water interface, remineralization of organic matter in the interior of the ocean is much less extensive. The POC flux at  $\sim 1000$  m was less than two times the POC flux at  $\sim 4000$  m, suggesting remineralization of less than half of the POC flux through the deep water column.

PIC fluxes also decrease with depth (Survey 2, Figs. 2 and 4). However, in contrast to POC, 5–10% of PIC produced accumulates in the sediment at most stations. Nevertheless, it is surprising

that so little PIC reaches the sediment. PIC is supersaturated in the upper ocean (the thermodynamic saturation depth for this region for calcite is  $> 1000$  m; Broecker and Peng, 1982), and yet nearly 80% of produced calcium carbonate is apparently redissolved by 105 m. Dissolution in sediment traps after collection (as determined from initial and final brine solutions from the traps) at most can account for 5% of this loss. The extent of PIC loss is not just an artifact of sediment traps; Zhang and Quay (1997) calculate a ratio of POC to PIC export of about six using an independent carbon mass balance approach, which leads to the same conclusion. Two mechanisms to account for this loss include dissolution in acidic microzones of particle aggregates due to respiration, and dissolution in acidic guts of zooplankton. Quantifying the former would be challenging. The latter was studied by Harris (1994) in a feeding experiment, which showed a 50–73% loss of ingested PIC when *Emiliania huxleyi* was grazed by *Calanus helgolandicus* and *Pseudocalanus elongatus*. If these are typical values, then calcareous tests — as with OM — might have to pass through animal guts multiple times before leaving the epipelagic zone to account for an 80% loss, if animals are the primary removal mechanism. This is clearly an area that needs further investigation.

#### 4.2. Compositions

With almost complete remineralization of PP and extensive solubilization of  $\text{CaCO}_3$  tests through the water column, the question remains as to what processes affect the composition of particulate material intercepted at each depth, i.e. why is some material preserved while other material is lost?

##### 4.2.1. Organic matter versus calcium carbonate

If one assumes (a) that POC makes up half the weight of POM (the calculated POC to POM ratio from the sediment traps of Honjo et al. (1995) average 0.52) and (b) that all PIC occurs in the form of calcium carbonate (12 wt% PIC), then the amount of each material present in plankton and trap samples can be roughly estimated from elemental carbon data. In the plankton samples those two components account for 50–80% of total sample mass during Survey I and 40–100% during Survey II, indicating that the other likely component, biogenic silica, accounts for as much as 60% of the material. This inference is supported by visual inspection of the plankton samples, which showed a large proportion of diatoms.

In contrast to the plankton samples, POM and  $\text{CaCO}_3$  are sufficient to account for all of the mass in the 105 m trap sample during Survey I and nearly all (80–95%) during Survey II (Table 1). Visual inspection of trap material during Survey II did indicate the presence of diatoms. By difference, biogenic silica would account for 5–20% of the total mass of these samples. Interestingly, this corresponds to a one-to-one molar relationship between silica and nitrogen, which is also the molar ratio attributed to diatoms (Brzezinski, 1985). Thus, potentially all of the POC collected at 105 m during Survey II can be attributed to diatoms. Dugdale and Wilkerson (1998) make the argument that all new production during Survey II was attributable to diatoms, but estimated that only a third of exported nitrogen (and by inference one-third of exported organic carbon) was directly due to sinking diatom tests. In any case, the extent of contributions to POC export out of the epipelagic zone at  $140^\circ\text{W}$  by diatoms appears to be minimal during Survey I, but potentially quite large during Survey II.

In the moored traps, calculated OM plus  $\text{CaCO}_3$  accounts for  $\sim 60\%$  of the bulk flux (Table 1), indicating the presence of up to 40% biogenic silica. Honjo et al. (1995) report for their moored traps biogenic silica contents consistently in the 20–40% range. Estimates by Honjo et al. (1995) of lithogenic contributions to the total mass flux in the study region (based on measured aluminum fluxes) are less than 1%. Finally, in the underlying sediments, McManus et al. (1995) report biogenic silica contents generally below 10%. This trend is consistent with our sediment samples, in which OM plus  $\text{CaCO}_3$  account for 85–90% of all sample mass except at the extreme ends of the transect.

Overall, the relative reactivities of POM and  $\text{CaCO}_3$  are as expected — %POM decreases steadily from source to sink while % $\text{CaCO}_3$  steadily increases. Biogenic silica reactivity appears to be intermediate with relatively constant %biogenic silica in the water column followed by a pronounced decrease at the sediment/water interface.

#### 4.2.2. OC versus TN

The OC:TN ratio of POM can often reflect the extent of remineralization. In a typical pelagic or benthic system, nitrogen is removed from POM preferentially relative to OC during heterotrophic utilization (Redfield et al., 1963; Knauer et al., 1979; Cowie and Hedges, 1996). In the water column, the OC:TN ratio in the organic remnant associated with sinking particles often increases with depth (e.g. Knauer et al., 1979). However, elemental discrimination during degradation does not appear to be an important factor for EqPac sediment trap materials, which retain a near-Redfield

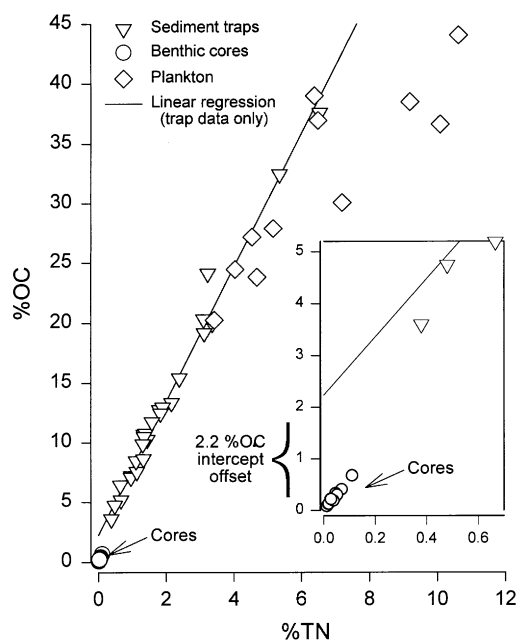


Fig. 7. %OC versus %TN for all plankton, sediment trap, and sediment core samples. The regression line for all sediment trap samples is shown. Regression statistics for sediment trap data: slope = 6.61, intercept =  $2.24 \pm 1.04$   $r^2 = 0.984$ . Regression statistics for sediment core data (inset): slope = 5.78, intercept =  $0.03 \pm 0.03$   $r^2 = 0.976$ . Plankton samples were not included in regressions.

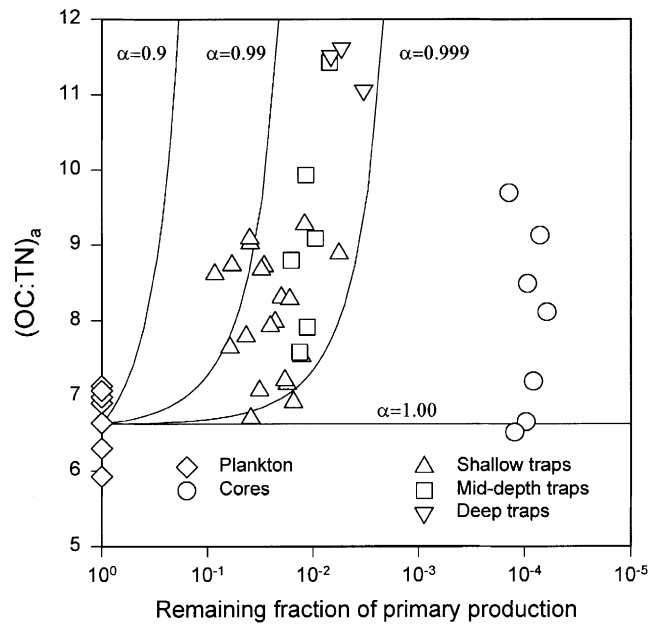


Fig. 8. (OC:TN)<sub>a</sub> versus remaining fraction of primary production (PP) for various fractionation values. The initial primary production (OC:TN)<sub>a</sub><sup>PP</sup> is assumed to be Redfield, i.e. 6.625. The fraction of PP remaining is represented by *f*<sub>OM</sub> and the fractionation factor, *α*, is equal to

$$\alpha = \frac{[\text{OC/TN}]^{\text{respired}}}{[\text{OC/TN}]^{\text{PP}}}$$

For any given *α* and *f*<sub>OM</sub>,

$$\text{OC}^{\text{respired}} = (1 - f_{\text{OM}})(\text{OC}^{\text{PP}} + \text{TN}^{\text{PP}}) \frac{\text{OC}^{\text{PP}} \alpha}{\text{OC}^{\text{PP}} \alpha + \text{TN}^{\text{PP}}}$$

and

$$\text{TN}^{\text{respired}} = (1 - f_{\text{OM}})(\text{OC}^{\text{PP}} + \text{TN}^{\text{PP}}) \frac{\text{TN}^{\text{PP}} \alpha}{\text{OC}^{\text{PP}} \alpha + \text{TN}^{\text{PP}}}$$

(OC:TN)<sub>a</sub> is then calculated as

$$\left[ \frac{\text{OC}}{\text{TN}} \right]_a = \frac{\text{OC}^{\text{PP}} - \text{OC}^{\text{respired}}}{\text{TN}^{\text{PP}} - \text{TN}^{\text{respired}}}$$

signature (e.g. OC:TN ≈ 6.6) throughout the water column (Fig. 7). Previously reported OC:TN ratios for marine sediment on a transect across the equator from 164°W to 169°E in the Pacific varied from 3.4 to 18.1, with the majority having twice Redfield values (Grundmanis and Murray, 1982). Just as with the sediment trap material, however, EqPac OC:TN ratios for surface sediments along 140°W appear to be largely Redfield (Fig. 7). Finally, most OC:TN ratios of our plankton net tows are also in the Redfield range (Table 3, Fig. 7). The four plankton outliers all have low OC:TN ratios, suggesting a higher proportion of zooplankton. Overall, it appears that

organic matter along 140°W in the central equatorial Pacific is largely degraded non-selectively according to Redfield ratios.

Because only ~0.01% of the original PP is actually preserved in the sediments, even the slightest selectivity in elemental recycling should lead to exaggerated ratios of OC:TN in the preserved material (in a manner similar to Rayleigh distillation). Fig. 8 shows (OC:TN)<sub>a</sub> versus remaining fraction of PP plotted along with Rayleigh distillation-type curves (e.g. Broecker and Oversby, 1971). The sediment trap data are suggestive of preferential nitrogen utilization, with a fractionation factor between 0.99 and 0.999. However, a fractionation that small is well below the detection limit in the epipelagic zone where most remineralization occurs. Further, the sediment core data clearly do not reflect the same trend, as the (OC:TN)<sub>a</sub> ratios should increase exponentially at such low levels.

Finally, an interesting feature of Fig. 7 is the 2.2% OC offset between (OC:TN)<sub>a</sub> of the sediment traps and the sediment cores. Two scenarios could account for this: (1) the presence of a nitrogen-poor organic component (such as carbohydrates or lipids) that is associated protectively with the mineral fraction, and (2) a nitrogen-poor reduced carbon component (such as black carbon) that is inherently recalcitrant. In the first case, the disappearance of the nitrogen-poor reduced carbon in the sediment would go hand-in-hand with dissolution of the protective mineral. In the second case, much longer residence times of particles in the sediment versus the water column might provide sufficient time to remineralize even recalcitrant components (Hartnett et al., 1998).

## 5. Conclusions

The US JGOFS EqPac Process Study links together the entire continuum of OM production, diagenesis, and preservation in the open ocean. Considering the highly contrasting environments of the epipelagic zone, the interior of the ocean, and the sediment, together with > 99.99% POM remineralization, it is remarkable that so much of the PP pattern along the transect is retained in the sediments and that remineralization appears largely to follow Redfield values. One explanation for this persistent link is to look toward other components of sinking particles and sediments that also reflect PP, namely CaCO<sub>3</sub> and biogenic silica. If CaCO<sub>3</sub> and biogenic silica are affording protection to POM, then dissolution of the mineral phases may be a primary factor in regulating organic matter burial. Therefore, it becomes even more important to elucidate the mechanisms for the dissolution of CaCO<sub>3</sub> and biogenic silica in the epipelagic zone and at the sediment/water interface.

In many regards, the US JGOFS EqPac Process Study was also a testing ground for intercomparison of existing techniques for determining carbon fluxes. Clearly, there are issues that still need to be addressed with all of the techniques, which nevertheless combine to constrain the true export fluxes. Perhaps more importantly, these comparisons point toward ways in which future measurements and data interpretations might be improved. In this sense, it seems prudent to follow up in at least three areas: (1) POC and <sup>234</sup>Th comparisons between different types of sediment traps should be further evaluated as means of possibly calibrating sediment trap-based particle fluxes out of the surface ocean; (2) the relationships between particle size and trapping efficiency, <sup>234</sup>Th corrections to trap fluxes, and <sup>234</sup>Th-scavenging models need to be determined. In particular, it may be

necessary to incorporate the relationship between particle size, density, and hydrodynamic behavior in  $^{234}\text{Th}$ -scavenging models; (3) finally, the role of particle density in all upper ocean processes needs reassessment, especially given the potential for differences in excess density by factors  $> 10$ . Considering that  $> 95\%$  of OC is recycled in the upper 200 m, it is paramount that we better understand the different processes that contribute to degradation and export in this critical region. In particular, better sampling methods are needed for particles in the physically and biologically dynamic upper half kilometer of the ocean.

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