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Long time-series monitoring of an abyssal site in the NE Pacific: an introduction

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1. Introduction

Abyssal regions of the world ocean cover more than 50% of the Earth's surface (Gage and Tyler, 1991) but the biogeochemical processes in the sediments and deep water column of this vast expanse of our globe are poorly understood. The cycling of material through these deep-sea regions is intimately linked to the organic matter produced in the euphotic zone. The material sinks as particulate matter, undergoing various physical and biochemical transformations in the water column before reaching the seafloor.

Temporal variability of plankton production in the upper ocean is well documented. The fraction of this production that escapes the euphotic zone as particulate organic matter sinking into the deep sea also exhibits temporal variability, reflecting the changes in surface water production. Independent long time-series measurements of particulate organic matter fluxes to abyssal depths (e.g. Deuser et al., 1981; Honjo, 1982; Deuser, 1986; Haake et al., 1993) and time-lapse photographic records of phytodetrital pulses reaching the sea floor (e.g. Billett et al., 1983; Lampitt, 1985; Rice et al., 1986), although taken in widely separated areas of the deep ocean, have been invaluable for predicting events in other regions.

However, the cycling of organic matter in the deep ocean has been difficult to evaluate because synoptic measurements on sufficiently long time scales are rare. The lack of long time-series measurements to examine concurrently the input of a pelagically derived food supply and its impact on benthic boundary layer (BBL) processes

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prompted us to establish a long-term, abyssal study site in the NE Pacific in June 1989. The resulting 7-year study of the BBL at a single site represents the longest continuous time-series study of any abyssal area in the world ocean. Over the past 7 years we monitored continuously the flux of sinking particulate matter through the BBL and employed time-lapse photography to record dynamic benthic processes. During this same time period, we and our colleagues made seasonal measurements of particulate, suspended, and dissolved organic and inorganic fractions through the water column and in the sediments, and have monitored sediment community oxygen consumption (SCOC). More intensive studies of BBL processes also were carried out using the visual and manipulative capabilities of the deep submergence vehicle *Alvin* during two cruises in August and September 1994 and one cruise in April 1995.

2. Area of investigation

The principal criteria for establishing this long time-series station were the following: (1) a low-relief area at abyssal depths with no recent evidence of turbidity flows or slumping, (2) strong seasonal variability in surface water productivity, and (3) logistically convenient location for seasonal occupation by research vessels. We chose a single abyssal station (Fig 1; Sta. M; centered at 34°50′N, 123°00′W; 4100 m depth) in the NE Pacific, 220 km west of Point Conception off the central California coast (Smith et al., 1992). The sea floor at this site is characterized by silty-clay sediments and had little topographic relief (< 100 m over 1600 km^2). Surface waters of the California Current overlying this site have well-developed spring plumes of chlorophyll that persist into summer (Smith et al., 1988; Michaelsen et al., 1988) and exhibit interannual variability (Pelaez and McGowan, 1986). We anticipated that this temporal signal in surface production would be observed in the BBL.

For our studies we defined the BBL as the sediments and the overlying 600 m of the water column. The 600-m altitude was above the zone of resuspension that extended from the sea floor up to ~ 200 m above bottom (mab) (Smith et al., 1994). Current meter records at 2.5, 50 and 600 mab showed the highest flow at 50 mab with an average of 3.8 cm s^{-1} and a maximum of 18.2 cm s^{-1} (Beaulieu and Baldwin, 1998). Light transmission profiles suggested the benthic mixed layer extended up to 80 mab with an average of 45 mab (Beaulieu and Baldwin, 1998). Fluxes of sinking particulate matter entering the BBL varied seasonally, with a primary peak in early summer and a secondary peak in late fall (Smith et al., 1994; Baldwin et al., 1998). However, there were significant interannual deviations in flux patterns, especially during climatic perturbations such as the 1992–1993 El Niño Southern Oscillation (ENSO) event when sinking particulate matter fluxes were greatly reduced (Baldwin et al., 1998). Detrital aggregates (defined as clumps of amorphous-looking particulate matter observed in photographs of the sea floor and distinguished by color, shading, or texture) were observed on the sea floor at Sta. M, typically arriving in summer and remaining visible through late fall (Smith et al., 1994, 1998; Lauerman and Kaufmann, 1998).

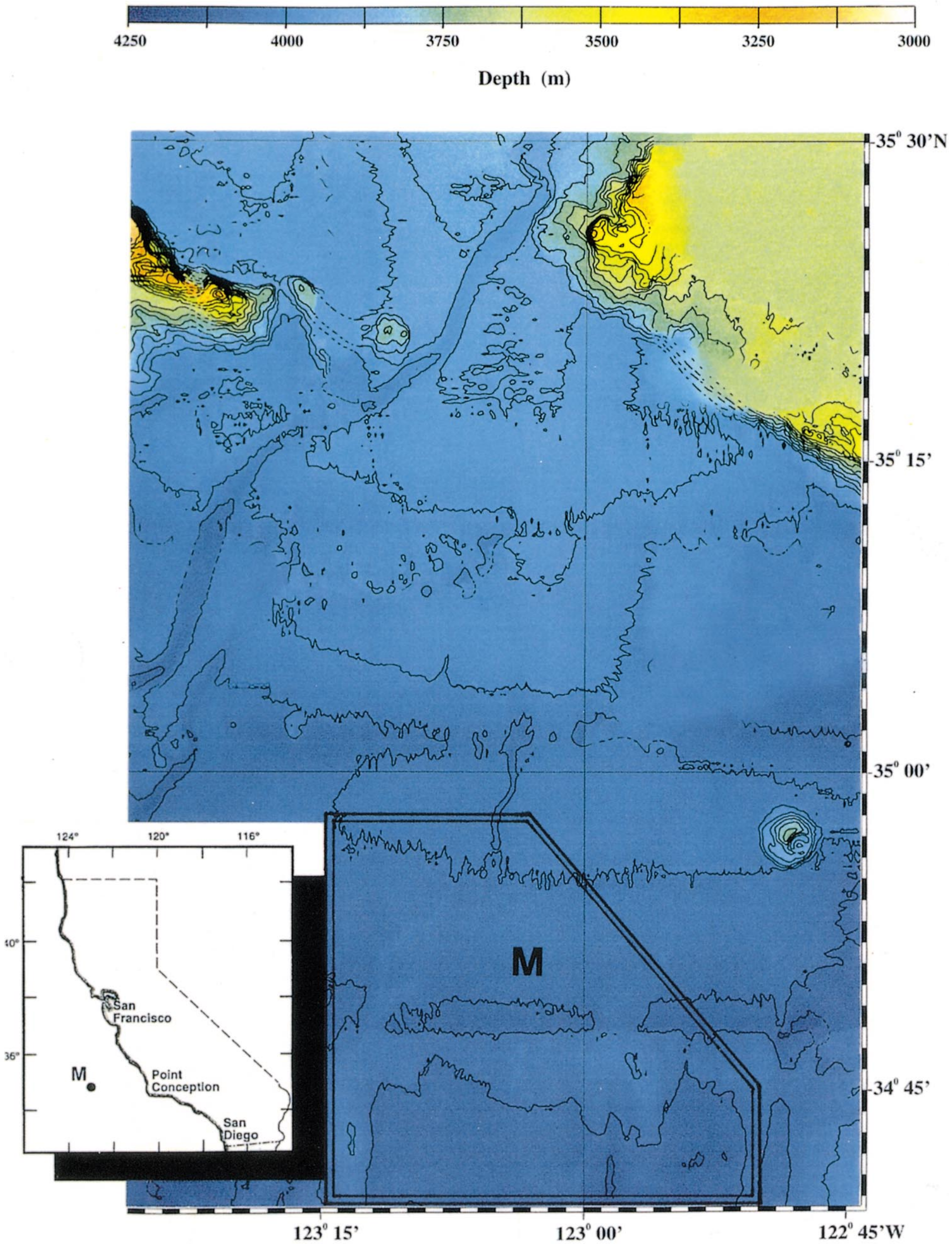

Fig. 1. Bathymetric chart of the sea floor off the central coast of California including the Sta. M site. The bathymetry was generated from a multibeam acoustic survey conducted in November 1996 (R/V Revelle with hull-mounted Sea Beam array) with 20-m vertical resolution.

Sinking particulate matter fluxes at 50 mab were greater than at 600 mab, suggesting resuspension or lateral advection of material into the study area nearer to the bottom (Baldwin et al., 1998). Resuspension of material from the local area or laterally advected from distant sources on the continental margin was suggested by the chemical composition of dissolved (Bauer et al., 1998), suspended, and sinking particulate fractions (see Bianchi et al., 1998; Druffel et al., 1998; Shaw et al., 1998; Sherrell et al., 1998) collected at 150–1500 m and below 2500 m depth (1600 mab). Distinct seasonal variations were explained by the dynamic interactions between these size fractions. During this time-series study, evidence for the local resuspension of sediments at Sta. M was indicated only during one brief 3-h period (using observations of time-lapse photographs and concurrent flow measurements; Beaulieu and Baldwin, 1998). Beaulieu and Baldwin note that the recently deposited, flocculent detritus would be resuspended more readily than the sediments given the flow environment at Sta. M.

3. Instrumentation

A critical aspect of our 7-year study was to incorporate as many long-term monitoring systems as was possible within budgetary constraints to provide a "continuous picture" of some of the principal processes within the BBL. Sediment traps were the first monitoring instruments deployed at Sta. M (Table 1; Smith et al., 1994). Each sediment trap was equipped with sequencing collection cups to provide 10-day sampling resolution with servicing every four months (Baldwin et al., 1998). Sediment traps were first deployed at 600 and 50 mab. Subsequently, another sediment trap was added at 650 mab to provide additional samples required for the radiocarbon analyses (see Druffel et al., 1996). The sampling altitudes of 600 mab and 650 mab were selected to place the sediment traps above any zone of resuspension or advection-related turbidity. The sampling altitude of 50 mab was chosen to provide an estimate of the composition and flux of sinking particulate matter in close proximity to the bottom for comparison with sea floor processes and to assess the magnitude of any input from lateral advection and/or resuspension.

Shortly after the sediment trap moorings were installed, a time-lapse camera system was fabricated and deployed in October 1989 (Table 1) to monitor the presence of detrital aggregates and the movements of epibenthic megafauna over a 20 m^2 area of the sea floor (Smith et al., 1993). Smith et al. (1994) presented the early portion of this photographic series. Broader spatial coverage of the sea floor was gained by towing a camera sled at least once during each seasonal cruise, providing photographic transects from which to estimate the distribution and abundance of epibenthic megafauna and detrital aggregates (Lauerman et al., 1996; Lauerman and Kaufmann, 1998).

In November 1993, an array of current meters moored at 600, 50, and 2.5 mab was deployed to evaluate the collection efficiency of each sediment trap and provide records of current flow in close proximity to the sea floor at 2.5 mab (Table 1). This current meter mooring was serviced seasonally until its loss in June 1996 during a recovery operation.

Seasonal sampling programs were conducted on 30 cruises over the course of our study. Water sampling was conducted routinely with Niskin bottles and Go-Flo bottles (5, 12 and 30 l) to obtain samples for analysis of carbon, nitrogen, oxygen and trace metals from surface waters to the sea floor. *In situ* pump samplers, including the Yentsch pump and Sherrell pump (Table 1), were used to filter large volumes of water at depth to analyze the suspended particulate fraction (see Druffel et al. 1998; Sherrell et al. 1998; Gao and Sherrell, submitted). Transmissometer casts were conducted on seasonal cruises to profile the distribution of particulate matter in the water column, primarily the suspended fraction (Beaulieu and Baldwin, 1998). Sediment community activity was estimated from seasonal *in situ* measurements of sediment community oxygen consumption (SCOC) made with a free vehicle grab respirometer (Smith, 1987). Because of the high temporal variation we encountered with these measurements, an instrument was developed to continuously measure SCOC along a transect of sites over 4-month periods of time. This instrument, ROVER, was deployed at Sta. M for a four-month period from February to June 1996 (Table 1). The results of this continuous record of SCOC were presented elsewhere with the description of the instrument (Smith et al., 1997).

Our finding of seasonal pulses of detrital aggregates to the sea floor led to an intensive, submersible-based benthic program to study the impact of detrital aggregates on the sediment community and the importance of aggregates in the cycling of organic matter. Three sampling periods were chosen in addition to the regular seasonal sampling program, two during the expected peak in abundance of detrital aggregates (August and September 1994) and one when no aggregates were visible on the sea floor (April 1995) (Table 1). The submersible *Alvin* was used to selectively core detrital aggregates to include a range of sizes and appearances for analysis of biota and chemical composition (Beaulieu and Smith, 1998; Smith et al., 1998). In addition, tube core respirometers were fabricated and used to measure in situ oxygen consumption of detrital aggregates and the surrounding sediments enclosed within each core (Smith et al., 1998).

4. Significant findings

Our 7-year study of the BBL at Sta. M represents the longest continuous time-series study of any abyssal soft-bottom area in the world ocean. This unique data set is described and analyzed in the papers included in this volume. The seasonal variability in the fluxes of sinking particulate matter impacts the suspended particulate and dissolved matter in the water column with the ultimate responses observed in the sediment community. The most significant findings of these studies at Sta. M are listed below:

- Analysis of current flow within the benthic boundary layer revealed energetic mesoscale and seasonal oscillations as well as tidal and inertial forcing (Beaulieu and Baldwin).

- Light transmission profiles showed the benthic mixed layer extended up to 80 mab with an average of 45 mab (Beaulieu and Baldwin).
- Dissolved inorganic radiocarbon distribution through the water column was controlled by the circulation of the California Current System and physical perturbations induced by climatic events such as ENSO (Masiello et al.).
- Remineralization of dissolved and particulate organic carbon in the water column was not responsible for the temporal variability in the inorganic radiocarbon (Masiello et al.).
- Sinking particulate matter fluxes through the benthic boundary layer showed seasonal peaks in summer and fall but with considerable interannual variability (Baldwin et al.).
- Sinking particulate matter fluxes at 600 mab were correlated with the Bakun upwelling index revealing a lag time of ~ 50 d between these climatically mediated events at the surface and the fluxes at 3500 m depth (Baldwin et al.).
- During periods of lower particular fluxes, the suspended $\Delta^{14}C$ was depleted by 50–60‰ between 85 and 1600 m depth. During peaks in the sinking flux of particulate organic carbon (i.e. September 1994) there was no detectable decrease in the $\Delta^{14}C$ values of the suspended particulate fraction (Druffel et al.).
- Resuspension of organic carbon from local or distant sediment sources was suggested from radiocarbon of suspended particulate matter collected deeper than 2500 m (Druffel et al.).
- Both mixing along density surfaces and turbulent mixing could explain distribution of dissolved organic carbon (DOC) through the water column from slope depths to abyssal depths (Bauer et al.).
- Sources and contributions of DOC from the following three processes: off-shelf and slope transport, particulate organic carbon solubilization, and sediment porewaters remained unresolved (Bauer et al.).
- Pyrophaeophorbide-*a*, a degradation product of chlorophyll-*a*, occurred in low concentrations in suspended POC from the surface to mesopelagic depths in the water column and then increased with depth (Bianchi et al.).
- The ratio of pyrophaeophorbide-*a* to suspended particulate organic carbon was negatively correlated with $\Delta^{14}C$ of suspended particulate matter, suggesting that the high concentrations of this pigment at deeper depths is derived from older resuspended material, likely from the continental margin (Bianchi et al.).
- Suspended particulate matter concentration varied seasonally throughout the water column, being highest in summer and lowest in winter, corresponding to the seasonal pattern in sinking particulate matter fluxes, but also reflecting changes in abundance of lithogenic particles of shelf/slope origin (Sherrell et al.).
- Dynamic interactions between suspended and sinking particulate matter, including large aggregates, suggested turnover rates of $\leqslant 1$ year for the deep suspended fraction with respect to vertical removal (Sherrell et al.).
- Phytodetritus reaching the sea floor and collected with *Alvin* in 1994 varied temporally in composition from a dominance of chain-forming diatoms in August to phaeodarians in September (Beaulieu and Smith, this volume).

- Differences in composition of sinking particulate matter collected by the sediment trap at 50 mab and phytodetritus on the sea floor suggested undersampling of the large sinking aggregates by sediment traps (Beaulieu and Smith).
- Sediment accumulation rates for total mass and excess^{230}Th significantly exceeded sinking particulate matter fluxes supporting evidence of undersampling by sediment traps. Ex^{230}Th accumulation exceeded water column production by a factor of twenty suggesting a major sink for dissolved ex^{230}Th advected from the ocean's interior (Shaw et al.).
- A flocculent layer of detrital material carpeted the sea floor from July through November 1994 in contrast to previous years when the detrital cover was less pronounced indicating substantial interannual variability (Lauerman and Kaufmann).
- Estimates of radionuclide flux and mass flux associated with the large detrital aggregate fall suggested that periodic flocculent deposition events provide a large fraction of the mass and radionuclide (ex^{234}Th, ex^{210}Pb, ex^{230}Th) accumulation at Sta. M. Such events appeared responsible for seasonality in the water column inventories of lithogenic particles, ex^{210}Pb and ex^{230}Th (Shaw et al.).
- There was a lack of consistent correlation between the distribution and abundance of epibenthic megafauna (i.e. echinoderms) and the presence of detrital material on the sea floor (Lauerman and Kaufmann).
- Concentrations of total and organic carbon, total nitrogen, chlorophyll *a*, and phaeopigments in detrital aggregates collected on the sea floor were similar to those concentrations in the sinking particulate matter collected 50 mab but higher than those in the surface sediments (Smith et al.).
- Annual oxygen consumption associated with detrital aggregates represented a minor contribution (0.34%) to the annual sediment community oxygen consumption estimated at Sta. M in 1994–1995 (Smith et al.).
- Nitrate concentrations in near-bottom water were reduced during periods of high fluxes of sinking particulate matter and may be due to nitrate respiration in microzones within sinking particles and detrital aggregates on the sea floor (Wolgast et al.).
- Protozoans and five dominant metazoan macrofaunal taxa exhibited seasonal increases in density during winter months after detrital aggregates had disappeared from the seafloor (Drazen et al.).
- Protozoan density and biomass increased significantly over a four week period following a sedimentation event of detritus to the sea floor indicating a response time of these animals to organic inputs on time scales of weeks (Drazen et al.).

These results suggest that Sta. M is physically complex and is influenced by the continental margin to the east and/or north (Fig. 1). Although our studies represent the most detailed long time-series study of any benthic boundary layer in the World Ocean, this in-depth analysis has only accentuated the need for increased sampling resolution and a greater diversity of measurements to resolve the cycling of carbon and other nutrients in the deep ocean. Long time-series studies are essential for resolving such cycles given the high variability on time scales of hours to years.

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