# Group Proposal: VERtical Transport In the Global Ocean (VERTIGO)

PROJECT SUMMARY

We propose to address the question: What controls the efficiency of particle transport between the surface and deep ocean? More specifically, what is the fate of sinking particles leaving the upper ocean and what factors influence remineralization length scales for different sinking particle classes? This proposal sets out to test two basic hypotheses regarding remineralization control, namely: 1. particle source characteristics are the dominant control on the efficiency of particle transport; and/or that 2. mid-water processing, either by zooplankton or bacteria, controls transport efficiency. To test our hypotheses, we will conduct process studies in the field focused on particle flux and composition changes in the upper 500-1000m of the ocean. The basic approach is to examine changes in particle composition and flux with depth within a given source region using a combination of approaches, many of which are new to the field. These include neutrally buoyant sediment traps, particle pumps, settling columns and respiration chambers, along with the development of new biological and geochemical tools for an integrated biogeochemical assessment of the biological pump. We have chosen two sites to study on 3 week process study cruises- the Hawaii Ocean Time-series site (HOT) and a new moored time-series site in the subarctic NW Pacific (Japanese site K2; 47°N 160°E) - where there are strong contrasts in rates of production, export, particle composition and expected remineralization length scales.

Evidence for variability in the flux vs. depth relationship of sinking particles is not in dispute but the controls on particle transport efficiency through the twilight zone remain poorly understood. A lack of reliable flux and particle characterization data within the twilight zone has hampered our ability to make progress in this area, and no single approach is likely to resolve these issues. The proposed study will apply quantitative modeling to determine the net effects of the individual particle processes on the effective transport of carbon and other elements, and to place the shipboard observations in the context of spatial and temporal variations in these processes. For rapid progress in this area, we have organized this effort as a group proposal taking advantage of expertise in the US and international community.

The efficiency of particle transport is important for an accurate assessment of the ocean C sink. Globally, the magnitude and efficiency of the biological pump will in part modulate levels of atmospheric $CO_2$. We maintain that to understand present day ocean C sequestration and to evaluate potential strategies for enhancing sequestration, we need to assess possible changes in the efficiency of particle transport due to climate variability or via purposeful manipulations of C uptake, such as via iron fertilization.

This basic research proposal is designed to have maximum intellectual impact but there are broader outcomes and impacts from this proposal as submitted. The main PI's (Buesseler, Boyd, Siegel, Silver, Steinberg and Trull) have a strong record of student training and mentoring, and this project is no exception. Directly funded here will be both graduate and undergraduate involvement. Involvement of non-US PI's encourages exchange of students and post-docs between labs in different countries. In addition, our groups will continue to maintain science web sites that are designed for both public and scientific exchange where the broader and specific goals and outcomes of this work can be exchanged. Buesseler has institutional support as an "Ocean Life Fellow" at WHOI to support broad audience talks and has established a record of leading broader audience publications (most recently for example as guest editor, The Oceanography Society; editor/producer "A New Wave of Ocean Science" brochure) that will be continued and directed towards research in the twilight zone. Steinberg will use the significant education and public outreach infrastructure at VIMS to offer public lectures and a web cast on the ocean's twilight zone. Finally, we are eager to help organize appropriate public sessions at national meetings.

## RESULTS OF PRIOR RESEARCH

**Ken Buesseler** has received NSF support since 1987.  This research has involved the use of artificial and natural radionuclides as tracers of a wide variety of oceanographic processes. Of particular relevance to this proposal are those grants that used $^{234}$Th as a tracer of upper ocean export, conducted primarily under the Joint Global Ocean Flux Study (JGOFS). The most recent JGOFS award was for participation in the AESOPS study (PI: Buesseler, OPP-9530861, $521,950, 9/01/96 to 6/30/00).  We measured $^{234}$Th distributions on seven JGOFS cruises and derived POC, PON and bSi fluxes (all data at: http://usjgofs.whoi.edu/southern.html).  We also developed a new method for $^{234}$Th that requires only 2-4 liter samples.  We have presented our findings at major national (n=5) and international (n=2) meetings and have written 8 manuscripts related to this proposal.  A current NSF award (J. Price lead PI, OCE-9912044) ending in Feb. 2003 to develop the neutrally buoyant sediment trap forms the basis for VERTIGO as described in this proposal and on the PI's web site: http://cafethorium.whoi.edu.

**Deborah Steinberg** has received NSF support since 1997.  Her research has focused on the role of zooplankton in biogeochemical cycling and marine snow/particle dynamics.  Most relevant to this proposal is the JGOFS Bermuda Atlantic Time-series Study (BATS) grant (PI's: Knap, Steinberg, Carlson, Bates, OCE-9801950, $2,099,992, 5/1/98 to 4/30/01).   BATS is one of two oceanic time-series stations established in 1988 as part of US JGOFS that have been instrumental in characterizing open ocean biogeochemical processes and how they are thought to vary through time.  Steinberg's research focused on the role of zooplankton in biogeochemical cycling and marine snow/particle dynamics.  This grant has resulted in 11 peer-reviewed papers plus 24 published abstracts with Steinberg as author, and one PhD dissertation.

**Mary Silver** has not received NSF funding since 1996, though prior to that she received NSF support nearly continuously since 1979 for studies on particle flux and marine snow.  Her NSF-supported work initially was concerned with characterization of microbial communities on marine snow particles in surface (diver accessible) waters.  Subsequently most of her studies involved collections with submersibles (i.e. *Alvin*) or with sediment traps, mostly on the VERTEX project.  Her work investigated the nature of the microbial (both heterotrophic and photoautotrophic) communities found on the particles and whether they were true members of the "regeneration" community.  Many of the themes of her work were expressed in her 1991 paper with Gowing (Silver & Gowing, 1991).

**Tom Trull** received NSF support for the first time in 2001. He is an Adjunct Scientist in the Marine Chemistry and Geochemistry Department at WHOI. He has directed the Biogeochemical Cycles (BGC) Program at the Antarctic Cooperative Research Centre in Hobart, Tasmania since 1997 (www.antcrc.utas.edu.au).  The BGC program has made major contributions to Southern Ocean carbon cycle research (e.g. 17 articles published as a special section of JGR-Oceans in Dec. 2001). His research focuses on the comparison of dissolved and particulate C and N isotopic compositions to identify ecosystem processes regulating organic matter export.  A recent NSF Office of Polar Programs grant (PI's: Honjo, Francois and Trull, OPP-0087530) for deployments of deep moored sediment traps and associated study of $^{230}$Th/$^{231}$Pa resulted in a first comparison of Australian and AESOPS data (Trull *et al.*, 2001), and 2 articles applying modern C and N isotopic compositions of sinking particles to the interpretation of the Southern Ocean sedimentary record (Lourey et al., *submitted*).

**Dave Siegel** has been funded by NSF since 1991.  His research focuses on the application of physical and optical oceanographic approaches to the study of ocean biogeochemical cycles and biological processes.  Foremost in these efforts is the Bermuda Bio-Optics Program, or BBOP (PI's Siegel, Smith [OCE-91-16372] and Michaels [90-16990], $649,600, 6/1/91 to 4/30/94).  For more than a decade, BBOP has operated as part of the BATS program (now supported by NASA's SIMBIOS program).  More than 35 papers, theses and dissertations have been written based upon the BBOP data and data are available to all interested scientists (www.icess.ucsb.edu/bbop/bbop.html). BBOP remains an integral component of NASA's satellite ocean color algorithm development and product validation efforts and the BBOP data set is central to the PhD dissertations of three graduate students presently at UCSB.

# 1. INTRODUCTION

We propose to address the question: **What controls the efficiency of particle transport between the surface and deep ocean?** More specifically, what is the fate of sinking particles leaving the upper ocean and what factors influence remineralization length scales for different sinking particle classes?

The null hypothesis is that remineralization rates do not change in response to either changes in particle source characteristics or mid-water processing. This would result in a single, global relationship between particle flux and depth. VERTEX (VERtical Transport and EXchange) observations from drifting Particle Interceptor Traps (PIT's) deployed in the upper 500-1000m give rise to the "Martin" curve, $F(z) = F_{100}(z/100)^{-b}$, where $F(z)$ is the particle flux profile, $F_{100}$, the flux at 100m, z is depth in meters and b is an empirically determined constant (Martin *et al.*, 1987). For particulate organic carbon (POC), they found $F(z) = 1.53(z/100)^{-0.858}$ in units of mol m$^{-2}$ y$^{-1}$. This "Open Ocean Composite" (OOC) is commonly used to model vertical transport in global 3-D ocean carbon cycle models and is the basis for predictions of C sequestration and export from surface production (e.g. Suess, 1980; Pace *et al.* 1987; Berger *et al.*, 1988; Sarmiento et al. 1993).

There are, however, many reasons to reject the null hypothesis. Variations in b, the remineralization term, are not uncommon, even in the VERTEX data set (b ranges from –0.32 to –0.97 for sites sampled by Martin *et al.*, 1987). Looking from below at the deep trap flux relative to shallow export and/or production, there is strong evidence for variability in mid-water transport efficiency (Fisher et al., 2000; Berelson, 2001; Antia et al., 2001; Lutz et al., 2002; Francois et al., 2002), even though the mechanisms responsible for this variability are debated (see **BACKGROUND**). In addition, seasonal, regional and global ocean models achieve improved fits to observed nutrient distributions when remineralization length scales are allowed to vary regionally, and to differ for different nutrient elements (Schlitzer, 2002; Usbeck, 2002; Wang et al., 2001). Finally, the obvious mismatch between spatial patterns in primary production and the export of carbon to the deep ocean (Fig. 1) indicates that a complex suite of transformations must occur in the "twilight zone", the region below the surface euphotic zone and the deep ocean. For example, high surface production in the N. Atlantic and N. Pacific does not necessarily lead to high C sequestration and burial in the deep sea (Fig. 1).



**Figure 1a** Left panel- Behrenfeld & Falkowski 1997 annual surface ocean carbon uptake (g m$^{-2}$ y$^{-1}$) estimated using a primary productivity model and SeaWiFS average annual chlorophyll field. **1b.** Right panel, Jahnke 1996 annual estimates of deep carbon flux (mol m$^{-2}$ y$^{-1}$) at 1000m estimated from sediment composition and benthic flux correlation.
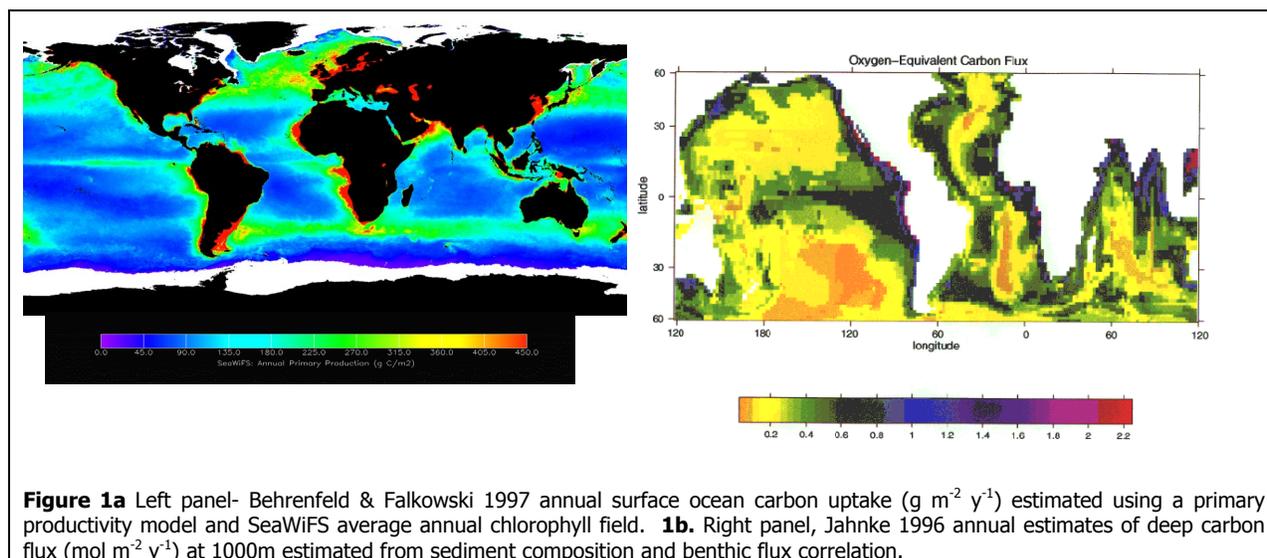
We are thus at a juncture in ocean biogeochemistry, where we know from field data and models that significant variability exists in flux vs. depth patterns. However, the depth region where the most marked attenuation of the particle flux occurs (100-500m) has a striking gap in flux data (Fig. 2). This region has been under-sampled for a variety of reasons, including problems associated with surface-tethered free-

drifting sediment traps, such as hydrodynamic bias, resolubilization in traps, and swimmers (see Gardner, 2000). This proposal sets out to fill this gap and test two basic hypotheses regarding remineralization control, namely: 1. particle source characteristics are the dominant control on the efficiency of particle transport; and/or that 2. mid-water processing, either by zooplankton or bacteria, controls transport efficiency.
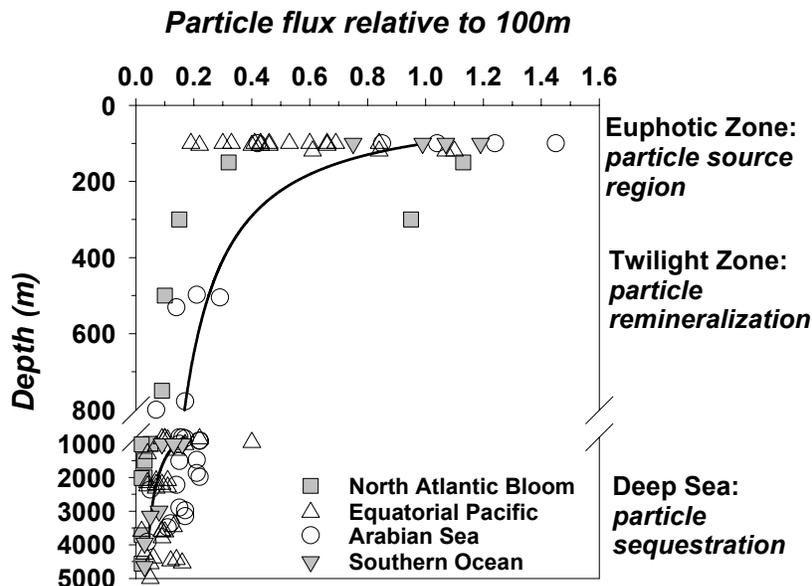


**Figure 2**. A compilation of all particle flux vs. depth data available from the last decade of JGOFS studies shows a significant data void between the upper ocean (fluxes at 100m derived from shallow traps or [234]Th methods) and fluxes >500m derived from deep ocean traps (redrawn from Berelson, 2001; not all shallow data plotted). Solid line is Martin curve for POC with b=-0.858. These data are plotted as fluxes relative to 100m to facilitate comparisons between basins.

To test our hypotheses, we will conduct process studies in the field focused on particle flux and composition changes in the upper 500-1000m of the ocean. The basic approach is to examine changes in particle composition and flux with depth within a given source region using a combination of approaches, many of which are new to the field. These include neutrally buoyant sediment traps, particle pumps, settling columns and respiration chambers, along with the development of new biological and geochemical tools for an integrated biogeochemical assessment of the biological pump. We have chosen two sites- the Hawaii Ocean Time-series site (HOT) and a new moored time-series site in the subarctic NW Pacific (Japanese site K2; 47**°**N 160**°**E) - where there are strong contrasts in rates of production, export, particle composition and expected remineralization length scales. These sites were selected in part due to the wealth of scientific and logistical support that will allow us to place the physical and biogeochemical context of our process cruises within the framework of seasonal to long-term studies. The proposed study will apply quantitative modeling to determine the net effects of the individual particle processes on the effective transport of carbon and other elements, and to place the shipboard observations in the context of spatial and temporal variations in these processes.

## 2. SCIENTIFIC BACKGROUND

The transport of biogenic particles from the surface to the deep ocean is the key driver of the ocean's biological pump. Globally, the magnitude and efficiency of the biological pump will in part modulate levels of atmospheric $CO_2$ (Volk & Hoffert, 1985). From the paleoceanographic record there is evidence of elevated rates of POC export resulting from changes in the functioning of the pump (Kumar *et al.*, 1995). There is a need to better understand what are the key determinants of this pump in the present day, and how they might be altered in response to climate change (Bopp *et al.*, 2001; Sarmiento & LeQuéré 1996). For example, it is increasingly recognized that climate variability (such as ENSO) results in marked shifts in planktonic structure (Karl et al. 2001; Boyd & Doney, 2002) that may alter the export of carbon to depth (Michaels & Silver, 1988).

Sediment traps have advanced our understanding of the vertical transport of particles more than any other tool. Moored time-series traps in particular have been deployed in many biogeochemical settings

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allowing for a comprehensive view of deep ocean flux and composition variability. Below about 1-1.5 km, deep moored traps in the open ocean have been shown to quantitatively collect particles, based upon calibration with radionuclide budgets of $^{230}$Th and $^{231}$Pa (Scholten et al., 2001; Yu et al., 2001). Thus, in order to look at flux attenuation within the twilight zone, comparisons are made between the deep trap flux and independent estimates of upper ocean production and/or export, rather than study flux within the twilight zone directly. For example, Francois et al. (2002) find a strong correlation between depth, $CaCO_3$ content and surface f-ratio, with the transfer efficiency defined as $F_{deep}/EP$, where $F_{deep}$ is the organic C trap flux below 2000m and EP is shallow export production derived from satellite estimates of primary production and the temperature dependent food web model of Laws et al. (2000). Their global synthesis suggests that the transport efficiency is low in regions where on an annual average the flux is dominated by particles with a high $bSi:CaCO_3$ content, i.e. diatoms. In these settings the "silica pump" is characterized by enhanced shallow remineralization (larger negative "b's" in the Martin et al. curve) leading to a low deep ocean flux and export efficiency. This is in contrast to settings characterized by the "carbonate pump" which transfers more organic C to depth despite lower shallow export. In this study we can test this hypothesis directly using data collected within the twilight zone since we have chosen two sites with large difference in flux rates and the carbonate vs. silicate composition of that flux.

The carbonate ballast algorithm proposed by Francois et al. does not resolve the mechanism that controls transport efficiency, though Francois et al. and others (Armstrong et al., 2002), suggest that the ballasting effect of carbonate minerals and/or possibly a protection/packaging mechanism allow carbonate dominated aggregates to reach the deep ocean more efficiently. Antia et al. (2001) compared flux composition from polar opal-dominated, mid-latitude and tropical carbonate-dominated regions of the Atlantic. However, they attribute regional differences in export efficiency not to ballast per se, but to the temporal stability of flux, with highly pulsed flux events characterized by elevated shallow export but rapid remineralization. A faster sinking rate alone due to high density carbonate minerals may also explain enhanced transport efficiency in carbonate dominated systems (Berelson, 2002).

Lutz et al. (2002) confirm the large variability in remineralization length scales in their global synthesis of deep trap data. They suggest a two component flux model is better suited to fit deep trap data, that includes a more labile fraction with rapid remineralization and a refractory component, similar to Armstrong et al.'s (2002) differentiation between OC and ballast flux components. Lutz et al. define the s-ratio (= $F_{deep}/EP$) analogous to Francois transfer efficiency; however, they use measured rather than modeled EP (from $^{234}$Th, f-ratios or other mass balance approaches). In contrast to Francois et al., this s-ratio is lower in carbonate dominated systems, such as found at HOT and Bermuda, relative to diatom dominated blooms in the Southern Ocean (Fig. 5b in Lutz et al. (2002)). They demonstrate that the s-ratio varies by two orders of magnitude and follows regional patterns, but do not propose a single mechanism or algorithm to predict these changes in transport efficiency.

In summary, evidence for variability in the flux vs. depth relationship of sinking particles is not in dispute but the controls on particle transport efficiency through the twilight zone remain poorly understood. A lack of reliable flux and particle characterization data within the twilight zone has hampered our ability to make progress in this area, and no single approach is likely to resolve these issues.

## 3. PROJECT GOAL AND HYPOTHESES

This proposal sets out to answer the question: **What controls the efficiency of particle transport between the surface and deep ocean?** We define this efficiency as the fraction of any component of the sinking flux at depth, relative to the same flux out of the surface ocean. Of primary relevance to C sequestration is the efficiency of transport from the base of the mixed layer to below the depth of maximal winter mixing. Since most of the flux divergence occurs for relatively shallow depths (the POC flux decreases by ~75% within the upper 500m), our attention here is focused on the upper 500m while comparing our results with traditional deep trap fluxes measured on time-series moorings.

Our primary motivation for understanding processes in the twilight zone is to better quantify the magnitude of the ocean C sink and controls on C sequestration into the deep ocean. Particles must leave

the seasonally deepest (typically winter) mixed layer in order to have a net impact on the atmospheric C cycle. Thus physical controls on the depth of the euphotic zone and surface mixed layer plus the extent of upper ocean ventilation can affect the export of particulate carbon (Antia *et al.*, 2001). The extent of POC and PIC partitioning on sinking particles with depth is critical as well for understanding ocean C uptake (Antia *et al.*, 2001; Francois *et al.*, 2002), since photosynthesis and the production of POC decreases surface ocean $pCO_2$, while calcite production of PIC increases $pCO_2$. Changes in the strength of particle export are not necessarily sufficient to alter the ocean C sink and its influence on anthropogenic $CO_2$ if the upwelling of DIC and nutrients at Redfield ratio proportions (C:N:P molar ratio = 106:16:1) is balanced by export at equivalent ratios (e.g. Fig. 1 in Michaels *et al.*, 2001). Therefore changes in the relative remineralization length scales for C:N:P fluxes must also be considered. As there are considerable interactions among suspended and sinking particles in the ocean (e.g. Denman & Pena, 2002), we must also sample suspended as well as sinking particles.

**Our two initial hypotheses are that:**

1. **particle source characteristics determine transport efficiency of sinking particles**
2. **mid-water processes in the twilight zone determine transport efficiency.**

We refer to particle source characteristics as those fundamental properties related to sinking such as density and size, as well as chemical characteristics that might lead to enhanced preservation. Mid-water processes can be broken down into bacterial effects on particle degradation vs. those related to mid-water feeding and transport by zooplankton. These rather general hypotheses are not new, but they frame the basic questions of study if one were to reject the null hypothesis that flux vs. depth patterns are constant throughout the world ocean. These two hypotheses are not mutually exclusive and may work in tandem to produce interesting feedback mechanisms. For example, mid-water zooplankton may not be generalist particle grazers, but have specific adaptations to process slow or fast sinking particles. Changes in source characteristics may thus trigger changes in remineralization or packaging by mid-water communities. Carbon budgets over the upper 1000 m of the water column in the NE subarctic Pacific suggest that both heterotrophic bacteria and large migratory zooplankton are likely responsible for particle transformations in the twilight zone (Boyd *et al.*, 1999).

By choosing two study sites of contrasting particle source characteristics, we can test the algorithms developed from Francois et al. regarding the importance of $CaCO_3$ "ballast" in determining transport efficiency- our hypothesis 1. The lack of basic mid-water data on zooplankton and bacterial processes in conjunction with accurate flux and suspended particle composition work, has hampered progress on the second hypothesis. A major goal will be to acquire over appropriate time and spatial scales accurate flux vs. depth data within the twilight zone (see **4c**). These data will be used to evaluate flux vs. depth relationships such as the Martin OOC curve as well as relationships that include multiple flux components (Armstrong et al., 2002; Lutz et al., 2002; Francois et al., 2002). These combined surface and mid-water measurements will allow us to develop particle aggregation and flux models. In addition, we will compare these direct estimates of flux and remineralization with vertical profiles of major nutrients and their isotopic composition to put the data in context of long-term oceanic properties (see **5g**).

## 4. OVERVIEW OF PROPOSED RESEARCH

### 4a. General Approach

To better understand the key processes occurring in the 'twilight zone' three approaches are essential:

1. the development of new techniques to sample in the twilight zone
2. the concurrent use of both biological and geochemical tools to provide a true **biogeochemical** assessment of the biological pump
3. the modeling of individual particle formation and remineralization processes and the application of these results to regional and global C cycle models.

Our approach is to characterize the building blocks of marine particles in the surface ocean, and study changes in relative composition and flux with depth of carbon and associated elements. We detail below,

the characteristics of the field sites and the basic sampling design & cruise plan before we detail the individual project elements and roles of each PI (see **5**).

## 4b. Study Sites

We have chosen two field sites in the Pacific where we expect to find large differences in the magnitude of particle flux, the composition of sinking and suspended particles and remineralization length scales. These are the Hawaii Ocean Time-series (HOT- 22.75°N; 158°W) and a newly established and heavily instrumented time-series mooring site in the NW Pacific (K2- 47°N 160°E).

The contrasts between the two sites are large, in particular in the strength of the carbonate vs. silicate pump. HOT is an oligotrophic site, characterized by low chlorophyll, low f-ratios and low upper ocean export fluxes (Table 1). Using SeaWiFS data, it is clear that the surface chlorophyll levels are always much lower, by a factor of 5 on average, at HOT vs. the subarctic site K2 (Fig. 3a). K2 is near the center of the western subarctic gyre and is characterized by high surface nutrients, including silica (Talley 1999). The planktonic community at K2 is dominated by diatoms and prior study suggests relatively high f-ratios and high shallow export flux (Table 1). Interestingly, the deep POC fluxes are similar between sites (Fig. 3b; Table 1) as suggested by the higher transport efficiency of carbonate-rich particles through the twilight zone (Francois et al. 2002). We also chose these sites in part because of the relatively stable physical and biological conditions, compared to bloom settings or near margins where "event catching" would be difficult and 1-D particle flux interpretations problematic (Siegel et al. 1990).

**Table 1. Summary of sites**

| SITE | Chl avg[1] | Shallow POC flux[2] | f-ratio[3] | Deep POC flux[4] | bSi/$C_{inorg}$ deep trap[4] |
|---|---|---|---|---|---|
| | $mg/m^3$ | $g/m^2/yr$ | | $g/m^2/yr$ | (mole) |
| **HOT** | 0.1 | 17-22 | 0.15 | 0.51 | <1 est |
| **NW Pacific/K2** | 0.5 | 86 | 0.42 | 0.82 | 4.2 |

Sources: 1. Chl-a from SeaWiFS 1997-2002 analyzed for this study. 2. HOT data from data in Benitez-Nelson et al. (2001a) and modeled for HOT and K2 from Laws et al. (2000). 3. f-ratio from Laws et al. (2000). 4. HOT 4000m trap from 1993-1997 data provided by D. Karl; NW Pacific 5090m trap from 50°N, 165°E unpublished data M. Honda & summarized in Francois et al. (2002).
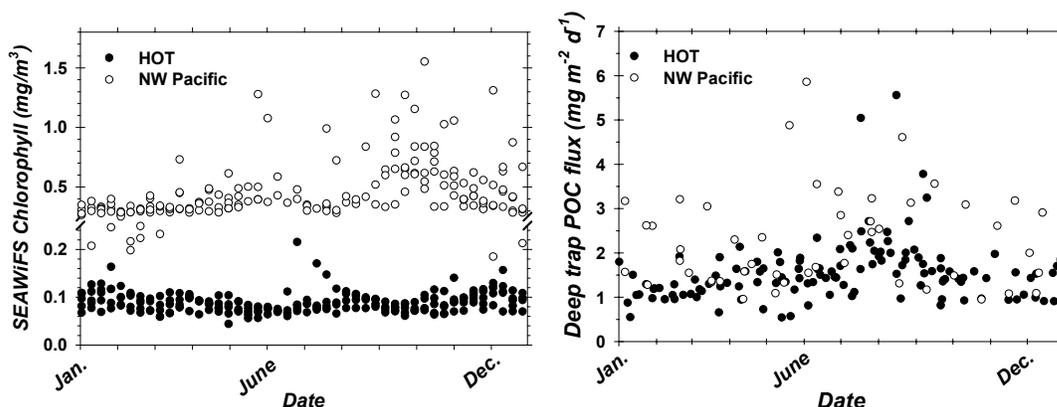


**Figures 3a** (left)- SeaWiFS derived chlorophyll concentration (note break in Y-axis at 0.3 mg/m³) and **3b** (right)- deep trap POC flux at HOT and K2 sites (data sources listed under Table 1)

Logistics and background support at both sites include appropriate physical and biogeochemical time series observations, including trap moorings. These data enable us to extend our detailed studies of twilight zone processes in the context of the annual cycles of production and export. Sampling at the HOT site has been conducted by the US JGOFS program since 1988 (e.g. Karl. et al., 2001; DSRII Special Issues- Karl & Michaels; 1996; Siegel et al., 2001). Of key relevance to this proposal are seasonal estimates of production, community structure and export on standard HOT cruises and the physical and bio-optical instrumentation and traps deployed on moorings (see attached letters from Dave Karl &

Tommy Dickey). We propose to use this site for a short instrumentation and methods test cruise in January 2004 and a detailed 3 week process study in the early summer of 2004.

K2 in the NW Pacific is one of three sites in a new 10 year Japanese time-series program that began roughly one year ago. There are two moorings at this site. One is designed to accommodate the "MMP" profiling system that samples the upper 2000m on a daily basis for hydrographic properties and currents. The second mooring includes three time-series sediment traps covering depths from 1000m to 500mab, which will be supplemented in October 2002 with 7 additional traps deployed between 150 and 1000m. The same mooring is also equipped with set of new instruments to characterize the upper ocean biogeochemistry including: in-situ $^{14}$C incubator (C. Taylor's SID); phytoplankton collector (48 time-series filters that are poisoned); large volume zooplankton collector and nutrient sampler (48 x 500ml water samples that are preserved in situ for later analyses); bio-optical observations. This is one of three sites in the NW Pacific where the Japanese have deployed remote instrumentation to collect decade long time series data as part of a program out of Mutsu Institute of Oceanography led by Dr. Sus Honjo (supporting letter attached). The central gyre site K2 was chosen over K1, due to possible boundary current effects at K1 related to the margin along Kamchatka, and a more southerly site K3 which will be within the frontal zone of the Kuroshio (T. Joyce, pers. comm., 2002). This site has considerably higher bSi fluxes and total annual fluxes compared with sites in the NE Pacific (i.e., Station Papa). We propose a 5 week cruise in 2005 to this site enabling a 3+ week occupation during early summer conditions (continued warming, low winds & seas ~1-2m are characteristic at this time).

## 4c. Sampling Considerations

If the ocean were in steady state and particle export uniform spatially, the vertical particle flux profile would simply decrease with depth without spatial variations. However, export fluxes are often pulsed in time and vary on a variety of spatial scales. This means that the source region from which particles have emanated (or the "statistical funnel") can cover significant spatial extent depending upon particle sinking rate, the mesoscale flow field, depth of sampling and time period of integration (Siegel *et al.*, 1990; Siegel & Deuser, 1997; Siegel & Armstrong, 2002). For deep moored traps (>1000m), the horizontal extent of the statistical funnel is generally >500km for a typical particle sinking speed of 100 m/day and this scale decreases for shallower moored trap deployments. In reality though, particles reaching any one depth/time horizon will have originated from separate source "streaks" at the surface within this statistical funnel (Siegel & Deuser, 1997). The width of these source region streaks is quite small (of order several to several 10's of km for moored traps deployed at 1000 m or so). This makes it difficult, if not impossible, to truly relate upper water export processes to moored deep trap fluxes.

The use of Neutrally Buoyant Sediment Traps (NBST's) proposed here (see **5c**) rectifies this situation enabling the study of upper ocean particle source characteristics and the fluxes of the twilight zone. NBST's drift within the large-scale flow field in which they are embedded. Hence, their statistical funnels will be much smaller compared with moored traps. Further as most horizontal kinetic energy is in the first vertical mode (see Siegel *et al.* 1999 and others), there will be little difference in the trajectories the NBST's take. This means that a vertical array of NBST's deployed simultaneously will sample the same particle source region. Our experience at BATS is that 150 & 300m NBST's remain within 1-2 km of each other after a 3-4 day deployment. **This greatly reduces the "streak" source region problem that plagues export production/sinking flux experiments with moored or drifting PIT arrays**. This represents a large advantage for NBST's when used in process studies, but does not replace the need for deep moored traps for longer and larger scale sampling of deep ocean fluxes.

## 4d. Process Study Plan

Our basic approach will be to use underway ship surveys (temperature, salinity, fluorescence) and near-real time, satellite remote sensing data (sea level from altimetry and ocean color from SeaWiFS; PI: Siegel) to pinpoint a specific deployment site. Sinking particles arriving at our 500m sampling horizon will have originated from the surface ocean within the past 2.5 to 15 days for sinking rates of >200 m/day to 33 m/day, respectively, so that with a 3 week study, sinking particles we sample at depth can be related

to euphotic zone processes we observe during our occupation. NBST deployments will be made at three key depths (150, 300, 500m) and replicate deployment of the vertical NBST arrays will be made to address the issue of horizontal variability of flux for differing source regions (n=3 NBST's at 3 depths total). These NBST deployments will be spaced several 10 to ~100km apart based upon underway ship surveys, ADCP velocity fields and available satellite imagery. Two drogued PITS (see **5c**) will also be deployed within the particle source region, along with the respirometer array (n=1; see **5f**) and in-situ trap degradation array (n=1; see **5f**). Similar spatial grids will be used for the CTD/Rosette (for ancillary samples and sensor data), MULVFS large volume pumping system, plankton nets, large volume settling column "snatcher" and deck pump. We anticipate needing two days to deploy the instruments, 3-4 days in the water during which ship based work is conducted, and another couple of days to retrieve and ready instruments for redeployment. This allows opportunity for multiple deployments at HOT and K2. With 3 deployments of 9 NBST's each with 4 sampling tubes, we will thus be analyzing 108 samples for the major flux components in both brine and particle phases. Combined with the drogued traps and other experiments, this intensive sampling of one region will provide a statistically representative sampling of particle flux characteristics during our occupation of each site.

We are of the view that more will be learned from an intensive process study at one site than by taking snap shots along a transect, as we cannot assume that particle sources and remineralization rates are constant. With these sampling time scales we hope to be able to catch potential changes in particle sources and transport efficiency. With multiple NBST deployments and replicate sampling in different locations, we hope to have a statistically meaningful set of flux and remineralization data for a given source region that can be related to observations from the ship. The opportunity to adjust sampling between multiple deployments at one site is also appealing. Thus by taking sampling replicates in space and time, using multiple depths for traps and size fractionated particles, analyzing both trap particles and brines, and looking at in-situ experimental samples, we will obtain a detailed characterization of particle sources, fate and transport in two very contrasting environments.

## 5. INDIVIDUAL PROGRAM ELEMENTS

Data to test our hypotheses will be gathered by employing a unique combination of concurrent geochemical and biological tools, including neutrally buoyant sediment traps, particle pumps, settling columns and respiration chambers. We review the major elements below, focusing in particular on new methods or those under development under this new project. In addition a breakdown by task and PI responsibility is provided in Table 2. This table and the following sections have been arranged to take the reader from the surface ocean to depth, i.e. from activities related to particle source characteristics in the surface ocean (key to *hypothesis 1*) to flux collection methods and remineralization studies in the twilight zone (key to *hypothesis 2*). We also detail the modeling components of VERTIGO and finally the contributions of several research groups that have offered assistance but are not seeking direct support under this proposal. These relationships are also described in supporting letters.

## 5a. Status of the Algal Community

The first of our two hypotheses: particle source characteristics determine transport efficiency of sinking particles refers to biological building blocks (sensu Silver & Gowing, 1991) such as cells, detritus and 'glues' present in the surface mixed layer. Their subsequent interplay results in particle production (primary) that will determine the initial particle populations that will sink into the twilight zone. To understand what causes variations in the number and type of building blocks – such as their size spectra, stickiness, ballast – information is required on the resident plankton community, including both autotrophs and heterotrophs. The community structure of the phytoplankton assemblage (Michaels & Silver, 1988; Boyd & Newton, 1995, 1999) and their physiological status (Kiorboe & Hansen, 1993) are both considered key determinants in the magnitude of downward particle flux. The former will also influence the structure of the grazer community in the upper ocean, which will in turn establish further (secondary) particle transformations via grazing (Michaels & Silver, 1988).

We propose several approaches to quantifying the pelagic particle assemblage and monitoring the physiological status of the resident cells. Firstly, microscopy will provide a detailed picture of the size spectra of the particles from heterotrophic bacteria to mesozooplankton (PI's- Steinberg & Silver) and the use of both epifluorescence, and selective stains (Verity *et al.*, 1996) will yield insights into the relative importance of detrital particles, which are so far poorly represented/constrained in models (Fasham *et al.*, 1990), compared with 'living particles'.

This approach will be complemented with estimates of the partitioning of phytoplankton stocks, carbon fixation, and nitrate uptake into various size classes. This approach, in tandem with microscopy, yields quantitative information on the relative biogeochemical roles of each of these sub-groups of pico-, nano- and micro- phytoplankton, that have been used successfully as predictors of the export flux out of the upper ocean (Boyd & Newton, 1999; Dauchez *et al.*, 1996). Moreover, this partitioning approach will be complemented and compared here to upper ocean estimates of export using [234]Th (Buesseler, 1998).

**Table 2. VERTIGO: Breakdown of tasks and responsibilities**

| Approach & Analyses | Lead PI | Suspended/Sinking Particle Interactions | |
|---|---|---|---|
| **Status of Algal Community** | | Deck pump- size fractionation- CHN, major elements microscopic ID; stains/TEP | Trull Buesseler/Trull Steinberg/Silver |
| size composition, physiological status- size-fractionated FRRF | Boyd | | |
| Algal community structure- microscopic analyses and identification, stains | Boyd/Silver/ Steinberg | Large volume pumps-(0-1000m) geochemistry microscopy | Bishop Bishop/Buesseler Steinberg/Silver |
| Primary production- [14]C | Boyd | C-ARGO floats | Bishop |
| New production- [15]N | Dehairs | Abundances- transmissometer | Bishop |
| Export production- [234]Th | Buesseler | | |
| | | Marine "snow-catcher"- geochemistry | Dehairs Dehairs/Buesseler |
| **Characterization of the Building Blocks** | | | |
| | | **Mid-Water Processes** | |
| Sinking/ascent rates- polyacrylamide gels settling columns | Trull Boyd | Bacteria- Abundance, communities | Silver |
| Ballast properties- bSi, CaCO$_3$ | Trull | Zooplankton- Biomass, composition repackaging, remineralization | Steinberg |
| Isotopes- C/N isotopes [234]Th | Trull Buesseler | | |
| | | **Remineralization Rates** | |
| **Direct Measurement of Flux vs. Depth** | | In-situ trap cup experiments | Trull |
| | | Bacterial respirometers | Boyd |
| Neutrally Buoyant Sediment Traps geochemistry, SEM-EDS, brine C/N isotopes ID, microscopy, swimmers | Valdes Buesseler Trull Steinberg/Silver | Geochemical proxies- Barium [234]Th | Dehairs Buesseler |
| | | **Modeling components** | |
| Drogued traps- Same as NBST & polyacrylamide gels | Buesseler Same as NBST Trull | Food-web/particle processes | Boyd |
| | | 1-D production/export model | Matear |
| | | Particle source regions | Siegel |

It is now well-established that the physiological status of phytoplankton cells will determine key properties that influence particle formation such as sinking rate (Maldonado *et al.*, 2001; Waite & Nodder, 2001) and the production of transparent exopolymers (TEP) (Corzo *et al.*, 2000). The former increases dramatically under environmental stress(es), while TEP are acknowledged to be biological glues that stick particles together (Alldredge *et al.*, 1993; Dam & Drapeau, 1995). An assessment of both the physiological status of the algal community and of each of the pico-, nano- or micro-phytoplankton can be rapidly conducted using fast-repetition-rate fluorometry (FRRF) (Kolber & Falkowski, 1993; Boyd & Abraham, 2001). Moreover, the use of selective carbohydrate stains for TEP (Alldredge *et al.*, 1993) and

algal settling columns (Waite *et al.*, 1992) provide corroborating ancillary data to accompany the FRRF analysis.

Previous studies, have focused – with little success - on exploring the links between the magnitude of primary production and downward export fluxes (Bishop, 1989), when it is clear that many other factors associated with the pelagic planktonic assemblage are intimately involved in determining export (Silver & Gowing, 1991; Boyd & Newton, 1999). Here, by providing a detailed description in space and time of both the nature of the particle assemblage, and their physiological status, we can bridge the gap between the sunlit waters and the rain of settling particles in the twilight zone.

## 5b. Characterization of the Building Blocks

The fate of particles exported from the mixed layer depends strongly on their physical, chemical and biological characteristics. Particle size, density, and coherence are key physical properties that affect sinking rates, and thus the depth of transport into the ocean interior. There is a need to determine these properties directly, as well as to determine the biogenic processes that produce them.

### *Particle Sinking rates*
Particle sinking rate determinations have been carried out with in-situ SCUBA diver measurements (e.g. Alldredge and Gotschalk, 1988), in shipboard settling columns (e.g. Bienfang, 1981; Waite & Nodder, 2001), with a combination camera and cylinder trap system (e.g. Asper, 1987) and from in-situ measurements using instruments mounted on ROV's (e.g. Pilskaln *et al.*, 1998). All of these methods have important limitations. SCUBA is limited to the upper 30m. Shipboard settling experiments generally obtain particles from bottles, which necessarily biases the determinations towards slow sinking rates (e.g. Waite & Nodder, 2001). Large volume "snow-catcher" bottles have been used to infer sinking rates from changes in suspended particle compositions after the bottle is brought on deck. This method is subject to biases from particle density changes induced by pressure, possible convection within the bottle and is also limited to slow sinking rates (Lampitt *et al.*, 1993a). Marine snow flux systems such as used by Asper (1987) derive sinking speeds assuming all particles of a given size have the same sinking rates. The primary limitations on in-situ sinking rate determinations using cameras are the costs and logistical difficulties associated with ROV's and proper statistical sampling of all particle types in a non-turbulent environment.

A promising, but as of yet unexplored approach, is to use a viscous medium in the cups of traps to slow the sinking rate enabling time sequence photography to determine particle sinking rates. Polyacrylamide gels with viscosities similar to honey have been used in sediment traps to enable intact individual particles to be optically examined after trap recovery (e.g. Waite & Nodder, 2001; Waite *et al.*, 2000). The upper layers of the polymer dissolve partially in seawater, forming a density gradient at the bottom of the trap. This allows the particles to slow gently without losing their structure, and then be examined by confocal microscopy. Aggregates up to 2mm in size have been recovered intact.

We propose to further develop this approach to permit sinking rate determinations. First, a range of gel viscosities will be examined in the laboratory to identify the appropriate formulation for the targeted sinking rates (20 to 200 m/d). Second, geometries and baffling required to prevent convection will be tested (simple filling of a cylindrical insert in the lower third of a PITS tube with gel is likely to be successful, but this will nonetheless be tested). Third, test deployments will be undertaken, with sinking rates determined by time-lapse photography after trap recovery, and in comparison to sinking rates of spherical beads of known density. When these aspects of the basic approach are functioning well, we will begin development of in-situ photographic characterization.

### *Particle density*
Density is strongly affected by particle composition, in particular the content of dense minerals such as carbonates, biogenic silica, barite, celestite, and silicate minerals of terrestrial origin. The content of these minerals will be determined on bulk and hand-separated fractions of sinking particles from sediment traps and size-fractionated suspended particles, following established techniques (e.g. Dehairs *et al.*, 2000; Cardinal *et al.*, 2001; Trull *et al.*, 2001).

*Stable C & N isotopes*
A key issue in the investigation of the ecosystem control of carbon export is assessing whether some taxa of phytoplankton are disproportionately responsible for export production in comparison to others. Microscopic examination of sediment trap materials is one approach to examining this issue (see **5e**). Stable carbon and nitrogen isotopic measurements offer a complementary approach. The $\delta^{13}$C of phytoplankton varies in response to euphotic zone environmental conditions (in particular the concentration of dissolved molecular $CO_2$) and in response to cell properties (in particular cell size and growth rate) e.g. Laws *et al.*, 1995; O'Leary *et al.*, 2001; Popp *et al.*, 1998; 1999; Rau *et al.*, 1997. Recent study of the $\delta^{13}$C of Southern Ocean phytoplankton has revealed a wide range of values as a function of size: from $-28$ in cells less than 5 $\mu$m to $-20$ in cells 70-200 $\mu$m in size (Trull & Armand, 2001). Comparison of these values to the seasonal increase in the $\delta^{13}$C of dissolved inorganic carbon suggests that the larger cells are preferentially exported.

The $\delta^{13}$C of mixed layer suspended particles and sinking particles intercepted by sediment traps can also be compared to examine the exchanges between these particle types. During the SOIREE experiment, the $\delta^{13}$C of sediment trap particles did not increase in response to the elevated $\delta^{13}$C of induced algal bloom, making it clear that during the 2 week observation period very little carbon was exported (Nodder & Waite, 2001; Trull & Armand, 2001). In conditions where export does occur, the strong size dependence of the $\delta^{13}$C of phytoplankton permits careful inferences on the primary origins of organic carbon in sediment traps to be made and to be compared with biological examination of these particles (Silver/Steinberg components). The $\delta^{13}$C variation with size may also help calibrate particle aggregation models – aggregates made up of primarily small cells will differ in $\delta^{13}$C composition from those made from a mix of large and small cells.

In addition it is possible to compare autotroph and herbivore carbon isotopic compositions to assist in our study of food web structure. From SOIREE it was possible to conclude that copepods did not feed appreciably on the iron-induced bloom of large pennate diatoms, because copepod $\delta^{13}$C resembled small phytoplankton and not large phytoplankton values. These food web inferences will be improved by including $^{15}$N determinations – which show larger increases with trophic level than does $\delta^{13}$C (e.g. Hobson *et al.*, 1995), and to examine remineralization, which strongly enriches remnant particles in $^{15}$N (e.g. Altabet, 1988). This will be done in tandem with microscopic study (Silver/Steinberg).

One clear target for these approaches will be to attempt to apply carbon and nitrogen isotopic mass balances to determine the relative efficiency of small coccolithophores and large diatoms in contributing to sinking particle organic carbon contents. This will contribute to addressing the roles of different "ballasts" and different "packaging" in the control of carbon export efficiency.

## 5c. Direct Measurement of Flux vs. Depth:  Sediment Traps

*Neutrally buoyant sediment traps*
Sediment traps offer the advantage of allowing direct collection and examination of the sinking particles. However, known problems with upper ocean sediment traps make this approach troublesome (reviewed in Gardner, 2000). Paired traps in the same setting provide the most compelling demonstration of these limitations. For example, Gust *et al.* (1992) found 2 to 5-fold differences in flux from paired drifting mid water traps as a function of horizontal flow across the trap mouth. In the Equatorial Pacific, VERTEX style PIT's traps had fluxes up to 10 times higher at 100m than a newly designed swimmer avoidance IRS trap (data in Murray *et al.*, 1996 and Hernes *et al.*, 1996). At Bermuda, there was roughly a factor of 5 or more difference in the average flux at 400m using PIT's vs. the deep moored traps at 500m (see Fig. 1 in Asper *et al.*, 1992). Not all between trap comparisons show this variability, but when using shallow PIT's it has been difficult to close C budgets better than a factor of 2 or 3 (Michaels *et al.*, 1994; Emerson *et al.*, 1997), and radionuclide budgets such as $^{234}$Th, better than a factor of 3-10 (Buesseler, 1991; Buesseler *et al.*, 1994; Murray *et al.*, 1996).

We have recently designed a solution to what is often considered the biggest problem with traps, namely hydrodynamic biases due to horizontal flow across the trap opening or other motions related to trap

moorings. The Neutrally Buoyant Sediment Trap (NBST) consists of standard cylindrical PIT collection tubes & brine treatment, mounted on a neutral density float such that the relative motion of the package at depth is near zero (Fig. 4). The NBST is preprogrammed to sink to a specific depth for a known time prior to closing and returning to the surface where it is located via satellite positioning (Valdes & Price, 2000).

Microscopic examination provides some of the clearest evidence for trap sorting in the PIT relative to a NBST (Fig. 5). Apparent in this view are differences in the abundance of background marine "snow" particles and the presence of large "swimmers" in the PIT. In an early comparison between PIT and NBST fluxes at 150m, the vertical flux of some components of the settling flux differed significantly - pellets, swimmers, $^{234}$Th, but not others- mass, POC (Buesseler *et al.*, 2000). This supports speculation that if trap collection biases are due to hydrodynamics, particle sorting can occur depending upon the relative rate of particle settling (Gust *et al.*, 1996). Sorting, in addition to flux biases, is a complicating factor in interpreting change with depth. As such, corrections to trap fluxes based upon expected and measured budgets of single elements, such as $^{234}$Th (for shallow traps- Buesseler, 1991) or $^{230}$Th & $^{231}$Pa (for deep traps- Yu *et al.*, 2001; Scholten *et al.*, 2001) cannot necessarily be applied to other components which might have different carrier phases and thus different sinking speeds and trapping biases.



**NEUTRALLY BUOYANT SEDIMENT TRAP**

**SURFACE TETHERED "PIT"**

**Figure 4.** (left)- photo of NBST-II

**Figure 5**. (right)- comparison under light microscope of material in NBST vs. PIT at Bermuda, 150m.
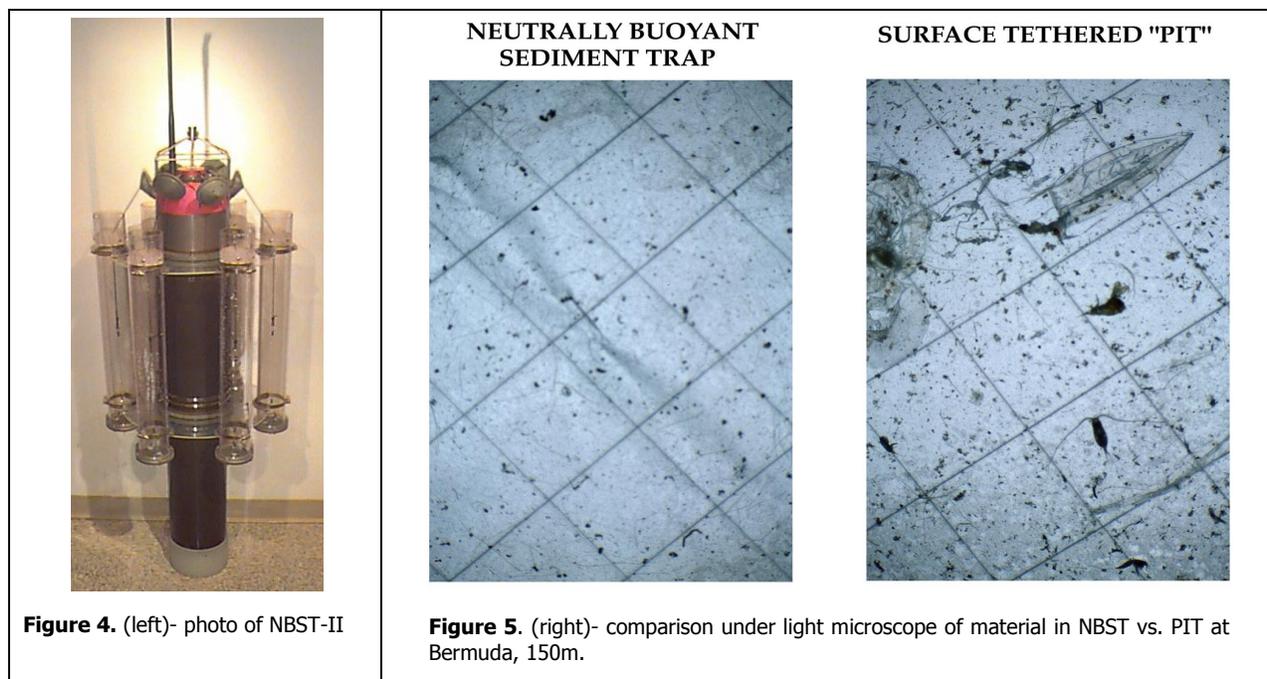
In June and September 2001, we deployed PITs and modified NBSTs, which had improved ballasting capabilities, more sample tubes (n=6), and an improved closing mechanism (Fig. 4). The goal of these deployments was to assess whether particle sorting was occurring. Our deployments caught conditions of low (June) and relatively high (Sept) flux at Bermuda. Despite similar mass and $^{234}$Th fluxes, the NBST fluxes are lower for Si, Ba, Ca and Al (Si and Ca shown in Fig. 6; full data in Stanley et al., 2002a and at http://cafethorium.whoi.edu). Bulk POC flux was statistically higher in the NBST, and neither the PIT or NBST flux vs. depth relationship fit the Martin curve (Fig. 7).

In this latest study, we have found variability in other flux components as well. For example, microscopic analysis detected large numbers of amphipod eggs in the 300m NBST but not in the 300m PIT during one September cruise (Stanley et al. 2002b). Equally intriguing are the presence of strikingly blue particles seen under a light microscope, that with SEM-EDS analyses show high weight percent of Al and Cu. In deep traps at the same site, similar "blue particles" were noted in the 500-1500m moored traps (Ralph *et al.*, 1998). We have no clear explanation at present for the source of these particles, which are

evident in varying numbers in the NBST deployments and deep traps but are never found in the PIT's (Stanley et al. 2002b).

**It appears that the NBST-II opens up a new window on upper ocean sediment fluxes. What we will see through this window is yet to be determined** and one of the main incentives for looking in more detail at different settings and depths with the NBST as proposed here. The NBST by design, reduces to near zero horizontal flow and vertical motions associated with drifting traps, and we attribute the differences found at BATS to removal of this hydrodynamic bias. While we cannot prove the NBST is accurate, the elimination of this known bias and potential for reduced swimmer flux lends confidence that with proper statistical sampling of the particle flux field (see **4c**), our results will allow us to quantify more accurately the particle transport efficiency through the twilight zone (additional background, discussion and presentation of NBST results to date can be found under "Hot Topics" at http://cafethorium.whoi.edu).
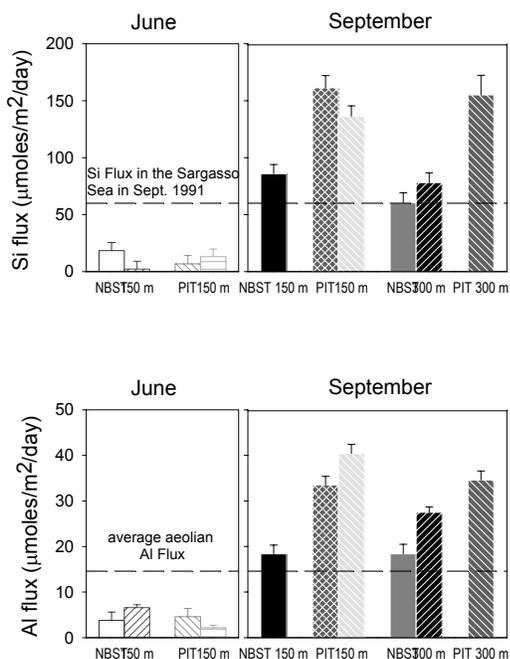


**Figure 6 (left panels)**. Biogenic Si, and aluminum fluxes in the NBST and PITS during June and September 2001 at Bermuda (BATS cruises 153 and 156 respectively). Adjacent bars are two tubes from the same trap at trap depth indicated. Dashed lines for Si and Al flux represent independent estimates of Sargasso Sea fluxes.
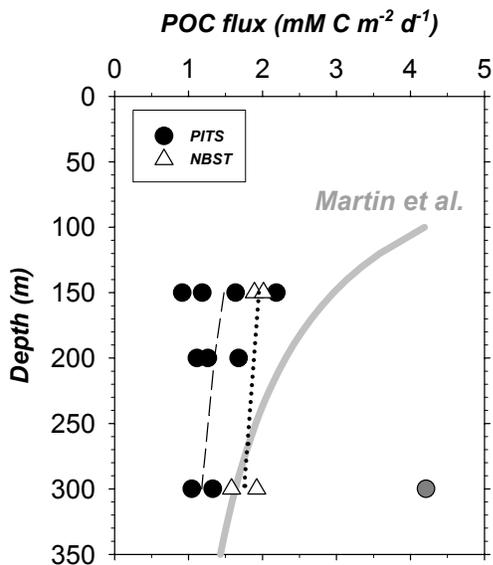
**Figure 7 (right plot)** Flux of POC in PITS (filled circles) and NBST (open circles) for Sept. 2001. Martin "OOC" curve plotted for comparison. Full data can be found at http://cafethorium.whoi.edu under "Hot Topics".

We have gained considerable experience testing and operating the new NBST design. Common to both NBSTs and PITS is tube-to-tube flux variability, which ranges from 2 to 68% (st. dev. between PIT tubes for POC flux for 1991-1998 record at BATS). We believe this is a reflection of the random nature of capturing rare sinking particles, therefore the only major NBST change we propose is to enlarge by a factor of 4 the collection area of the sampling tubes to obtain a better statistical sample. We have also developed procedures to determine all flux parameters- mass, POC, PON, bSi, Ca, major elements, [234]Th and isotopes - from the exact same tubes which will avoid aliasing of geochemical ratios by comparing data from different tubes.

We also need to focus more specifically on measuring not just the particles, but changes in the trap brine/poison that would reflect resolubilization in the collection tube. Like hydrodynamic sorting, selective solubilization of more labile components likely alters trap composition. We need to make appropriate corrections by analyzing the brine for all elements that we study in the particle phase. We

would continue our microscopic examination of each sample and the manual removal, identification and quantification of swimmers as part of this proposal, as we feel that even with the NBST, the careful and consistent treatment of gross & picked material, brines and swimmers is essential to the interpretation of sediment flux data.  This, of course, holds as well for drogued traps (see below).

We feel strongly that the current NBST is ready to move beyond these simple development tests at BATS to deployment within a major research program.  We are proposing to place three NBST's at 150, 300 and 500m (see **4d**).  Nine NBST's would be built under VERTIGO and 2 existing NBST's would serve as reserve for our cruises.  Additional traps also provide protection for the failure or loss of individual units at sea.  Other than the larger diameter tubes, we propose to make minor improvements in the NBST frame and lengthen the existing tether to improve retrieval.  To provide an added safety factor, we propose to test all of the NBST's during a 7 day cruise at HOT in Nov. 2003/Jan. 2004 (along with all other in-water equipment) to ensure that the new gear is ready for the major process cruises and to gain experience on the new Swath, *RV Kilo Moana*, which we believe will provide a stable and excellent platform from which to retrieve our NBST's and other packages (of course we would also use samples from this single deployment for analytical methods testing, and preliminary examination of flux vs. depth patterns).

### *Drogued PIT design*
Standard PIT's are deployed most commonly from a surface-tethered free-drifting mooring at multiple depths, which guarantees horizontal flow at some or all depths.  The only alternative to the NBST that we propose to explore is a PIT trap that is drogued at a single sampling depth.  The primary design features include thin wire, minimal surface flotation and a large drogue just below a modified PIT frame that is equipped with a high quality current meter, ARGOS transmitter and flasher.  A drogued trap should maintain relatively low velocity at the depth of the trap (slip rates near $\sim$1 cm/s expected).  Vertical motions on the mooring line and tilt may still be an issue (Gardner, 1985; Gust *et al.*, 1994) although we will minimize these by using a string of small floats at the surface which can sequentially submerge to dampen wind and wave stresses (Asper & Smith, 1999).  While some hydrodynamical issue will thus remain, we feel that it is worth exploring this alternative to the NBST since it also allows for easy addition of extra sampling tubes or specialized in-situ experiments (such as the in-situ gel filled settling columns-**5b**) that would not be possible with the NBST.  The drogued trap would be visible from the surface floats and provide a good idea of the NBST drift at depth.  We propose to build two traps of this design.

## 5d. Suspended/Sinking Particle Interactions

Marine particles are easily separated operationally into those that can be filtered from seawater ("suspended" particles), and those that are too rapidly sinking to be sampled effectively in this way ("sinking" particles).  For this logistical reason, suspended particles have been more consistently studied than sinking particles.  Of course these pools are not truly separate, and material is constantly exchanged and thus suspended/sinking particle interactions need to be examined within VERTIGO.

Only euphotic zone suspended particles can currently be examined by remote sensing.  While their abundance can be correlated with other measures of export (e.g. traps), improved export estimates will be obtained from better understanding of the pathways of transformation of the suspended particles into sinking ones.  These pathways are both biological (via grazing and fecal pellet formation) and physical (via aggregation) and affect the size distributions and compositions of both the sinking and remnant suspended particle populations (e.g. Jackson, 1995; Kriest & Evans, 1999).  Thus, euphotic zone suspended particles provide insights into particle source characteristics and their role in the transport efficiency of sinking particles (*hypothesis 1*).  Size fractionation is an important tool, because it provides an operational separation of different components of the food web, such as small and large phytoplankton, which often make different contributions to new and recycled production (e.g. Boyd & Newton, 1999; Laws *et al.*, 2000), and to aggregation and export processes (e.g. Kreist & Evans, 1999). The size-fractionation approach has also proved useful in assessing the relationship between aggregation and export as estimated from [234]Th deficits (e.g. Burd *et al.*, 2000).

Meso-pelagic particle transformations are also important to carbon transfer efficiency. Again both biological (via consumption by grazers) and physical processes (such as disaggregation) are likely to be involved, but their relative roles are poorly understood. Examining suspended particle populations can provide insights - if for example suspended particles at depth retain the compositions of the euphotic zone source particles then *hypothesis 2*, that mid-water processes determine transport efficiency, would be weakened. Of particular importance in the assessment of the role of meso-pelagic processes, is the relative magnitude of variations in suspended particle populations in comparison to the magnitude of the sinking flux. Some observations have suggested that these variations can be large and rapid (for example, diel variations in marine snow abundance at 300m depth in the NE Atlantic reached values approximately equal to the euphotic zone export flux (Lampitt *et al.*, 1993a), suggesting that much of the sinking flux was transformed through a meso-pelagic suspended pool.

We plan to examine suspended particle properties using several approaches. At depths of 0-150m we will use a submersible pump, which returns water to the deck via a hose. This system provides large volumes (50 L/min) that can be distributed to different filtration systems, and is used to obtain several size fractions. The system functioned well during SOIREE, and provided particles on 1, 5, 20, 70 and 200 µm pore size filters which allowed hypotheses about export, aggregation and food web structure to be tested (Trull & Armand, 2001). In deeper waters, where particle abundances are lower and hoses are impractical, we plan to use in-situ large volume pumps capable of filtering thousands of liters at depths to 1000m (MULVFS system from Bishop). We will also size fractionate the deeper particles, though probably using fewer size classes, due to lower particle abundances. To augment both particle collections, particle distributions will be examined by transmissometry from both the CTD, and from autonomous profilers (C-ARGO; Bishop) deployed during our field work at both sites. These profilers are exciting new technology that were well demonstrated during the recent So. Ocean iron fertilization study. The data are transmitted to shore, providing daily estimates of the detailed structure of suspended particle concentration, and by difference and optical approaches, a qualitative estimate of flux changes. Funding for this component will be obtained through DOE's support of Jim Bishop's lab, and details of this effort can be found at Jim's web site (http://www-ocean.lbl.gov/NOPP.html) and in his attached letter.

## 5e. Mid-Water Processes

Biological processes that mediate remineralization of POC into a dissolved form in the mesopelagic zone include decomposition by microbes (bacteria and protozoans) and grazing by zooplankton. The microbial community associated with particles is usually assumed to remineralize much of the sinking detritus (e.g. Azam, 1998), but the relative importance of the microbial vs. zooplankton communities in the remineralization of particles at depth is not well known. Bacterial activity on sinking particles appears insufficient to account for the observed decrease in POC flux with depth, as measured by traps (e.g. Karl *et al.*, 1988, Taylor & Karl, 1991). Alternatively, carbon may be lost via fragmentation of sinking matter into small, slower settling particles, or via consumption by zooplankton or both. We propose a suite of measurements to characterize the microbial and zooplankton communities in the mesopelagic zone and determine their potential contribution to particle attrition and composition changes with depth.

### Midwater microbial community and processes
Profiles of bacterial abundance with depth generally show an exponential decrease in abundance, mirroring the POC fluxes with depth (Nagata *et al.*, 2000). These and other data suggest that the POC flux fuels the resident bacterial populations at depth. The coupling between flux and bacterial production appears close and is possibly related through the enzymatic hydrolysis of sinking particles to DOC, which then supplies the suspended bacterial pool that ultimately completes the remineralization of organic carbon (Cho & Azam, 1988, Smith *et al.*, 1992, Hoppe & Ullrich, 1999). Very high bacterial diversity in the mesopelagic has been recently confirmed (Moeseneder *et al.* 2001), possibly reflecting the spatially heterogeneous "organic matter continuum" described by Azam that is a fundamental feature of the microbial environment. Bacterial productivity and turnover can be highly variable and such estimates have potentially large errors because biomass estimates may include populations of relatively inactive cells, though very recent evidence suggests such cells may be a small fraction of the population (Nagata *et al.*, 2000, Karner *et al.*, 2001).

A complication in understanding mesopelagic communities is the very limited information about the most recently recognized group of bacteria-like prokaryotes in these deep waters, the archaea. Archaea, which are by most authors not differentiated from prokaryotes within the domain "bacteria", have been recognized as a large and diverse group of microorganisms whose mesopelagic abundance reaches that of bacteria but whose physiological roles at depth are almost unknown (Karner *et al.*, 2001).

The measurements related to the microbial regeneration of particles in this project include direct microscopic examination of microbial communities on particles obtained from trap and pump collections and from *in-situ* experiments. These measurements are, for the most part, relatively simple and direct and provide descriptions on the particle milieu and *in-situ* communities that are invaluable. Additionally, we will characterize the particle types to determine whether the particles (and some of the more readily identifiable organisms on them) likely represent populations from the same source or appear to be derived from sources outside the "statistical funnel" (see **4c**). Vertical and horizontal variations in particle types and communities can provide insight into regenerative rate processes, especially when sinking rates of those particles can be determined. We (Silver/Steinberg/Boyd) will quantify the major recognizable particle classes and one of us (Silver) will determine the abundance of major microorganism groups and recognizable taxa (e.g. of > 10 $\mu$m photoautotrophs and protozoa) on samples from traps, incubations and (as needed) from pump samples. Additionally Silver will enumerate the bacteria-like organisms.

Counts of microorganisms associated with particles will be made on subsamples of material obtained from sediment traps, incubation chambers and pumps in Silver's lab. Basically, subsamples will be counted on DAPI-stained (Porter & Feig, 1980) preparations in settling chambers using an inverted microscope for >2 $\mu$m cells, including small heterotrophic protozoans, flagellates, ciliates, sarcodines and photoautotrophs such as diatoms and dinoflagellates. Bacteria-sized cells will be enumerated on filters using epifluorescence microscopy on filters after particles have been disrupted (to more evenly disperse the bacteria) and stained with DAPI. For additional assistance in identifying selected taxa of protists, as needed, Silver will use her standard protocols for either scanning cell surfaces by SEM or investigating cellular features that are diagnostic, using TEM (techniques described in Silver & Alldredge, 1981). Subsampling and sample processing techniques for particulates will be those described previously (see Silver & Gowing, 1991, Silver *et al.*, 1998 and references therein). Additionally Silver will use histological stains on trap material, including stains for TEP (Passow & Alldredge, 1995), to attempt to recognize some of the less readily identifiable organic detritus so common in sinking POC.

### Midwater zooplankton community and processes
Evidence for a significant role for zooplankton in affecting remineralization of POC at depth originates from studies of diets of midwater zooplankton, including vertical migrators, and calculations of the carbon demand of the mid water zooplankton community. Detritus, or marine snow, is presumed to be an important food source for several deep-sea non-migrating (e.g. Gowing & Wishner, 1986, 1992, Steinberg 1995, Uttal & Buck, 1996) and migrating zooplankton species (Suh *et al.*, 1991, Flock & Hopkins, 1992, Lampitt *et al.*, 1993b, Dilling *et al.*, 1998, Schnetzer & Steinberg, 2002a). Furthermore, feeding and swimming activities of zooplankton can cause fragmentation of large sinking marine snow into smaller non-sinking aggregates (Dilling & Alldredge, 2000, Graham *et al.*, 2000). This process diminishes aggregate flux to depth and influences the contribution of fecal pellets and other sinking detritus to overall POC flux (Steinberg *et al.*, 1997, Dilling & Alldredge, 2000). Diel vertically migrating zooplankton may affect C flux at depth by defecating surface-ingested C after their descent to daytime mesopelagic residence depths (Flint *et al.*, 1991, Atkinson *et al.*, 1996, Morales, 1999, Schnetzer & Steinberg, 2002b) or by respiring and excreting this C in a dissolved form at depth (e.g., Longhurst *et al.*, 1990, Zhang & Dam, 1997, Steinberg *et al.*, 2000); this is termed the "active flux".

There are two qualitative measures of detrital feeding and repackaging of material at depth that we will employ. The first is the appearance of significant changes in the numbers, size, shape and color of pellets from the surface to deep water in our trap samples indicative of repackaging by the grazing community at depth (e.g. Honjo, 1978). For example, feces resulting from coprohagy or coprohexy (consumption or breaking of fecal pellets) are lighter in color than fresh feces, and the peritrophic

membranes surrounding the pellet may not be intact (Noji, 1991, Noji *et al.*, 1991, Urban-Rich *et al.*, 1999). We will microscopically examine subsamples of trap material collected at different depths.

The second method will be to examine gut contents and fecal pellets of the community at depth for evidence of detrital feeding. Studies that have compared the character of sinking material with the gut contents of deep-living copepods (Gowing & Wishner, 1986, 1992, Steinberg, 1995) and the fecal pellets or gut contents of a variety of vertical migrants (Lampitt *et al.*, 1993b, Schnetzer & Steinberg, 2002a) have found a "marine snow signature"– olive-green material, mucous feeding filters, or large numbers of cyanobacteria (too small to be ingested individually and presumably ingested within an aggregate)– within animal guts or feces. For non-migrating species, large numbers of phytoplankton fragments in guts is also evidence of consumption of phytoplankton aggregates. We will examine the foreguts or fecal pellets of several species of zooplankton collected at depth for such "marine snow" signatures according to the methods of Lampitt *et al.*, 1993a, Steinberg, 1995, and Schnetzer & Steinberg (2002b) using a combination of epifluorescence and scanning electron microscopy (SEM).

The contribution of zooplankton to remineralization of sinking particles has been estimated by comparing losses of sinking C measured by traps with zooplankton metabolic requirements (Lampitt, 1992, Koppelmann & Weikert, 1999, Sasaki *et al.* 1988, Steinberg *et al.*, 1997). We will estimate zooplankton respiratory carbon demand based upon measures of biomass and published relationships of zooplankton body weight and respiration rate (Sasaki *et al.*, 1988, Lampitt, 1992) using the appropriate stoichiometry and respiratory quotient to determine respiratory C demand (Parsons *et al.*, 1984, Gnaiger, 1983, Ikeda & Skjoldal, 1989). Respiration rates can be converted to C consumption rates using: C consumed = C respired/R x AE, where R is the fraction of assimilated C respired, and AE is the assimilation efficiency (fraction of C consumed that was assimilated). Values of R and AE will be taken from the literature for mesopelagic zooplankton (e.g. Lampitt 1992, Wishner & Gowing, 1987, Steinberg *et al.*, 1997).

Biomass and major taxonomic composition of the mesopelagic and migrating zooplankton community will be determined from net tows taken in 100m depth intervals from the surface to 1000m with a 1 m$^2$, 200 $\mu$m multiple opening/closing net (MOCNESS: Wiebe *et al.*, 1985) in oblique hauls during both day and night. Samples will be split on board using a Folsom plankton splitter with half the samples preserved in 4% buffered formaldehyde, and half size-fractionated for determination of wet and dry weight. Mesozooplankton size-fractionated biomass will be determined on cruises according to standard JGOFS protocols (Landry *et al.*, 2001, Madin *et al.*, 2001). Zooplankton tows will be fractionated by wet sieving through nested sieves with mesh sizes of 5, 2, 1, 0.5 and 0.2 mm, with individual fractions transferred to tared disks of 200 $\mu$m nitex netting (Madin *et al.*, 2001). These will be immediately frozen for subsequent wet and dry weight analyses. Subsamples of preserved tows will be analyzed microscopically for composition of major taxa.

## 5f. Remineralization Rates

### *In-situ trap cup experiments*
We propose a novel method for this approach, in which we will collect sinking particles into an automated rotating cup sediment trap (Honjo design with the funnel replaced by a modified PIT style cylinder, and with each cup divided into 2 halves – one with HgCl$_2$ poison the other without). The cups will collect and then close, allowing remineralization and solubilization to proceed. After periods of a few days to a week the traps will be recovered and the compositions of the poisoned and unpoisoned materials will be compared. This will allow remineralization to be examined at in-situ pressures. If we can establish that polyacrylamide gels represent an inert medium in which this remineralization can occur, we will try some cups with gels to examine remineralization without the added effect of contact among many particles.

### *Respirometers/in-situ chambers*
An alternative yet complementary approach to using sediment traps in the twilight zone to derive information on the vertical attenuance of biogenic particles is provided by measurement of bacterial activity, since these rates may provide an estimate of remineralization of particles (Hoppe *et al.*, 1993; Azam, 1998; Ploug *et al.*, 1999; Rivkin & Legendre, 2001). Such depth-dependent estimates of bacterial

activity have recently been incorporated into particle flux models where they can be compared with long-established relationships between particle flux and depth such as the Martin curve (Boyd & Stevens, 2002). Measurements of bacterial rates include growth (Turley, 1993), exo-enzyme activity (Hoppe *et al.*, 1993) and respiration (Ploug *et al.*, 1999; Sherry *et al.*, 1999). However, problems exist with such approaches, since they are restricted to bacterial sampling from depth, followed by shipboard incubation at *in-situ* temperatures but at surface pressure. Pressure has been shown to influence strongly bacterial physiology (Turley, 1993). Furthermore, such sampling has been mainly limited to volumes < 300 ml due to bottle sizes that can be accommodated using the Microwinkler technique to measure respiration (Boyd *et al.*, 1999). Thus, large rare settling particles are likely to be under-sampled (Gardner *et al.*, 1993).

We propose an alternative approach – that of large volume respiration chambers – to overcome many of these problems. A vertical array of 5L opaque chambers will be deployed in the twilight zone, and spaced exponentially, securely attached onto a wire cable in the upper 50-250 m of the water column. After deployment, the vessels, initially filled with freshwater, are pre-programmed to open and sample water, containing particles and bacteria, at *in-situ* pressure and temperature via a relatively large diameter (90 mm) opening.  The manufacturer has successfully conducted dye studies to ensure that the sample is well mixed within the chamber, both after the fill cycle is completed and during the incubation.  Upon closure, an incubation of up to 96 h duration (depending on the magnitude of the respiration signal, but short enough to minimize any significant sensor drift (drift measured over 33 h at 120 m depth was 0.001 +/- 0.002 micromol $Kg^{-1}$ $h^{-1}$) takes place at *in-situ* pressure and temperature. Respiration over this time-course is determined continuously using high sensitivity $O_2$ micro-electrodes (previously calibrated using the Microwinkler technique). The respiration rates are not straightforward to interpret as the term will include the solubilization of suspended and sinking particles, (see discussion in Wakeham & Canuel, 1988; Boyd *et al.*, 1999) and thus care must be taken in the interpretation of these data. However, ancillary data from other concurrent approaches during the proposed studies will provide information on the likely magnitude of these particle pools and fluxes (see **5f**, above). Although these chambers were custom-built, they are essentially modifications of a tried and tested design used on moorings and free drifting arrays to investigate rates of photosynthetic oxygen evolution and respiration in the open ocean (Langdon *et al.*, 1995); this basic design has also been employed in the deep ocean as part of the sensor suite on benthic landers (MANOP).  Recently, a vertical array of 4 chambers was successfully deployed (36 h) and tested in the open ocean waters east of the South island of New Zealand. Respiration rates of 1.5 +/- 0.13 micromol $Kg^{-1}$ $d^{-1}$ were observed at 50 m depth (below the base of the mixed layer), with a pronounced decrease in rates at depth (0.21 +/- 0.05 micromol $Kg^{-1}$ $d^{-1}$ at 120 m).

Due the non-intrusive nature of this approach, at the end of each deployment a 5L volume of water containing particles modified by bacteria during the incubation (and a bacterial assemblage that has solubilized resident particles) may be sub-sampled. A subset of the following bacterial or biogeochemical assays will be performed- bacterial abundance, viability (Sherry *et al.*, 1999), community structure (Cottrell & Kirchman, 2000), exo-enzyme activity (Hoppe *et al.*, 1993), particulates (POC, opal), and stable isotopes (N, C). These may be compared with time-zero samples collected using a CTD rosette. Thus, a coupled dataset of both rates of bacterial respiration and its impact on bacterial processes and the biogeochemistry of the particles can be obtained.

### Excess $^{234}$Th
Low activities of the naturally occurring radionuclide $^{234}$Th ($t_{1/2}$ = 24.1 days) relative to its soluble parent, $^{238}$U (i.e. $^{234}$Th/$^{238}$U activities <1), can be quantitatively related to the flux of $^{234}$Th on sinking particles out of the surface ocean (e.g. Coale & Bruland, 1987).  Excess $^{234}$Th features ($^{234}$Th/$^{238}$U) associated with the release of $^{234}$Th on settling particles have been seen in earlier studies just below the mixed layer, but were generally limited to single data points due to sampling and analytical difficulties.  However, a new method for total $^{234}$Th requires only 2-4L volumes collected from the CTD/rosette and samples are quickly processed and counted at sea (Buesseler *et al.*, 2001; Benitez-Nelson *et al.*, 2001b).  Now we can sample selectively along density gradients and in association with supporting biogeochemical and optical data, to identify sinking particle source depths and shallow remineralization features associated with microbiological or heterotrophic processes.  Combining the $^{234}$Th flux and the measured ratio of POC (or

PON or bSi) to [234]Th on sinking particles (collected here using NBSTs), one can estimate elemental fluxes of C and associated elements out of the surface ocean (summarized in Buesseler, 1998 and references therein). We will use [234]Th primarily to determine EP, the shallow export flux in the particle source region. [234]Th cannot be used to resolve flux patterns throughout the twilight zone, but it will aid to quantify **shallow** export rates and transport efficiencies.

### *Barium*
Oceanic profiles of particulate non-lithogenic Ba (a large fraction of which is barite) are generally characterized by a broad concentration maximum at **mesopelagic** depths (e.g. Collier & Edmund. 1984, Dehairs *et al.*, 1991) coinciding with the depth zone where POC content and flux decrease sharply (i.e. approx. between 100 and 600m). The magnitude of this Ba maximum is related to the intensity of algal production and export processes. The response time of the mesopelagic Ba stock in relation to surface processes is likely on the order of one month. In combination with assessment of ^{15}N new production and [234]Th deficit, the process of carbon export can thus be investigated over different time scales, extending from hours to one month, and depth scales, from the surface to mesopelagic. In addition to information on export, Ba profiles also contain information on the remineralization of organic matter in the subsurface waters. For Ba this is inferred from correlations between stocks of mesopelagic Ba and $O_2$ consumption, identifying Ba as a proxy for remineralization of exported organic matter in the mesopelagic zone (Dehairs *et al.*, 1997). Further comparison of mesopelagic Ba stocks with in-situ remineralization/respiration rates (see **5f**, above), as well as with plankton community composition is a prerequisite to validating this proxy. If the elaboration of algorithms relating Ba with remineralization rates were successful, it would be possible to use highly depth-resolved vertical distributions of particulate Ba as templates for remineralization length scales. The proposed fieldwork sites that contrast strongly with respect to coccolithophorids versus diatoms sources are ideal for an assessment of possible effects of community composition on the Ba proxy.

## 5g. Modeling Components

Interpretation of the proposed process observations require quantitative modeling of particle production, transport, and transformation processes at several scales. We propose a 3-strand approach:

**i. In order to assess temporal variations in particle production and export** we will simulate a full year of upper ocean processes using a high resolution (5 m vertical, 6 hour temporal) 1-D model of the dynamics of the upper 1000m, which is driven with surface forcing (e.g. NCEP data). This model has been used successfully to simulate dynamics at sites in the Southern Ocean (Wang & Matear, 2001) including in the sub-Antarctic at 47°S which gives us confidence that it can be applied at 47°N. The physical model simulates temperature, salinity, mixed layer depth, intensity of mixing, and the entrainment and de-entrainment of nutrients and particles. The physical model will be coupled to biological models to predict export production. Two general approaches will be pursued – using either a prognostic biological model, e.g. as used recently to simulate nutrient cycling at Station Papa (Wong & Matear, 1999) or via assimilation of Chl-*a* concentrations estimated from SeaWiFS observations, e.g. as done to estimate export production in the Southern Ocean (Wang et al., 2001). The 1-D approach may be extended to include advective transports estimated from field data or general circulation models (Wang et al., 2001) if we find these corrections are required. Modeled estimates of export will be based on very simple parameterizations, such as linear function of primary production and will not be able to fully simulate the seasonal cycle of export in an exact manner. Thus they will serve primarily as a null model for comparison with more sophisticated models formulated from the field observations. The seasonal simulations will be very useful to look at the possible influence of day to week timescale temporal pulsing of nutrient inputs, production and particle de-entrainment on the observed particle fields. They will also provide a framework for the quantitative comparison of the observed particle fluxes with the magnitude of depletion of the dissolved nutrient field. This will permit the examination of varying remineralization length-scales and non-Redfield remineralization stoichiometries from both particulate and dissolved nutrient fields. Strand 1 will be led by Richard Matear (letter attached), who has extensive experience with both mixed layer and global carbon cycle models, with observational and conceptual input from Tom Trull and the VERTIGO team.

ii. **To address the issue of spatial variations in particle production and export**, we will model the mesoscale variations of the paths of particle export which "funnel" particles to the proposed sediment traps.   This work draws on approaches applied previously to deep sea moored traps (Siegel et al., 1990; Siegel & Deuser, 1997; Siegel & Armstrong, 2002).  Velocity data from 1) moored upward looking ADCP deployments at both the HOT and K2 sites (see attached letters of support), 2) shipboard ADCP and geostrophic velocity determinations (from initial site surveys), 3) satellite-based measurements of sea-surface height (altimetry) and winds (scatterometry) and 4) mesoscale structure function analyses (derived from CTD data) will be used to model time/space dependent velocity fields.  Using these 4-D velocity fields, Langrangian models of particle source regions will be constructed for both NBST and moored sediment trap deployments.  The resulting time dependent estimates of particle source region will be compared with satellite ocean color and in situ data to best assess the coupling between export and trap collections.  Particle source models to date have assumed a constant particle sinking rate. An opportunity to refine this approach considering aggregation/disaggregation effects on sinking rates (an aspect of strand 3) and thereby on the extent of the particle source region will be an important outcome of the proposed work. Dave Siegel will lead strand 2 in collaboration with the VERTIGO team.

iii. **To address the role of initial particle characteristics and subsequent transformations in the efficiency of particle export** we will apply a food-web based particle production, disaggregation, and export model, as applied recently to the northeast Atlantic (Boyd & Stevens, 2002).  The model incorporates aspects of food-webs models - which have not directly addressed coagulation during blooms (e.g. Boyd & Newton, 1999) - by consideration of aggregation processes based on field observations such as stickiness and cell size (Burd & Jackson, 1997). The model uses observations to initialize a particle size spectrum, including distinguishing between sinking-particle nuclei and those particles that will form the residual particle field. The model also incorporates mixed layer particle residence times and vertical gradients - such as particle concentration, and bacterial solubilization – measurements made by VERTIGO. The model will derive the POC flux at any depth, along with concurrent information on sinking rates, C content, C:N ratio, volume and mass of each of the representative particle nuclei along with accrued/scavenged particles.  Importantly, the NE Atlantic results revealed that simulated particle sinking rates were faster than those observed typically in the ocean.  This suggests the importance of disaggregation and/or other particle transformations in the mesopelagic zone.  The model will focus primarily on the field results, but will also draw on inputs from modeling strands 1 and 2.  This includes consideration of spatial variations in particle production from the satellite observations, phytoplankton surveys and mesoscale modeling of particle source regions in strand 2, as well as the estimation of the vertical and temporal variability in mixed layer turbulence modeled in strand 1 (for example the particle model uses turbulent flow quantities to quantify particle contact rates within the mixed layer).

The proposed modeling strands have as their first focus the quantitative assessment of VERTIGO field observations, but each strand also proposes general improvement in the description and parameterization of export efficiency.  The application of these new parameterizations in ocean carbon models will allow the sensitivity of air-sea $CO_2$ fluxes to particle export fluxes to be evaluated (and compared with classical power-law remineralization simulations) at both regional and global scales.  The refined estimates of the control of the efficiency of particle export of carbon can then be used to improve estimates of the response of the biological pump to climate change (e.g. Matear & Hirst, 1999), decreased overturning circulation (Matear *et al.*, 2000), and purposeful iron fertilization (Boyd *et al.*, 2002).  The application of improved particle export parameterizations to large-scale carbon cycle simulations is beyond the scope of this proposal (and no support is requested for this work here), but nonetheless this perspective informs the overall strategies of the 3 modeling strands and the design of the field experiments.

## 6. ROLES OF EACH PI/RELATIONSHIP TO OTHER PROGRAMS

Innovative tools and concurrent measurement of biological, geochemical and physical parameters are needed to investigate twilight zone processes, as is expertise in modeling of particle processes and nutrient fluxes at local to global scales.  We therefore organized this proposal around the minimum set of expertise's in the US and international community to provide the maximum return from a coordinated

biogeochemical and modeling assessment of particle transport efficiency in the twilight zone. Table 2 outlines major PI tasks and responsibilities of this VERTIGO group.

While developing VERTIGO we also identified ancillary approaches and science questions that would add value to VERTIGO, including colleagues interested in seeking separate funding later for this work. These potential contributors include, but are not limited to: natural radionuclides- Pb/Po (M. Sarin- letter attached); in-situ camera studies (C. Pilskaln- letter attached); particulate iron (P. Sedwick- letter attached); mesopelagic archaea (D. Karl- letter attached); organic biomarkers; additional trap designs; etc. Our priority is to pursue the core research strategy presented in this proposal, while remaining open to other synergies as they are developed and judged on their own merit.

Finally, we have taken advantage of interagency interest and responsibilities as outlined in the US Carbon Cycle Science Plan, and if successful, anticipate co-funding of this VERTIGO proposal and budget as presented here to NSF, through DOE's Ocean Carbon Sequestration Research Program.

## 7. BROADER IMPACTS

This basic research proposal is designed to have maximum intellectual impact but there are broader outcomes and impacts from this proposal as submitted. The main PI's (Buesseler, Boyd, Siegel, Silver, Steinberg and Trull) have a strong record of student training and mentoring, and this project is no exception. In addition, our groups will continue to maintain science web sites that are designed for both public and scientific exchange where the broader and specific goals and outcomes of this work will be presented. Despite high levels of public confidence in scientists, an understanding of how science works (i.e., *science literacy*) remains mysterious to many lay people. The highly interdisciplinary nature of the proposed research, its use of sophisticated technology, and its relevance to important societal concerns combine to make it an ideal project for widespread dissemination to the general public. Steinberg will use the significant education and public outreach infrastructure at VIMS (VIMS is an NSF- funded COSEE-Center for Marine Science Education Excellence- site, and home of the Sea Grant Marine Advisory Program) to offer public lectures and a web cast on the ocean's twilight zone. Through a new NSF Biocomplexity grant on which Steinberg is co-PI, VIMS is offering a "mini-school" (a six-week series of evening seminars on various aspects of marine science and policy for the general public and local educators) on the ocean carbon cycle. As part of this annual series, Steinberg will give an additional public talk on VERTIGO (at no cost to this proposal). She will also work with VERTIGO PIs and VIMS outreach staff to develop a web cast on the ocean's twilight zone (see Cohen-VIMS letter). This will be advertised widely through VIMS and WHOI outreach programs.

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