BENTHIC CHAMBERS, NUTRIENT FLUXES AND THE BIOGEOCHEMISTRY OF THE SEAFLOOR FROM PORT PHILLIP BAY, AUSTRALIA

by W M Berelson, T E Kilgore & D T Heggie

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Benthic chambers, nutrient fluxes and the biogeochemistry of the seafloor from Port Phillip Bay, Australia.

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[In confidence]

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Executive Summary

As part of 'The Port Phillip Bay Environmental Study', a review of existing data highlighted that relatively little was understood about the seafloor of Port Phillip Bay, particularly the influence of sedimentary processes on seawater nutrient concentrations.

During January of 1994, staff from the Australian Geological Survey Organisation, the University of Southern California, Dept. of Geological Sciences and the Marine Science Laboratories of the Victorian Dept. of Fisheries and Conservation conducted a series of seafloor experiments in Port Phillip Bay using benthic chamber technology.

The primary objective of the work was to determine the fluxes of nutrients (nitrate, ammonia, phosphate and silicate), and other metabolites associated with the cycling of organic matter, between the sediments and the overlying waters. Benthic fluxes of oxygen, phosphate, ammonia, nitrite, nitrate, silicate, alkalinity, total carbon dioxide and radon were measured at ten sites in the bay, including offshore the Werribee Treatment Complex, within Corio Bay (Geelong) and Hobsons Bay, offshore the Patterson River area and in the relatively deep water sediments of the Central Zone of the Bay.

The sediments are a net sink for seawater oxygen and as such are important sites of organic matter and nutrient recycling. Oxygen fluxes varied by a factor of about five at the sites surveyed: the higest oxygen flux was measured offshore from the Werribee Treatment Complex. The benthic fluxes measured indicate Port Phillip Bay is not an oligotrophic environment. Benthic photosynthesis appears to be occurring at some sites, but respiration dominates during both night and day, resulting in a net release of nitrogen (probably as N_2, ammonia with minor amounts of nitrate) and phosphate, from particulate material, to the pore waters and subsequently to the overlying water column. Biological oxygen reduction accounts for most of the organic carbon oxidised, and sulphate reduction appears to be of secondary importance, accounting for

about 20-30% of the organic matter oxidised. Organic nitrogen appears to be converted to nitrous oxide or nitrogen gas via ammonification, nitrification and nitrate reduction. Nitrate reduction probably results in a loss of utilisable nitrogen from the system. Denitrification may be significant in controlling primary production in the Port Phillip Bay. Phosphate is generally not recycled as efficiently as carbon in most of the bay sediments and is apparently being retained in the sediments, perhaps by reaction with sedimentary iron phases.

The fluxes of radon and silica into the benthic chambers and the flux of cesium from the chamber into the sediments, and the visual observation of extensive burrowing activity by the benthic community indicate that irrigation of the sediments, by benthic infauna, is an important sedimentary process in the bay which enhances the fluxes of nutrients from the sediments to the overlying water. Irrigation is patchy, but nine of the twelve chamber deployments showed significant irrigation transport of sediment pore waters to the overlying water.

This work has identified denitrification and benthic irrigation as potential important controls on the concentrations of nutrients in the overlying water, and as such, should be investigated further to establish the environmental conditions which support and sustain these processes. Benthic fluxes of oxygen measured in Port Phillip Bay are comparable to, but generally higher than, the ranges of oxygen fluxes measured in other nearshore environments which receive anthropogenic inputs, including sediments near an ocean outfall site offshore Los Angeles, and are more than an order of magnitude higher than oxygen fluxes measured in 'unimpacted' continental shelf sediments of eastern Australia

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Introduction

As part of the Port Phillip Bay Environmental Study: Status Review (Skyring et al, 1992), a knowledge of the sediment inventories of nutrients, notably nitrogen and phosphorus, and specifically the role which the sediments play in regulating the seawater concentrations of these essential nutrients was identified as poorly known. It has long been recognised that, particularly in shallow water and coastal marine environments, the cycle of organic matter production and respiration and the remineralisation of nutrients from biological debris and perhaps anthropogenic sources, in near-surface sediments exerts an important control on the nutrient status of the sediments and the overlying waters, and consequently on the potential for enhanced marine productivity and eutrophication of nearshore marine environments. As part of the Port Phillip Bay Project Design (1992) several tasks were identified concerning the nutrient status of sediments in the Port Phillip Bay. This report deals with three of those identified tasks (i) N3.1. 'The nutrient status of Port Phillip Bay sediments'; N3.2.'Is the flux of nutrients from sediments into the water column quantitatively important to nutrient recycling in Port Phillip Bay?', and N3.3 'Oxygen, nitrate and sulfate reduction rates in sediments and the trophic status of Port Phillip Bay.' Specifically, this report focuses on tasks N3.2 and N3.3, although the results reported here are strongly linked to task N3.1, which documents the pore water concentrations of nitrogen and phosphorus species and other metabolites and also the solid (sediment) phase concentrations of these elements. The field data and results of task N3.1 are being conducted and compiled by the Marine Science Laboratories of the Victorian Dept. of Conservation and Fisheries, and these will be reported separately.

Program Objectives.

To address tasks N3.2 and N3.3, a field program was planned for January 1994. The primary objective of the field program was to determine benthic fluxes of oxygen,

carbon (total carbon dioxide), nitrogen (ammonia, nitrate and nitrite), phosphorus (as phosphate) and silica from several different sediment facies to the overlying waters, and as such to contribute data to an integrated ecosystem and management model of the Port Phillip Bay. Secondary objectives included (i) to evaluate the key transport processes controlling the transfer of solutes between the interstitial fluids and bottom waters (ii) to identify key sites of benthic metabolism and sites of organic matter and nutrient remineralisation (iii) to infer the existence of benthic algal-mat communities in the Port Phillip Bay from the benthic chamber oxygen data and (iv) to use benthic flux data to constrain pore water models of sedimentary processes.

To achieve these objectives staff from the University of Southern California, Dept. of Geological Sciences and the Australian Geological Survey Organisation joined with those from the Victorian Department of Conservation and Natural Resources at the Marine Science Laboratories in Queenscliff for a period of about four weeks to conduct a series of benthic flux studies using specially designed benthic chambers that are able to measure benthic fluxes in-situ. The rationale for measuring benthic fluxes in-situ includes the following:

(i) Benthic fluxes calculated from pore water gradients are limited by the scale of sampling near the sediment-seawater interface. Current technology allows pore waters to be separated and processed at centimetre scale intervals, but many benthic processes are occurring at millimetre scales or less at the sediment-seawater interface. Benthic fluxes determined from modelling of pore water data are also limited by an incomplete knowledge of the processes used in models developed to describe benthic exchanges. Direct measurements of benthic fluxes are not constrained by these uncertainties.

(ii) Benthic fluxes determined from laboratory incubations of cores are subject to a variety of uncertainties created by removing a core from the natural environment and storing it within a laboratory environment while experiments are conducted. During this period the activities of organisms may suffer as a result of the changed

environmental conditions, including temperature and pressure effects, core disturbance and changed substrate concentrations. Also, cores sample a smaller area of sea floor area than benthic chambers, thus the exchange rate determined from cores may vary as a result of small-scale heterogeneity in sea floor and sub-sea floor conditions. Benthic fluxes measured in-situ are not subject to these uncertainties.

(iii) In addition, benthic fluxes measured in-situ can help quantify irrigation fluxes and advective fluxes that are not easily identified and modelled from pore water data or from laboratory incubations of parts of sediment cores. Furthermore, in-situ flux data, when combined with pore water data (which document the inventories of dissolved components in the interstitial sediment spaces), constrain all models of both physical and biogeochemical processes occurring in the sediments.

The measurement of benthic fluxes in situ is however, not a simple matter. The technology of in-situ benthic chambers has been evolving for about a decade and today chambers are being deployed in a variety of deep-sea and nearshore environments to develop an understanding of benthic processes and their importance in maintaining nutrient balances in both the open oceans and coastal environments (Berelson et al., 1986, 1987a, 1990a).

From a consideration of the distributions of sediment facies in Port Phillip Bay, a cluster analysis of the sediment and pore water data gathered thus far (Longmore and Nicholson, personal communication), and estimates of benthic fluxes from existing pore water data (Longmore and Nicholson, personal communication), several sites were chosen for benthic chamber deployments that would represent each of the major sediment facies in Port Phillip Bay. Several of these sites were also important geographical locations and these included (i) the Werribee Treatment Complex area (ii) Corio Bay (Geelong) (iii) the Central Zone of Port Phillip Bay (iv) the Patterson River area, and (v) Hobsons Bay. A site was chosen in the northern part of Port Phillip Bay, downstream of the Hobsons Bay site, which should provide a comparison

of a relatively unimpacted site (northern Port Phillip Bay) with the Hobsons Bay site which is at the entrance to the Yarra River and which receives the runoff from the Yarra River catchment.

The sites sampled are summarised in Table 1, and their locations are shown in Figure 1. Brief descriptions of seafloor conditions noted by divers during deployments of the benthic chambers are included in Table 2. The data shown in Tables 1 and 2 are recorded in chronological order in which the sites were occupied. Elsewhere throughout the text, data are assembled and grouped according to the locations from which they were collected.

Table 1. Summary of benthic chamber deployments.

Site (date occupied)	Water depth (m)	Coordinates (degrees S; E)	Area of Port Phillip Bay
Site 11 (Jan 10)	17	38° 05.73'; 144° 46.88'	Central Zone
Site 8 (Jan 10)	9	38° 03.11'; 144° 36.26'	Werribee Treatment Complex
Site 13 (Jan 10)	22	38° 02.46';144° 53.57'	Central Zone
Site 22 (Jan 11)	8	38° 13.98'; 144° 48.26'	Central Zone
Site 3 (Jan 14)	9	38° 05.86'; 144° 24.38'	Corio Bay
Site 16 (Jan 17)	8	37° 51.60'; 144° 54.68'	Yarra River estuary
Site 14 (Jan 17)	12	37° 53.49'; 144° 53.90'	Hobsons Bay
Site 37 (Jan 18)	24	38° 09.47'; 144° 52.25'	Central Zone
Site 19 (Jan 18)	13	38° 04.51'; 145° 05.08'	Patterson River
Site 6 (Jan 20)	9	38° 04.56'; 144° 33.49'	Werribee Treatment Complex
Site 8 (Jan 20)	9	38° 03.05'; 144° 35.95'	Werribee Treatment Complex

Table 2. Summary of seafloor conditions at deployment Sites.

Site (date occupied)	Visual description of seafloor
Site 11 (Jan 10)	Soft muddy/silty sediment Filamentous micro-algae present; many burrows of various diameters probably as a result of poychaete and ghost shrimp (*Callianassids*) activity.
Site 8 (Jan 10)	Sandy /shelly sediment, irregular topography; clumps of cunjevoi, filamentous red/brown algae and many fan worms (*Sabellids*).
Site 13 (Jan 10)	Very soft flocculent sediment which the diver could easily insert an arm to the shoulder; Lander had to be deployed with sleds to prevent the incubation chamber sinking into the sediment; several animal burrows; no visual evidence of benthic mats.
Site 22 (Jan 11)	Very clear sandy, rippled and hummocky seafloor; strong tidal current, flowing and sediment appears scoured; some but little evidence of burrowing organisms.
Site 3 (Jan 14)	Soft flocculent sediment which the diver could easily insert an arm to the shoulder; clay/mud sediment with some shell grit present; many large animal burrows in the sediment with mussels and oysters and many fan worms (*Sabellids*) present; large patches of clear sediment surface with no micro-algal mats apparently present.
Site 16 (Jan 17)	Very soft seafloor of floc material to about 35 cm with a hard clay-like material below; Lander deployed with skids; few animal burrows.
Site 14 (Jan 17)	Soft sediment where a diver could easily insert a hand and part of the arm, sediments probably mud/silt/clay; some animal burrows as well as isolated patches of benthic fauna such as shellfish; no visual evidence of benthic mats.
Site 37 (Jan 18)	No diving was conducted at this Site.
Site 19 (Jan 18)	Sandy seafloor with clay/silt present; some burrows and large benthic fauna such as shellfish and occasional cunjevoi; no visual evidence of benthic mats.
Site 6 (Jan 20)	Soft sediment probably sand/silt/clay mixture; abundant coverage of sediment with filamentous green and red/brown micro-algae and a thin reddish-tinged layer which could have been settled (dead?) Nitzchia? diatoms; crustaceans and abundant animal burrows evident.
Site 8 *(Jan 20)	Redeployment off Werribee Treatment Complex; abundant benthic mats and animal activity.

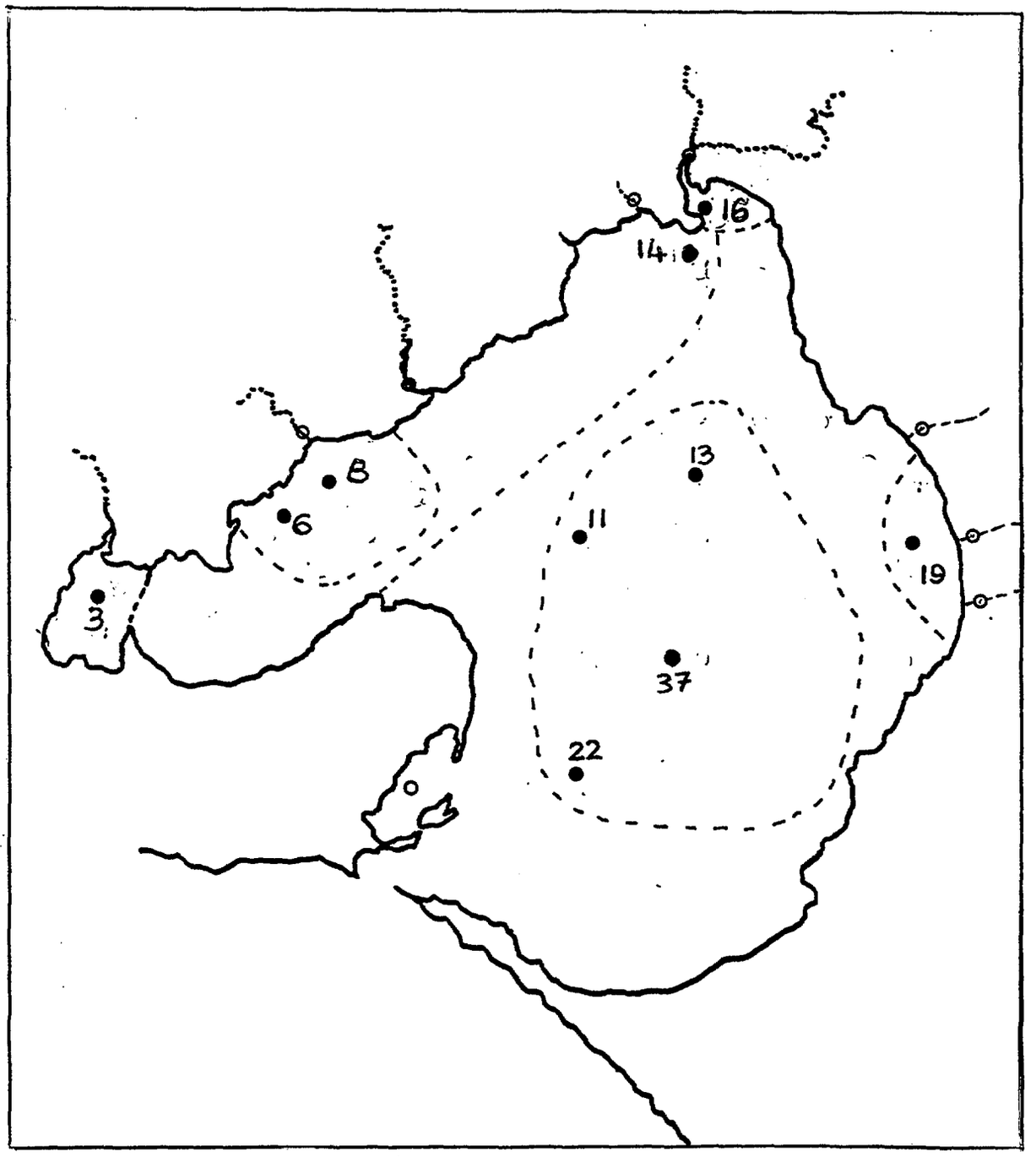

Figure 1. Map of the Port Phillip Bay showing the sites of benthic chamber deployments. The number refers to the Site shown in Tables 1 and 2.

Benthic chamber technology and methods

The benthic incubation chamber utilised by the USC group, schematically depicted in Figure 2, has been described by Berelson et al. (1989). The device was deployed from the Victoria Marine Science Laboratories research vessel (*FRV. Melita*) by lowered hand-line; chamber seating on the sea floor was confirmed by divers. The chamber (PVC cylinder, 30-cm diameter) entered the sediment slowly, with an open lid to allow flushing of water through the cylinder. After deployment, a signal from a pre-programmed computer on the device closed the lid and sealed the chamber, enclosing 7-10 litres of bottom water in contact with the sea floor. The chamber is mixed by a paddle, rotating at a rate of 5-6 revolutions per minute (except at Site 3-Y, where the rate was 1 rpm). This stir rate has previously been determined to set up an average diffusive boundary layer thickness of ~400 μm. Six samplers, 3 of 120 mL and 3 of 300 mL, withdrew water from the chamber at specifically programmed times during the course of an incubation. A narrow tube (0.3 cm id) connecting the chamber to the ambient environment allows the inflow of bottom water during a chamber draw. Samples for nutrient analyses were stored in plastic tubes (40 ml) and samples used for radon analyses, taken with the 300-mL draws, were stored in glass tubes (100 ml).

Polarographic electrodes, operated in a pulsed mode, monitored oxygen concentration at 6-minute intervals in both the ambient and the chamber water. Raw electrode data was calibrated to oxygen concentrations determined by Winkler titration of samples collected by Niskin bottle at the time of the benthic chamber experiment. Nutrients (PO_4^{3-}, NO_3^-, NO_2^-, SiO_2 and NH_4^+) were measured by autoanalyser techniques on an aliquot of 20 ml of chamber water. Alkalinity (measured by Gran titration) and pH were measured on a split of 10 ml. Radon was determined by scintillation counting using the techniques described by Berelson et al. (1987b). The chamber volume was determined by measuring the dilution of a spike of CsCl, which was added to the chamber during the incubation by calibrated syringe. Cesium was measured by atomic emission techniques.

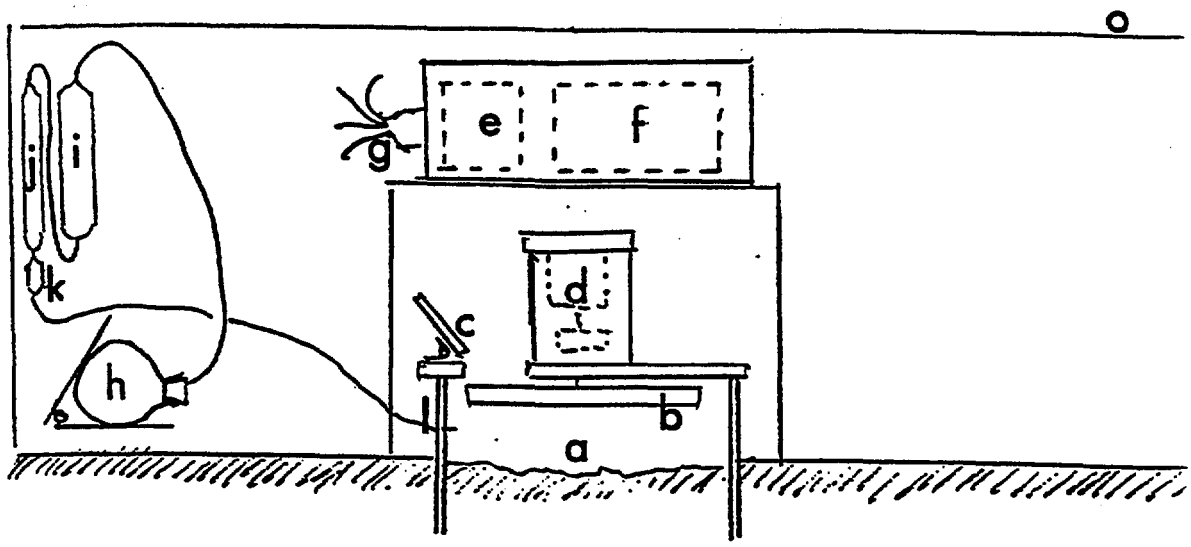

Figure 2. Schematic of the benthic chambers. Unit consists of a single cylindrical chamber (a), supported by an aluminium frame (o), that is approximately 1.2m x 0.5m x 0.5m. Other components include; chamber stirring paddle (b), hinged lid to top of chamber (c), pressure case with magnet-turning motor (d), pressure case with timing unit/micro-processor (e) and batteries (f) with burn wire leads (g), bulb that draws samples (h), sample tubes (i, j, k), tubing leading out of chamber (l).

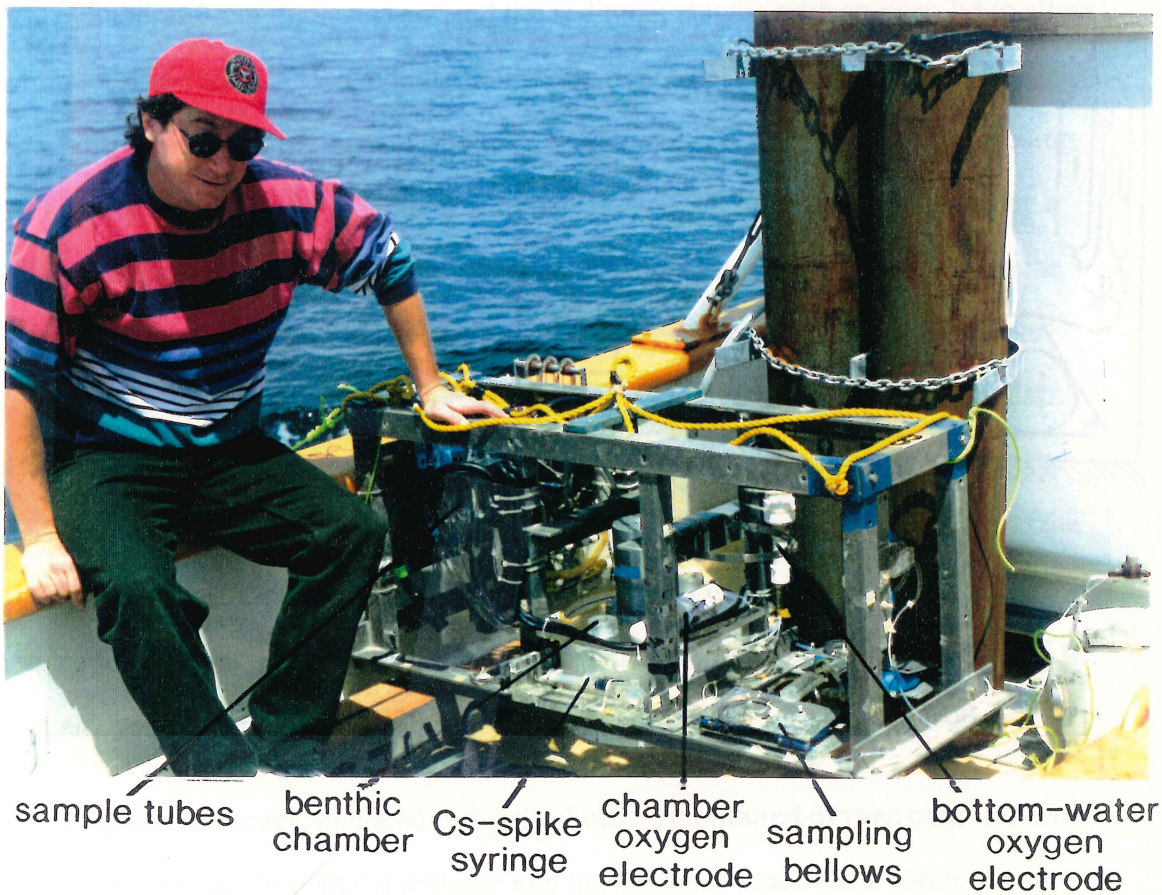

Figure 3. Photograph of the benthic chamber used in Port Phillip bay for these shallow-water deployments-key parts are highlighted.

Benthic Chamber Results

All data from the benthic chambers are summarised in the following figures and tables. Figure 4 shows an example of the raw data collected for each site occupied, and data points are plotted as concentration (μM or μeq/l) vs time (hr). This composite plot is shown here only to illustrate the metabolite changes in the benthic chamber during the course of a deployment. The data point on the y axis represents the Niskin sample concentration; the 6 other data points represent chamber concentration measured on samples collected during the incubation. The y axis is concentration in μM (except alkalinity which has units μeq/l) and the x axis is incubation time in hours. These types of plots are not necessary to calculate benthic fluxes, which are computed from least square fits to the types of data shown here. The complete data set is summarised in Tables 3-14. Plots of oxygen data versus incubation time are shown for each site (Figures 5-11). Each of these plots includes data from an electrode inserted into the chamber (open circles) and of an electrode mounted outside the chamber (solid squares). Short vertical lines on each plot indicate the timing of sample collection and the withdrawal of water from the chamber to the sample tube. The dashed, horizontal line shows the time period over which the oxygen flux was calculated. It should be noted that the rate of oxygen uptake within a chamber is not always linear.

The tables (Tables 3-14) that accompany these figures show the timing of chamber deployments and provide a record of all measurements made on chamber samples. Note that radon was only measured on samples 4, 5, and 6. Total (TCO_2) was calculated from alkalinity and pH measurements. Nitrate + nitrite (N + N) and nitrite were measured; nitrate was calculated as the difference. Before calculating fluxes, the data are corrected for the dilution that takes place when a sample is drawn and ambient water enters the chamber. The results of this correction are not shown in the table; however, the magnitude of this correction is typically no more than 15% and primarily affects the later draws. Also shown in these tables are the concentrations of analytes from Niskin bottle samples and the analytical uncertainty of each measurement.

Bottom water concentrations used in the determination of fluxes are also shown. These data are usually identical to the Niskin data, except where a Niskin sample was not collected or problems were encountered with this analysis. In these cases, the concentration determined for the first draw may be shown as the bottom water value.

The flux calculations determined from least square fits to the analyte data (corrected for dilution) versus time are shown below the data tables The y-intercept is included for comparison with bottom water concentrations. The 'source' term indicates the source of the predominant uncertainty in the slope of the regressed line: either the analytical uncertainty or the uncertainty derived from the fit of the line to the data. The flux, for everything except radon, is the product of this slope and the effective chamber height (chamber volume/chamber area). The flux of radon was determined by fitting the radon data to an equation that corrects for radon decay during incubation (Berelson et al., 1987c).

Some data have been omitted from the flux calculation. This has been indicated, for all sites except Station 22, by a thin line drawn through the value in the data table. Data were excluded from the flux calculation for one of two reasons: (1) measurement uncertainties or (2) samples were drawn during a non-linear portion of the oxygen profile. Examples of the latter would be draw 6 at Site 8 and draws 4-6 at Site 6. The unusual trace of the oxygen electrode at Station 22 warranted two approaches to reducing the data; an average flux was determined from all the sample draws and a maximum flux was determined using only the last 3 draws. The flux units in all of the accompanying tables are mmol m^{-2} day^{-1} except alkalinity which is meq m^{-2} day^{-1}. Radon fluxes are always reported as atoms m^{-2} sec^{-1}.

In the following, all plots and data tables have been assembled and grouped according to the locations at which deployments were made.

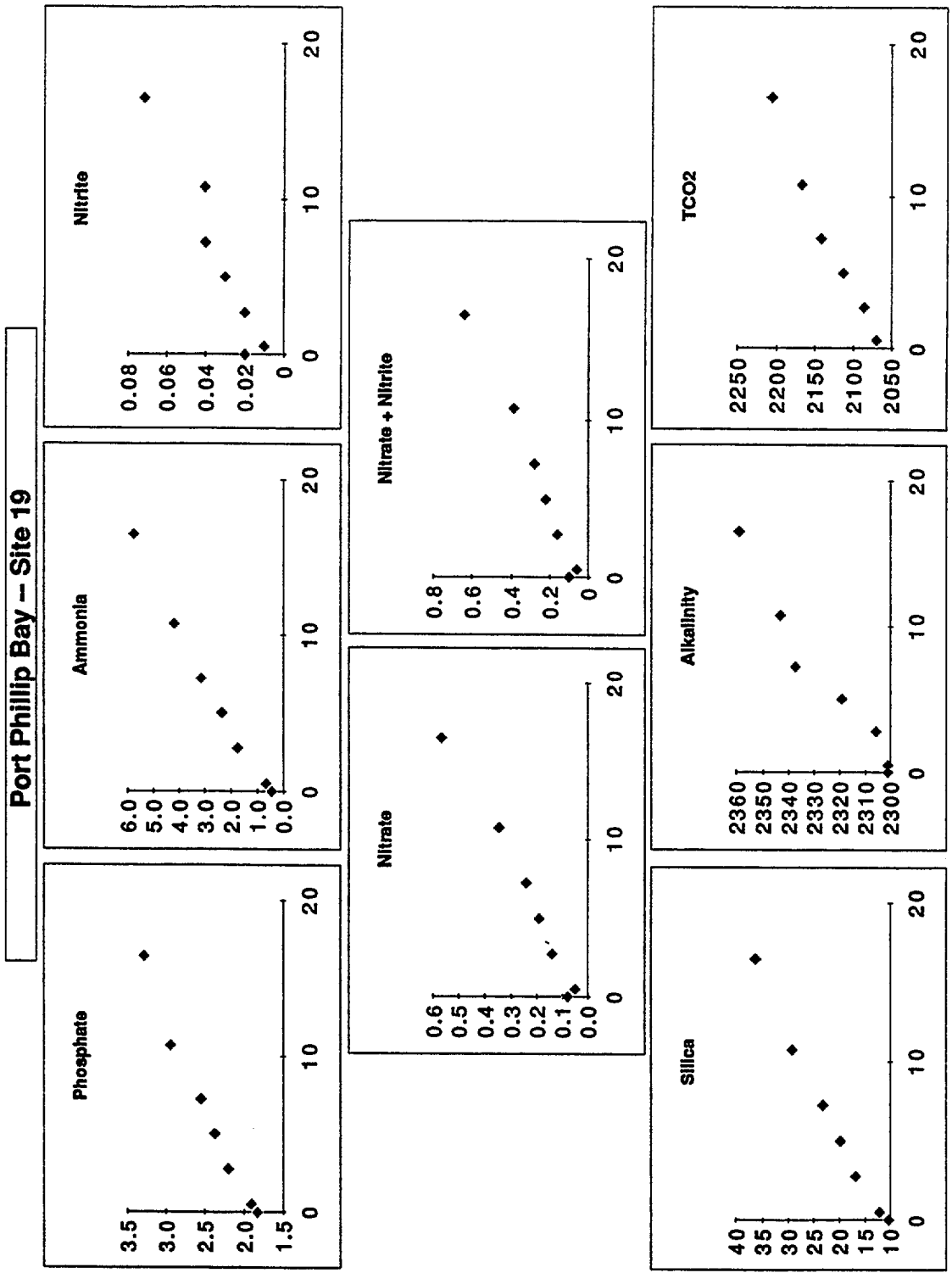

Figure 4. An example of benthic chamber data from the deployment at Site 19 (Patterson River area).

Werribee Treatment Complex (Sites 8, 8* and 6)

Oxygen concentrations from the three sites occupied near Werribee Treatment Complex are summarised in Figures 5 and 6. Data from these sites are summarised in Tables 3 through 5.

Site 8* was occupied about ten days later than Site 8, and was located at not exactly the same location (Table 1). Oxygen fluxes at this site were comparable, although the flux at Site 8 was about thirty percent lower than that at Site 8*. Site 6 had the highest oxygen flux, and this was about three-fold the fluxes measured at the other two sites off the Werribee Treatment Complex. Positive fluxes of phosphate, ammonia, nitrate+nitrite, silicate and alkalinity were measured at all Sites, indicating a flux of nutrients from the sediments to the overlying waters. While there was a significant depletion in bottom water oxygen, there was considerably less nitrate released to the overlying water than expected from the nitrification reaction assuming Redfied stoichiometry (see below).

Radon fluxes at Sites 8* and Site 6 were more than an order of magnitude higher than that measured at Site 8, a result which is indicative of an enhanced flux, greater than that accounted for by diffusion exchange, probably by the irrigating activities of burrowing benthic organisms (see below).

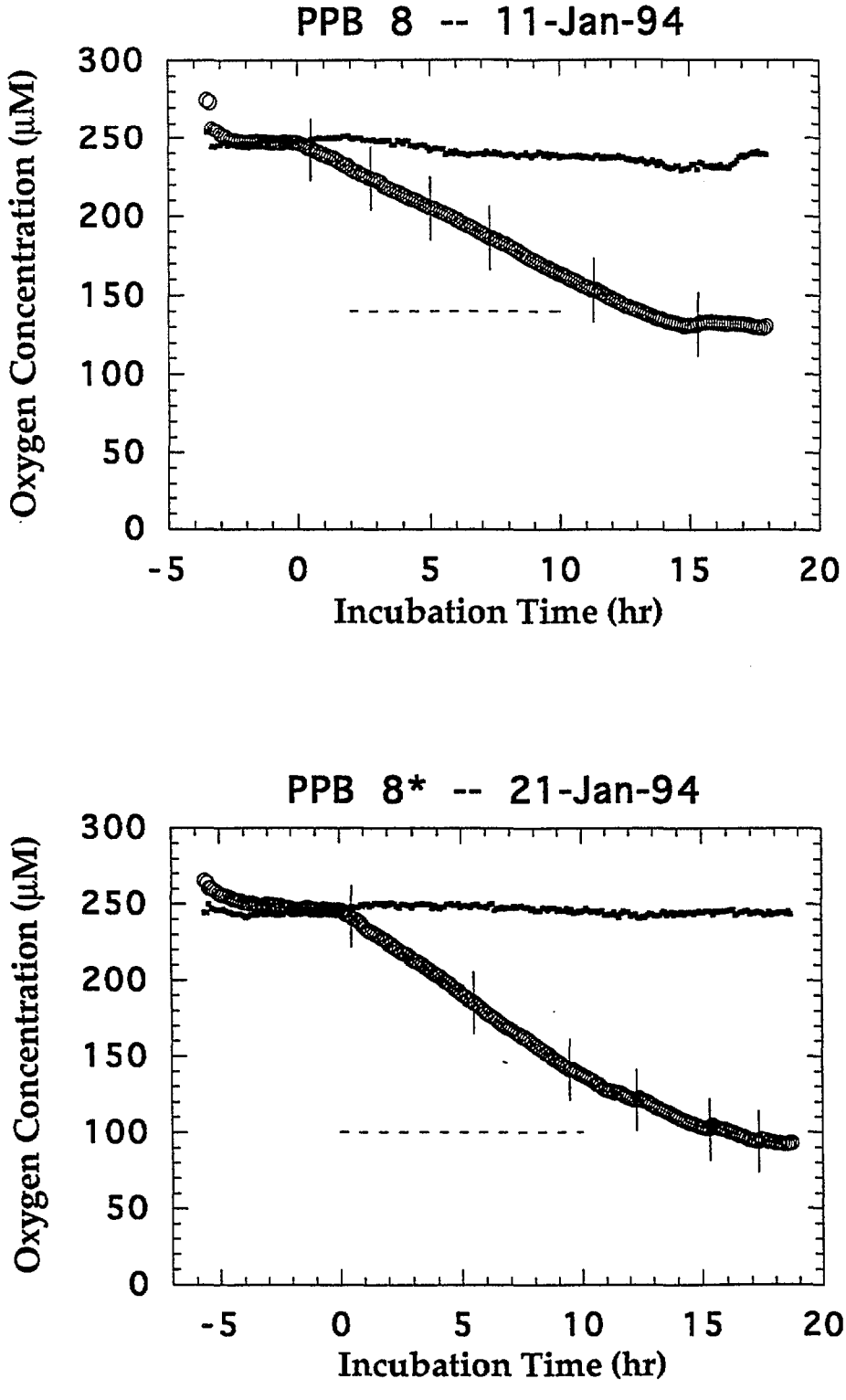

Figure 5. Plot of oxygen concentration versus incubation time from the two deployments at Site 8 and 8* offshore the Werribee Treatment Complex.

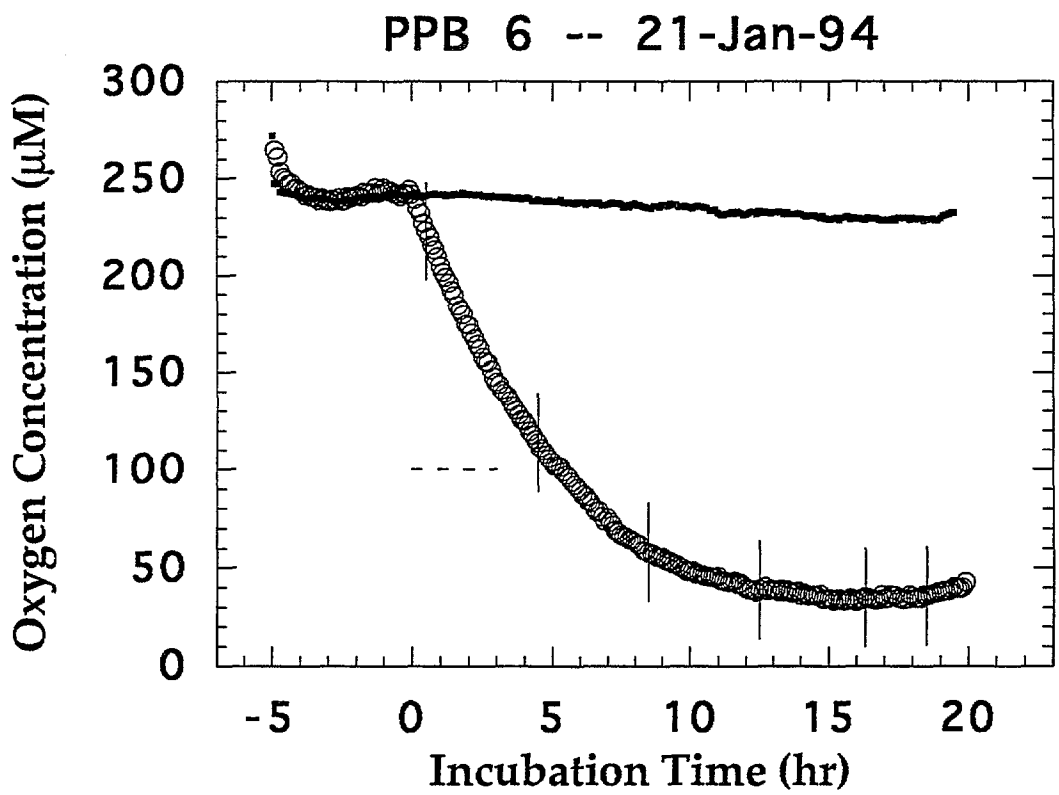

Figure 6 Plot of oxygen concentration versus incubation time from Site 6 offshore the Werribee Treatment Complex.

Table 3. Concentrations of species in benthic chamber samples and calculated fluxes from Site 8 off the Werribee Treatment Complex.

PPB Station 8 (Blue)

Cruise: PPB **Station:** 8 **Lander:** Blue Date Printed: 17:29 23-Jan-94

Time of Lid Drop	10-Jan 17:00
Height of Blue Chamber (cm)	13.2
± uncertainty	±1.6
Height of Red Chamber (cm)	
± uncertainty	
Height of Yellow Chamber (cm)	
± uncertainty	
Chamber Area (m^2)	0.073

	Clock Time	Elapsed Time
Draw 1	10-Jan 17:30	0.50
Draw 2	10-Jan 19:45	2.75
Draw 3	10-Jan 22:00	5.00
Draw 4	11-Jan 0:15	7.25
Draw 5	11-Jan 4:15	11.25
Draw 6	11-Jan 8:15	15.25

Original Data

Sample	Volume mL	Phosphate µM	Ammonia µM	Nitrite µM	Nitrate µM	N + N µM	Silica µM	Alkalinity µeq/L	Calculated TCO2 µM	Radon dpm/L	pH
Blue-1	130	2.2	0.5	0.02	0.08	0.10	9.60	2365	2107		8.112
Blue-2	130	2.4	1.8	0.04	0.27	0.31	11.68	2378	2132		8.089
Blue-3	130	2.4	2.4	0.09	0.43	0.52	13.27	2401	2169		8.059
Blue-4	300	2.6	3.2	0.12	0.56	0.68	14.26	2388	2168	1.2	8.037
Blue-5	300	2.7	4.2	0.15	0.83	0.98	15.64	2403	2205	1.3	7.991
Blue-6	300	~~2.8~~	~~5.0~~	~~0.17~~	~~0.92~~	~~1.09~~	~~17.42~~	2414	~~2231~~	1.9	7.958
Niskin		2.2	0.7	0.07	0.00	0.01	8.91	2368	2113		8.101
Uncertainty		±0.05	±0.08	±0.01	±0.05	±0.05	±0.50	±5	±6.0	±1.0	
Bottom Water		2.2	0.7	0.07	0.00	0.01	8.91	2368	2107	0.5	

y-Intercept	**2.2**	**0.7**	**0.04**	**0.0**	**0**	**10**	**2369**	**2107.9**
Source	Analysis	Fit	Fit	Fit	Analysis	Fit	Fit	Fit
Error in Slope	0.0052	0.0203	0.0025	0.0052	0.0052	0.0666	0.9098	0.9302
Flux (unit/1000/m2/day)	**0.139**	**1.070**	**0.033**	**0.244**	**0.277**	**1.954**	**10.60**	**29.04**
Error in Flux	**±0.024**	**±0.145**	**±0.009**	**±0.034**	**±0.037**	**±0.317**	**±3.16**	**±4.59**

Table 4. Concentrations of species in benthic chamber samples and calculated fluxes from Site 8* off the Werribee Treatment Complex.

PPB Station 8* (Blue)

Cruise: PPB **Station:** 8* **Lander:** Blue Date Printed: 19:00 23-Jan-94

			Clock Time	Elapsed Time
Time of Lid Drop	20-Jan 17:30	Draw 1	20-Jan 18:00	0.50
Height of Blue Chamber (cm)	14.2	Draw 2	20-Jan 23:00	5.50
± uncertainty	±1.5	Draw 3	21-Jan 3:00	9.50
Height of Red Chamber (cm)		Draw 4	21-Jan 5:45	12.25
± uncertainty		Draw 5	21-Jan 8:45	15.25
Height of Yellow Chamber (cm)		Draw 6	21-Jan 10:45	17.25
± uncertainty				
Chamber Area (m^2)	0.073			

Original Data

Sample	Volume mL	Phosphate µM	Ammonia µM	Nitrite µM	Nitrate µM	N + N µM	Silica µM	Alkalinity µeq/L	Calculated TCO2 µM	Radon dpm/L	pH
Blue-1	130	2.49	1.00	0.02	0.07	0.09	10.1	2350	2117		8.067
Blue-2	130	2.90	3.58	0.06	0.24	0.30	16.2	2378	2168		8.019
Blue-3	130	3.22	5.67	0.09	0.34	0.43	21.4	2373	2192		7.957
Blue-4	300	3.37	6.60	0.11	0.37	0.48	23.7	2419	2248	28.3	7.930
Blue-5	300	~~3.56~~	~~7.47~~	~~0.12~~	0.40	~~0.52~~	~~26.2~~	2420	2264	28.6	7.898
Blue-6	300	~~3.57~~	~~7.87~~	~~0.12~~	0.43	~~0.55~~	~~27.7~~	2426	2278	35.2	7.878
Niskin		2.48	1.06	0.01	0.09	0.10	9.6	2361	2131		8.060
Uncertainty		±0.1	±0.1	±0.01	±0.1	±0	±1	±5	±6.0	±3.0	
Bottom Water		2.48	1.06	0.01	0.09	0.10	9.6	2361	2131	0.5	

y-Intercept	**2.5**	**0.9**	**0.01**	**0.1**	**0**	**10**	**2353**	**2119.3**
Source	Analysis	Fit	Analysis	Analysis	Analysis	Analysis	Fit	Fit
Error in Slope	0.0046	0.0174	0.0009	0.0046	0.0046	0.0463	0.7752	1.1865
Flux (unit/1000/m2/day)	**0.261**	**1.641**	**0.028**	**0.087**	**0.115**	**4.087**	**17.99**	**35.22**
Error in Flux	**±0.032**	**±0.183**	**±0.004**	**±0.018**	**±0.020**	**±0.460**	**±3.25**	**±5.49**

Table 5. Concentrations of species in benthic chamber samples and calculated fluxes from Site 6 off the Werribee Treatment Complex.

PPB Station 6 (Yellow)

Cruise: PPB **Station:** 6 **Lander:** Yellow Date Printed: 0:30 24-Jan-94

Time of Lid Drop	20-Jan 15:45
Height of Blue Chamber (cm)	13.1
± uncertainty	±1.5
Height of Red Chamber (cm)	
± uncertainty	
Height of Yellow Chamber (cm)	
± uncertainty	
Chamber Area (m^2)	0.073

	Clock Time	Elapsed Time
Draw 1	20-Jan 16:15	0.50
Draw 2	20-Jan 20:15	4.50
Draw 3	21-Jan 0:15	8.50
Draw 4	21-Jan 4:15	12.50
Draw 5	21-Jan 8:00	16.25
Draw 6	21-Jan 11:30	19.75

Original Data

Sample	Volume mL	Phosphate µM	Ammonia µM	Nitrite µM	Nitrate µM	N + N µM	Silica µM	Alkalinity µeq/L	Calculated TCO2 µM	Radon dpm/L	pH
Blue-1	130	2.60	1.36	0.04	0.10	0.14	10.0	2381	2175		8.01
Blue-2	130	3.08	3.45	0.09	0.14	0.23	18.1	2423	2260		7.91
Blue-3	130	3.27	2.96	0.11	0.25	0.36	23.1	2442	2326		7.80
Blue-4	300	~~3.42~~	~~3.36~~	~~0.11~~	~~0.18~~	~~0.29~~	~~25.5~~	~~2467~~	~~2370~~	26.5	7.75
Blue-5	300	~~3.47~~	~~3.23~~	~~0.11~~	~~0.16~~	~~0.27~~	~~26.9~~	~~2481~~	~~2396~~	26.2	7.72
Blue-6	300	~~3.47~~	~~3.45~~	~~0.10~~	~~0.18~~	~~0.28~~	~~26.7~~	~~2426~~	~~2348~~	24.1	7.70
Niskin											
Uncertainty		±0.1	±0.1	±0.01	±0.1	±0	±1	±5	±6.0	±2.0	
Bottom Water		2.60	1.30	0.04	0.10	0.14	10.0	2381	2175	0.5	

y-Intercept	**2.6**	**1.5**	**0.04**	**0.1**	**0**	**10**	**2381**	**2171.7**
Source	Fit	Fit	Analysis	Analysis	Analysis	Fit	Fit	Fit
Error in Slope	0.0120	0.1118	0.0015	0.0073	0.0073	0.1284	0.9514	0.8963
Flux (unit/1000/m2/day)	**0.267**	**0.721**	**0.028**	**0.055**	**0.082**	**5.136**	**24.15**	**58.35**
Error in Flux	**±0.049**	**±0.361**	**±0.006**	**±0.024**	**±0.025**	**±0.713**	**±4.07**	**±7.25**

Corio Bay (Site 3)

Oxygen concentrations from duplicate deployments in Corio Bay are shown in Figure 7. All data are summarised in Tables 6 and 7. Stirring rates were 1 rpm in Chamber 3-Y and 5 rpm in Chamber 3-B.

At this Site oxygen fluxes were identical despite the stirring rates being different by a factor of five, suggesting that the oxygen flux is not controlled primarily by the thickness of the benthic boundary layer. Positive fluxes of phosphate, ammonia, nitrate+nitrite, silica were found indicating fluxes of these nutrients from the sediments to the overlying water. However, similarly to Werribee, significant fluxes of oxygen into the sediments were not accompanied by significant releases of nitrate to the bottom water. The highest nutrient fluxes were measured in the chamber which was stirred at the slower rate. Radon fluxes in the chamber (3-Y), which was stirred the slowest, were about ten-fold higher than those in the other chamber. This result suggests different physical processes are controlling the exchange of solutes between the sediments and the overlying waters in these two chambers. The radon flux from the chamber (3-B) stirred at 5 rpm is comparable to that predicted if transport is controlled by molecular diffusion, but a ten-fold higher flux in the other chamber suggests irrigation of these sediments (see below).

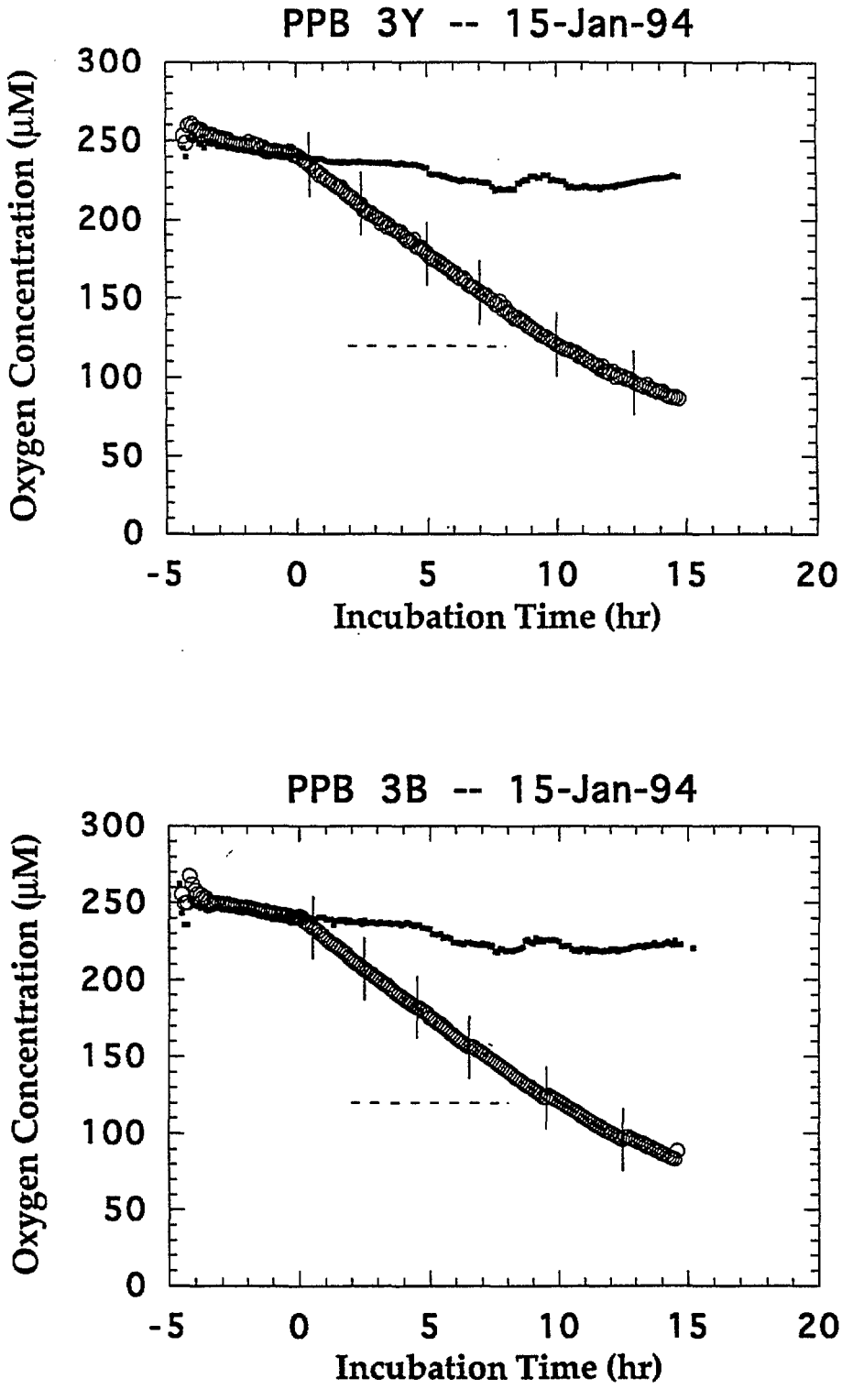

Figure 7. Oxygen concentration versus incubation time from Site 3 in Corio Bay.

Table 6. Concentrations of species in benthic chamber samples and calculated fluxes from Site 3-Y from Corio Bay (Geelong).

PPB Station 3-Y (Yellow)

Cruise: PPB **Station:** 3-Y **Lander:** Yellow Date Printed: 18:06 23-Jan-94

			Clock Time	Elapsed Time
Time of Lid Drop	14-Jan 22:00			
Height of Blue Chamber (cm)	10.4	Draw 1	14-Jan 22:30	0.50
± uncertainty	±1.5	Draw 2	15-Jan 0:30	2.50
Height of Red Chamber (cm)		Draw 3	15-Jan 2:30	4.50
± uncertainty		Draw 4	15-Jan 4:30	6.50
Height of Yellow Chamber (cm)		Draw 5	15-Jan 7:30	9.50
± uncertainty		Draw 6	15-Jan 10:30	12.50
Chamber Area (m^2)	0.073			

Original Data

Sample	Volume mL	Phosphate µM	Ammonia µM	Nitrite µM	Nitrate µM	N + N µM	Silica µM	Alkalinity µeq/L	Calculated TCO2 µM	Radon dpm/L	pH
Blue-1	130	2.93	0.44	0.00	0.04	0.04	6.75	2447	2130		8.202
Blue-2	130	3.11	0.73	0.01	0.00	0.00	8.13	2450	2135		8.199
Blue-3	130	3.30	1.13	0.01	0.03	0.04	10.13	2453	2163		8.156
Blue-4	300	3.41	1.68	0.02	0.06	0.08	12.12	2474	2202	7.8	8.123
Blue-5	300	3.56	2.41	0.02	0.08	0.10	15.25	2473	2234	9.9	8.062
Blue-6	300	3.71	3.29	0.04	0.06	0.10	18.13	2485	2274	10.6	8.008
Niskin		3.07	0.44	0.00	0.02	0.02	4.90	2449	2123		8.216
Uncertainty		±0.05	±0.08	±0.01	±0.05	±0.05	±0.50	±5	±6.0	±2.0	
Bottom Water		2.93	0.44	0.00	0.04	0.04	6.75	2447	2130	0.5	

y-intercept	**2.9**	**0.2**	**0.00**	**0.0**	**0**	**6**	**2444**	**2117.7**
Source	Analysis	Fit	Analysis	Analysis	Analysis	Analysis	Fit	Fit
Error in Slope	0.0044	0.0152	0.0009	0.0044	0.0044	0.0438	0.4492	0.9413
Flux (unit/1000/m2/day)	**0.170**	**0.607**	**0.008**	**0.009**	**0.017**	**2.470**	**8.43**	**31.81**
Error in Flux	**±0.027**	**±0.095**	**±0.002**	**±0.011**	**±0.011**	**±0.373**	**±1.65**	**±5.15**

Table 7. Concentrations of species in benthic chamber samples and calculated fluxes from Site 3-B from Corio Bay (Geelong).

PPB Station 3B (Blue)

Cruise: PPB **Station:** 3-B **Lander:** Blue Date Printed: 18:15 23-Jan-94

			Clock Time	Elapsed Time
Time of Lid Drop	14-Jan 22:00			
Height of Blue Chamber (cm)	10.3	Draw 1	14-Jan 22:30	0.50
± uncertainty	±1.5	Draw 2	15-Jan 0:30	2.50
Height of Red Chamber (cm)		Draw 3	15-Jan 2:30	4.50
± uncertainty		Draw 4	15-Jan 4:30	6.50
Height of Yellow Chamber (cm)		Draw 5	15-Jan 7:30	9.50
± uncertainty		Draw 6	15-Jan 10:30	12.50
Chamber Area (m^2)	0.073			

Original Data

Sample	Volume mL	Phosphate µM	Ammonia µM	Nitrite µM	Nitrate µM	N + N µM	Silica µM	Alkalinity µeq/L	Calculated TCO2 µM	Radon dpm/L	pH
Blue-1	130	3.00	0.29	0.02	0.07	0.09	6.50	2452	2121		8.223
Blue-2	130	3.03	0.51	0.02	0.07	0.09	8.13	2435	2122		8.197
Blue-3	130	3.03	0.66	0.02	0.02	0.04	9.25	2449	2150		8.172
Blue-4	300	3.07	0.73	0.04	0.02	0.06	10.88	2463	2185	1.2	8.135
Blue-5	300	3.17	0.91	0.06	0.00	0.06	12.50	2457	2208	1.2	8.084
Blue-6	300	3.17	1.17	0.04	0.07	0.11	14.00	2465	2244	1.7	8.029
Niskin		3.07	0.44	0.00	0.02	0.02	4.90	2449	2123		8.216
Uncertainty		±0.05	±0.08	±0.01	±0.05	±0.05	±0.50	±5	±6.0	±1.0	
Bottom Water		3.00	0.29	0.02	0.07	0.09	6.50	2452	2121	0.5	

y-Intercept	**3.0**	**0.3**	**0.02**	**0.1**	**0**	**6**	**2446**	**2110.1**
Source	Analysis	Analysis	Fit	Analysis	Analysis	Analysis	Fit	Fit
Error in Slope	0.0044	0.0070	0.0009	0.0044	0.0044	0.0438	0.7455	0.8954
Flux (unit/1000/m2/day)	**0.040**	**0.180**	**0.007**	**-0.007**	**0.000**	**1.627**	**3.54**	**26.99**
Error in Flux	**±0.012**	**±0.031**	**±0.003**	**±0.011**	**±0.011**	**±0.260**	**±1.91**	**±4.51**

Central Port Phillip Bay (Sites 11, 13, 22 and 37)

Oxygen concentrations from these four sites are shown n Figures 8 and 9. Data from these sites are summarised in Tables 8 through 11. The table for Site 22 contains two summary sections, the first fits all the data and the second fits only the last three samples.

Oxygen fluxes from Sites 11 and 13 (Figure 1) were comparable. Positive fluxes of phosphate, ammonia, nitrate + nitrite, silica were measured indicative of a flux of these nutrient species from the sediments to the overlying water. The oxygen flux from Site 37 in the eastern part of the Central Zone (Figure 1) was lower than that from the other sites, and near the lowest measured on the survey, but positive fluxes of nutrients indicated a transfer of these species from the sediments to the overlying water. The average oxygen flux at Site 22 in the southern sector of the Bay was comparable to that measured at Site 19, and small nutrient fluxes were measrued from the sediments to the overlying waters. Similarly as noted above for the other sites surveyed, significant depletions of oxygen from bottom water are not accompaned by increases in dissolved nitrate. The radon flux from the sediments was high at all sites, a result that suggests irrigation of the sediments (see below).

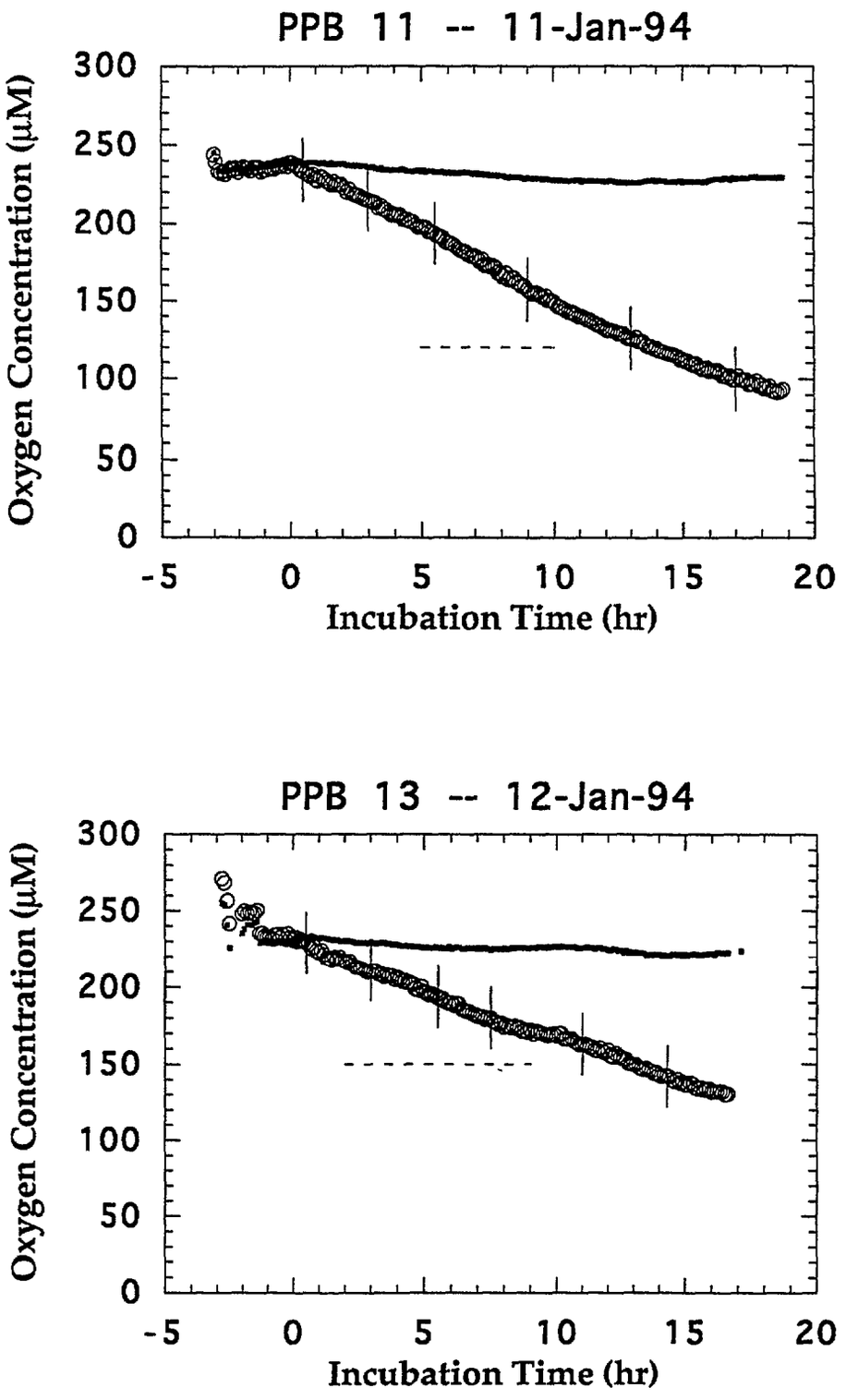

Figure 8. Oxygen concentration versus time from Sites 11 and 13 in the Central Zone of Port Phillip Bay.

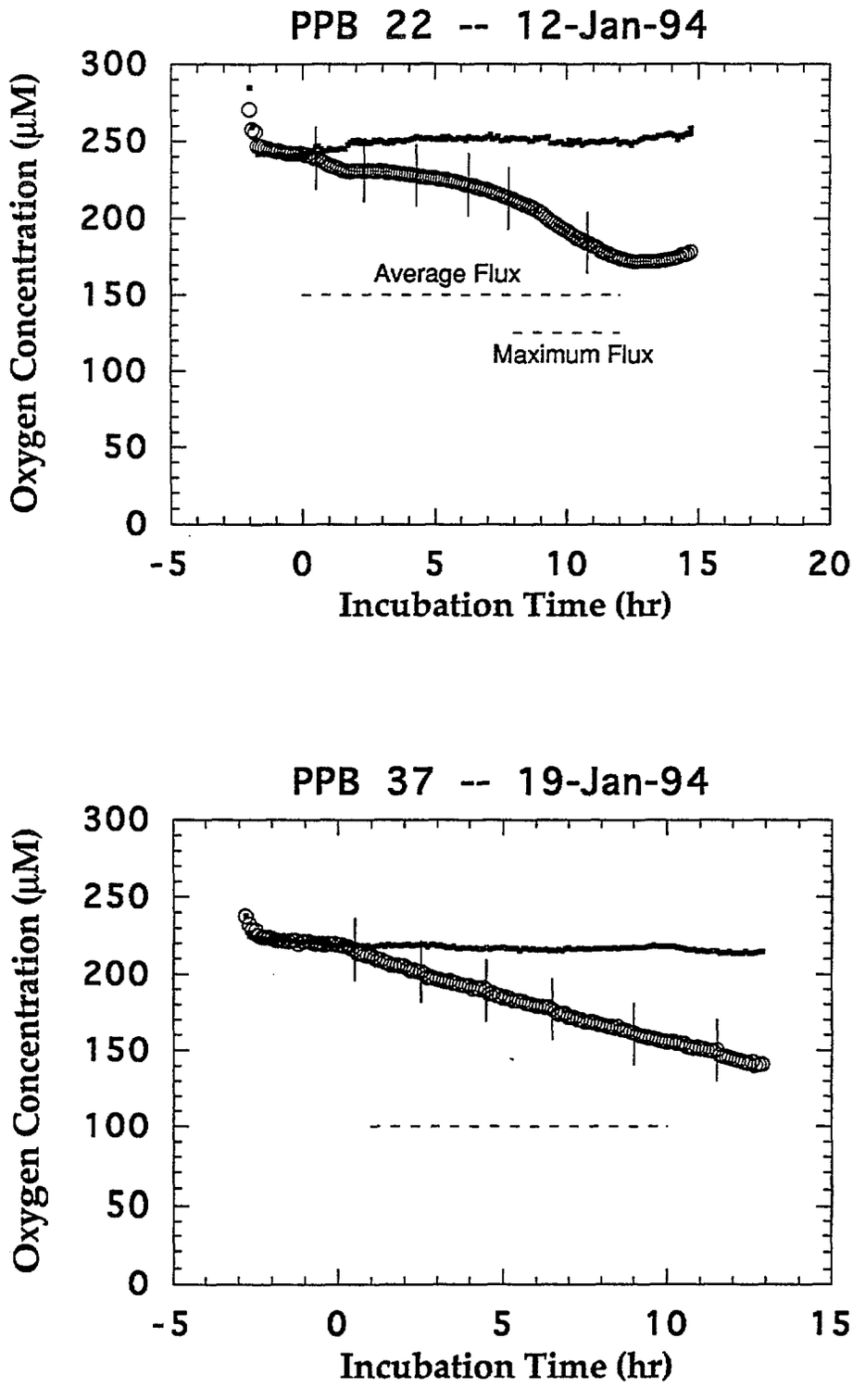

Figure 9. Oxygen concentration versus time from Sites 22 and 37 in the Central Zone of Port Phillip Bay.

Table 8. Concentrations of species in benthic chamber samples and calculated fluxes from Site 11 in the Central Zone of Port Phillip Bay.

PPB Station 11 (Yellow)

Cruise: PPB **Station:** 11 **Lander:** Yellow Date Printed: 16:52 23-Jan-94

			Clock Time	Elapsed Time
Time of Lid Drop	10-Jan 14:30			
Height of Blue Chamber (cm)	12.2	Draw 1	10-Jan 15:00	0.50
± uncertainty	±1.5	Draw 2	10-Jan 17:30	3.00
Height of Red Chamber (cm)		Draw 3	10-Jan 20:00	5.50
± uncertainty		Draw 4	10-Jan 23:30	9.00
Height of Yellow Chamber (cm)		Draw 5	11-Jan 3:30	13.00
± uncertainty		Draw 6	11-Jan 7:30	17.00
Chamber Area (m^2)	0.073			

Original Data

Sample	Volume mL	Phosphate µM	Ammonia µM	Nitrite µM	Nitrate µM	N + N µM	Silica µM	Alkalinity µeq/L	Calculated TCO2 µM	Radon dpm/L	pH
Blue-1	130	1.62	0.46	0.00	0.07	0.07	9.50	2317	2078		8.084
Blue-2	130	1.68	0.42	0.01	0.15	0.16	11.49	2324	2095		8.063
Blue-3	130	1.67	0.53	0.02	0.10	0.12	11.29	2333	2117		8.035
Blue-4	300	1.74	0.46	0.02	0.13	0.15	14.85	2358	2167	7.3	7.981
Blue-5	300	1.91	0.61	0.03	0.09	0.12	16.83	2376	2208		7.928
Blue-6	300	1.89	1.22	0.03			19.21	2388	2242	11.7	7.876
Niskin		1.49	0.53	0.00	0.00	0.00	7.92	2336	2095		8.084
Uncertainty		±0.05	±0.08	±0.01	±0.05	±0.05	±0.5	±5	±6.0	±2.0	
Bottom Water		1.49	0.53	0.00	0.00	0.00	7.92	2336	2085	0.5	

y-Intercept	**1.6**	**0.4**	**0.00**	**0.1**	**0**	**9**	**2320**	**2072.3**
Source	Fit	Fit	Analysis	Fit	Fit	Fit	Fit	Fit
Error in Slope	0.0050	0.0132	0.0006	0.0046	0.0047	0.0458	0.6028	0.5736
Flux (unit/1000/m2/day)	**0.077**	**0.101**	**0.006**	**0.014**	**0.021**	**1.922**	**12.02**	**30.49**
Error in Flux	**±0.017**	**±0.040**	**±0.002**	**±0.014**	**±0.014**	**±0.272**	**±2.30**	**±4.11**

Table 9. Concentrations of species in benthic chamber samples and calculated fluxes from Site 13 in the Central Zone of Port Phillip Bay.

PPB Station 13 (Yellow)

Cruise: PPB **Station:** 13 **Lander:** Yellow Date Printed: 17:20 23-Jan-94

			Clock Time	Elapsed Time
Time of Lid Drop	11-Jan 17:00			
Height of Blue Chamber (cm)	14.9	Draw 1	11-Jan 17:30	0.50
± uncertainty	±2.0	Draw 2	11-Jan 20:00	3.00
Height of Red Chamber (cm)		Draw 3	11-Jan 22:30	5.50
± uncertainty		Draw 4	12-Jan 1:00	8.00
Height of Yellow Chamber (cm)		Draw 5	12-Jan 4:00	11.00
± uncertainty		Draw 6	12-Jan 7:15	14.25
Chamber Area (m^2)	0.073			

Original Data

Sample	Volume mL	Phosphate µM	Ammonia µM	Nitrite µM	Nitrate µM	N + N µM	Silica µM	Alkalinity µeq/L	Calculated TCO2 µM	Radon dpm/L	pH
Blue-1	130	1.79	0.48	0.00	0.00	0.00	8.60	2294	2054		8.088
Blue-2	130	1.98	0.77	0.00	0.09	0.09	10.60	2327	2094		8.071
Blue-3	130	2.05	0.80	0.00	0.06	0.06	12.40	2334	2112		8.048
Blue-4	300	2.24	0.73	0.00	0.14	0.14	14.50	2342	2130	11.6	8.027
Blue-5	300	2.31	0.84	0.00	0.17	0.17	15.90	2346	2142	14.3	8.009
Blue-6	300	2.26	0.95	0.00	0.23	0.23	19.60	2354	2168	18.7	7.971
Niskin		1.59	0.37	0.00	0.00	0.00	7.60	2334	2094		8.082
Uncertainty		±0.1	±0.1	±0.01	±0.1	±0	±1	±5	±6.0	±2.0	
Bottom Water		1.79	0.48	0.00	0.00	0.00	8.60	2294	2054	0.5	
											Integrity
y-Intercept		**1.8**	**0.5**	**0.00**	**0.0**	**0**	**8**	**2302**	**2059.1**		
Source		Fit	Fit	Analysis	Analysis	Analysis	Analysis	Fit	Fit		
Error in Slope		0.0061	0.0069	0.0008	0.0038	0.0038	0.0381	0.7478	0.6403		
Flux (unit/1000/m2/day)		**0.142**	**0.110**	**0.000**	**0.058**	**0.058**	**2.805**	**15.62**	**29.57**		
Error in Flux		**±0.029**	**±0.029**	**#DIV/0!**	**±0.016**	**±0.016**	**±0.400**	**±3.40**	**±4.58**		

Table 10. Concentrations of species in benthic chamber samples and calculated fluxes from Site 22 in the Central Zone of Port Phillip Bay. See first flux summary averages all the data, the second only averages draws 4, 5 and 6.

PPB Station 22 (Blue)

Cruise: PPB **Station:** 22 **Lander:** Blue Date Printed: 18:15 23-Jan-94

			Clock Time	Elapsed Time
Time of Lid Drop	11-Jan 20:30			
Height of Blue Chamber (cm)	12.0	Draw 1	11-Jan 21:00	0.50
± uncertainty	±1.5	Draw 2	11-Jan 22:45	2.25
Height of Red Chamber (cm)		Draw 3	12-Jan 0:45	4.25
± uncertainty		Draw 4	12-Jan 2:45	6.25
Height of Yellow Chamber (cm)		Draw 5	12-Jan 4:15	7.75
± uncertainty		Draw 6	12-Jan 7:15	10.75
Chamber Area (m^2)	0.073			

Original Data

Sample	Volume mL	Phosphate µM	Ammonia µM	Nitrite µM	Nitrate µM	N + N µM	Silica µM	Alkalinity µeq/L	Calculated TCO2 µM	Radon dpm/L	pH
Blue-1	130	1.31	0.29	0.00	0.00	0.00	6.08	2329	2079		8.102
Blue-2	130	1.30	0.22	0.00	0.00	0.00	6.18	2332	2082		8.102
Blue-3	130	1.32	0.22	0.00	0.00	0.00	6.18	2346	2099		8.095
Blue-4	300	1.32	0.26	0.00	0.00	0.00	6.27	2338	2095	2.1	8.088
Blue-5	300	1.34	0.26	0.00	0.00	0.00	6.37	2337	2098	2.7	8.081
Blue-6	300	1.39	0.33	0.00	0.00	0.00	8.14	2389	2164		8.046
Niskin		1.42	0.29	0.00	0.00	0.00	6.76				8.104
Uncertainty		±0.1	±0.1	±0.01	±0.1	±0	±1	±5	±6.0	±1.0	
Bottom Water		1.31	0.29	0.00	0.00	0.00	6.08	2329	2079	0.5	

y-Intercept	**1.3**	**0.3**	**0.00**	**0.0**	**0**	**6**	**2323**	**2069.6**
Source	Analysis	Analysis	Analysis	Analysis	Analysis	Fit	Fit	Fit
Error in Slope	0.0052	0.0082	0.0010	0.0052	0.0052	0.0554	1.5374	1.8694
Flux (unit/1000/m2/day)	**0.020**	**0.009**	**0.000**	**0.000**	**0.000**	**0.446**	**12.94**	**19.48**
Error in Flux	**±0.015**	**±0.024**	**#DIV/0!**	**#DIV/0!**	**#DIV/0!**	**±0.169**	**±4.71**	**±5.91**

y-Intercept	**1.2**	**0.1**	**0.00**	**0.0**	**0**	**3**	**2248**	**1978.1**
Source	Analysis	Analysis	Analysis	Analysis	Analysis	Analysis	Fit	Fit
Error in Slope	0.0154	0.0247	0.0031	0.0154	0.0154	0.1543	4.6502	5.1825
Flux (unit/1000/m2/day)	**0.048**	**0.050**	**0.000**	**0.000**	**0.000**	**1.343**	**37.49**	**49.85**
Error in Flux	**±0.045**	**±0.071**	**#DIV/0!**	**#DIV/0!**	**#DIV/0!**	**±0.475**	**±14.19**	**±16.17**

Table 11. Concentrations of species in benthic chamber samples and calculated fluxes from Site 37 in the Central Zone of Port Phillip Bay.

PPB Station 37 (Yellow)

Cruise: PPB **Station:** 37 **Lander:** Yellow Date Printed: 18:47 23-Jan-94

			Clock Time	Elapsed Time
Time of Lid Drop	18-Jan 20:15			
Height of Blue Chamber (cm)	12.7	Draw 1	18-Jan 20:45	0.50
± uncertainty	±1.5	Draw 2	18-Jan 22:45	2.50
Height of Red Chamber (cm)		Draw 3	19-Jan 0:45	4.50
± uncertainty		Draw 4	19-Jan 2:45	6.50
Height of Yellow Chamber (cm)		Draw 5	19-Jan 5:15	9.00
± uncertainty		Draw 6	19-Jan 7:45	11.50
Chamber Area (m^2)	0.073			

Original Data

Sample	Volume mL	Phosphate µM	Ammonia µM	Nitrite µM	Nitrate µM	N + N µM	Silica µM	Alkalinity µeq/L	Calculated TCO2 µM	Radon dpm/L	pH
Blue-1	130	1.71	0.70	0.03	0.16	0.19	10.00	2329	2115		8.03
Blue-2	130	1.80	0.98	0.04	0.16	0.20	11.50	2321	2113		8.02
Blue-3	130	1.86	1.19	0.06	0.19	0.25	13.13	2330	2127		8.01
Blue-4	300	1.94	1.43	0.07	0.21	0.28	15.25	2334	2141	5.6	7.99
Blue-5	300	1.94	1.60	0.08	0.23	0.31	17.38	2348	2162	7.1	7.97
Blue-6	300	1.97	1.74	0.09	0.29	0.38	19.38	2351	2175		7.95
Niskin		1.66	0.49	0.01	0.12	0.13	9.75	2333	2115		8.04
Uncertainty		±0.05	±0.08	±0.01	±0.05	±0.05	±0.50	±5	±6.0	±2.0	
Bottom Water		1.66	0.49	0.01	0.12	0.13	9.75	2329	2115	0.5	

y-Intercept	**1.7**	**0.6**	**0.02**	**0.1**	**0**	**9**	**2323**	**2107.4**
Source	Analysis	Fit	Analysis	Analysis	Analysis	Analysis	Fit	Fit
Error in Slope	0.0047	0.0093	0.0009	0.0047	0.0047	0.0472	0.5607	0.6628
Flux (unit/1000/m2/day)	**0.085**	**0.337**	**0.021**	**0.040**	**0.061**	**2.738**	**7.05**	**17.78**
Error in Flux	**±0.018**	**±0.049**	**±0.004**	**±0.015**	**±0.016**	**±0.354**	**±1.90**	**±2.91**

Northern Port Phillip Bay (Site 14) and Hobsons Bay (Site 16)

Oxygen concentrations from this Site 14 are shown in Figure 10 and all data and fluxes are summarised in Table 12. Oxygen data from the Hobsons Bay Site 16 are also shown in Figure 10, and the data are summarised in Table 13.

Oxygen fluxes at these two sites were the highest recorded during the survey, except for the very high flux measured at Site 6 off the Werribee Treatment Complex. Despite the significant decreases in oxygen, very small fluxes of nitrate + nitrite were detected. However, positive fluxes of all nutrient species were measured indicating a transfer of solutes between the sediments and the overlying water. High radon fluxes were also measured, comparable to those high fluxes measured at most other locations.

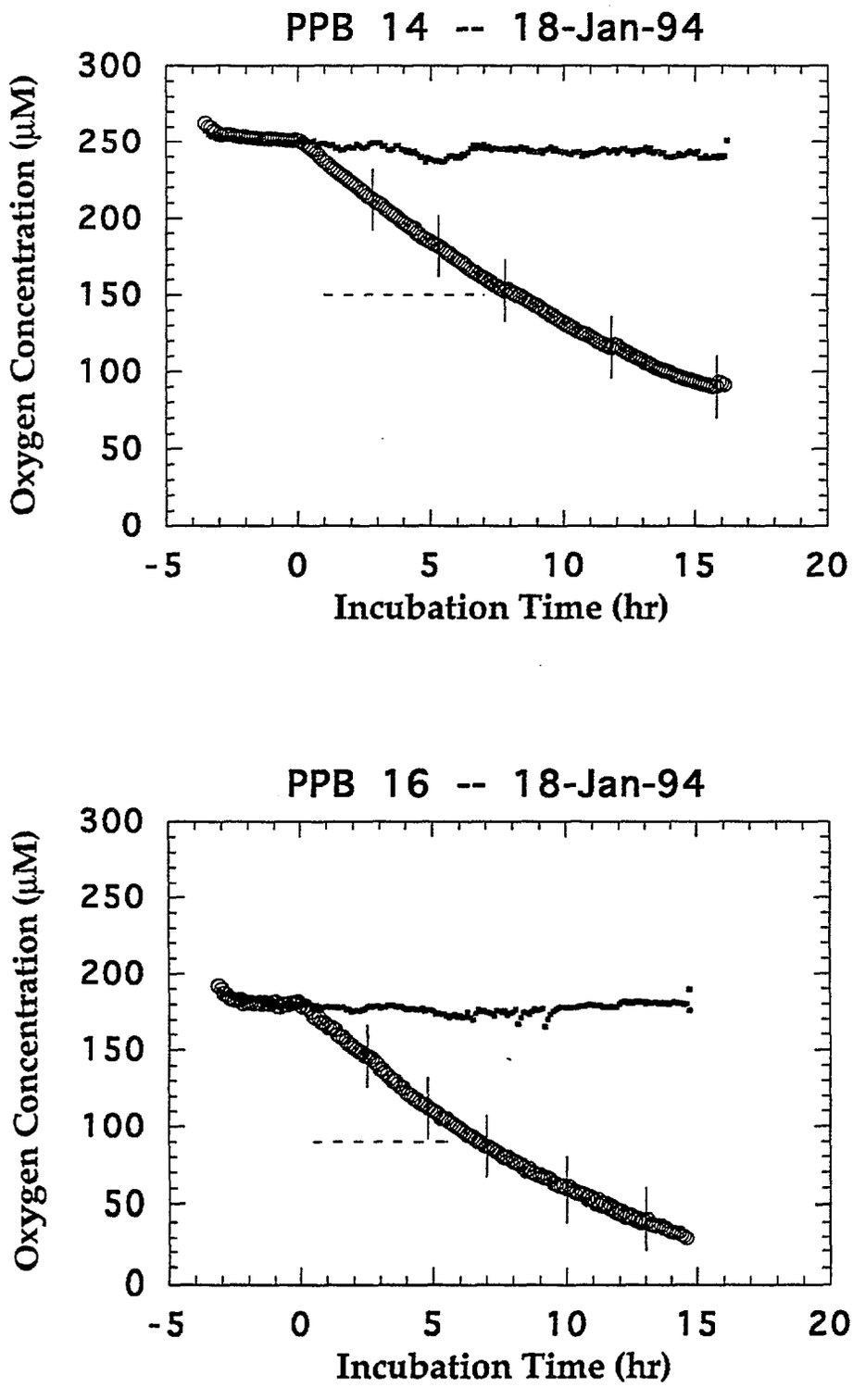

Figure 10. Oxygen concentrations versus incubation time from Sites 14 (northern Port Phillip Bay) and Site 16 in Hobsons Bay.

Table 12. Concentrations of species in benthic chamber samples and calculated fluxes from Site 14 in the Northern Port Phillip Bay.

PPB Station 14 (Blue)

Cruise: PPB **Station:** 14 **Lander:** Blue Date Printed: 18:27 23-Jan-94

			Clock Time	Elapsed Time
Time of Lid Drop	17-Jan 17:00			
Height of Blue Chamber (cm)	12.8	Draw 1	17-Jan 17:15	0.25
± uncertainty	±1.5	Draw 2	17-Jan 19:45	2.75
Height of Red Chamber (cm)		Draw 3	17-Jan 22:15	5.25
± uncertainty		Draw 4	18-Jan 0:45	7.75
Height of Yellow Chamber (cm)		Draw 5	18-Jan 4:45	11.75
± uncertainty		Draw 6	18-Jan 8:45	15.75
Chamber Area (m^2)	0.073			

Original Data

Sample	Volume mL	Phosphate µM	Ammonia µM	Nitrite µM	Nitrate µM	N + N µM	Silica µM	Alkalinity µeq/L	Calculated TCO2 µM	Radon dpm/L	pH
Blue-1	0										
Blue-2	130	2.34	2.24	0.11	0.72	0.83	20.68	2305	2099		8.02
Blue-3	130	2.70	3.55	0.16	1.12	1.28	25.75	2329	2141		7.98
Blue-4	300	2.86	4.42	0.18	1.69	1.87	30.69	2355	2184	15.1	7.94
Blue-5	300	3.25	6.50	0.21	1.72	1.93	35.96	2361	2213	17.2	7.89
Blue-6	300	3.33	7.54	0.21	1.81	2.02	42.47	2379	2250	23.6	7.84
Niskin		1.84	0.76	0.11		0.28	11.37	2312	2083		8.06
Uncertainty		±0.05	±0.08	±0.01	±0.05	±0.05	±0.50	±5	±6.0	±2.0	
Bottom Water		1.84	0.76	0.11	0.72	0.28	11.37	2300	2083	0.5	

y-Intercept	**2.0**	**1.0**	**0.11**	**0.7**	**1**	**14**	**2299**	**2080.1**
Source	Fit	Fit	Fit	Fit	Fit	Fit	Fit	Fit
Error in Slope	0.0129	0.0208	0.0013	0.0172	0.0233	0.1489	0.6569	0.8057
Flux (unit/1000/m2/day)	**0.300**	**1.403**	**0.024**	**0.257**	**0.358**	**6.053**	**17.09**	**35.74**
Error in Flux	**±0.053**	**±0.176**	**±0.005**	**±0.061**	**±0.083**	**±0.844**	**±2.84**	**±4.86**

Table 13. Concentrations of species in benthic chamber samples and calculated fluxes from Site 16 in the Hobsons Bay.

PPB Station 16 (Yellow)

Cruise: PPB **Station:** 16 **Lander:** Yellow Date Printed: 18:36 23-Jan-94

			Clock Time	Elapsed Time
Time of Lid Drop	17-Jan 18:00			
Height of Blue Chamber (cm)	14.1	Draw 1	17-Jan 18:15	0.25
± uncertainty	±1.6	Draw 2	17-Jan 20:30	2.50
Height of Red Chamber (cm)		Draw 3	17-Jan 22:45	4.75
± uncertainty		Draw 4	18-Jan 1:00	7.00
Height of Yellow Chamber (cm)		Draw 5	18-Jan 4:00	10.00
± uncertainty		Draw 6	18-Jan 7:00	13.00
Chamber Area (m^2)	0.073			

Original Data

Sample	Volume mL	Phosphate µM	Ammonia µM	Nitrite µM	Nitrate µM	N + N µM	Silica µM	Alkalinity µeq/L	Calculated TCO2 µM	Radon dpm/L	pH
Blue-1	0										
Blue-2	130	2.61	6.41	0.22	0.37	0.59	18.45	2288	2104.0		7.97
Blue-3	130	3.80	15.32	0.34	0.42	0.76	27.44	2332	2182.0		7.89
Blue-4	300	4.57	23.51	0.43	0.49	0.92	38.49	2378	2265.0	14.0	7.80
Blue-5	300	5.20	31.70	0.51	0.47	0.98	48.65	2416	2319.0	17.6	7.75
Blue-6	300	5.56	37.73	0.54	0.44	0.98	54.42	2464	2420.0	24.2	7.61
Niskin		2.15	0.98	0.06	0.36	0.42	12.80	2304	2096.0		8.02
Uncertainty		±0.05	±0.08	±0.01	±0.05	±0.05	±0.50	±5	±6.0	±2.0	
Bottom Water		2.15	0.98	0.06	0.36	0.42	12.80	2304	2096.0	0.5	

y-Intercept	**2.1**	**-0.1**	**0.09**	**0.4**	**0**	**11**	**2281**	**2072.4**
Source	Fit	Fit	Fit	Analysis	Fit	Fit	Fit	Fit
Error in Slope	0.0306	0.1650	0.0044	0.0064	0.0066	0.2538	2.7912	3.3050
Flux (unit/1000/m2/day)	**1.135**	**11.118**	**0.157**	**0.047**	**0.204**	**13.00**	**44.40**	**85.63**
Error in Flux	**±0.165**	**±1.380**	**±0.023**	**±0.022**	**±0.032**	**±1.707**	**±10.71**	**±14.82**

Patterson River area (eastern Port Phillip Bay, Site 19).

Oxygen concentrations from Site 19 are shown in Figure 11, and metabolite concentrations and fluxes are summarised in Table 14.

The measrued oxygen flux at this site was generally comparable to those measured at the Central Zone sites. Positive fluxes of nutrients are also indicative of a transfer of these species from the sediments to the overlying water. The radon flux was high.

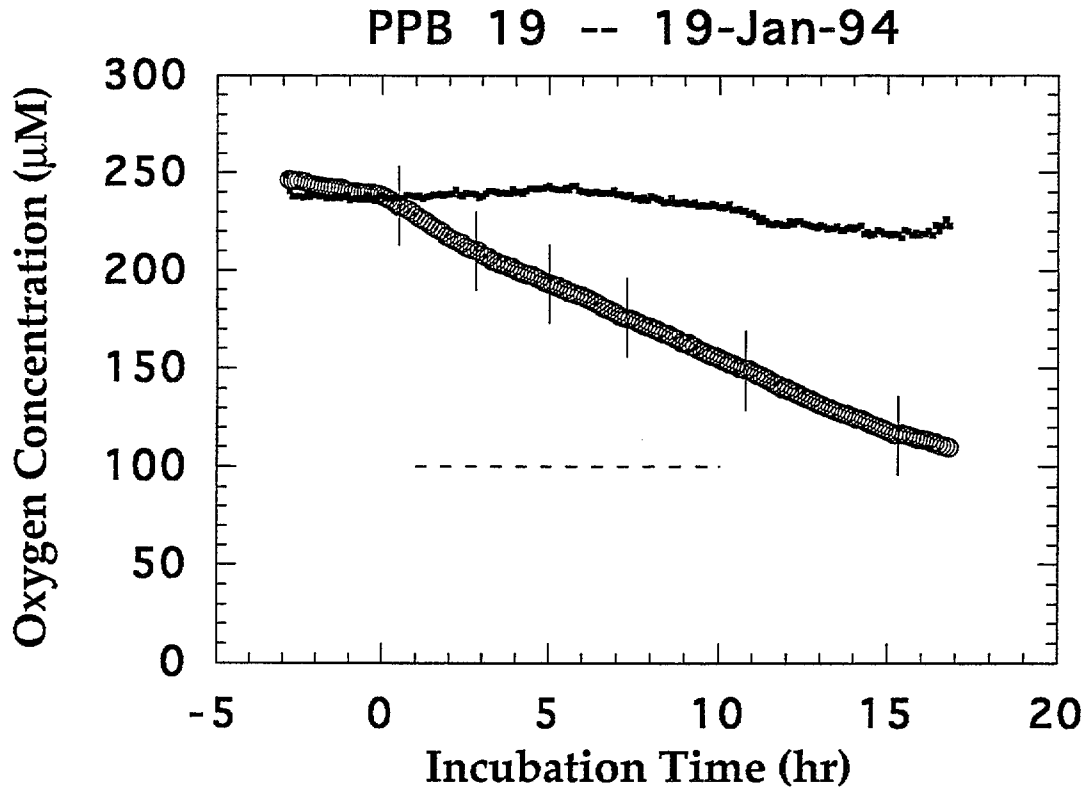

Figure 11. Oxygen concentration versus time from Site 19 in the Patterson River area, eastern Port Phillip Bay.

Table 14. Concentrations of species in benthic chamber samples and calculated fluxes from Site 19 in the Patterson River area of Port Phillip Bay.

PPB Station 19 (Blue)

Cruise: PPB **Station:** 19 **Lander:** Blue Date Printed: 18:43 23-Jan-94

			Clock Time	Elapsed Time
Time of Lid Drop	18-Jan 18:00			
Height of Blue Chamber (cm)	14.2	Draw 1	18-Jan 18:30	0.50
± uncertainty	±1.6	Draw 2	18-Jan 20:45	2.75
Height of Red Chamber (cm)		Draw 3	18-Jan 23:00	5.00
± uncertainty		Draw 4	19-Jan 1:15	7.25
Height of Yellow Chamber (cm)		Draw 5	19-Jan 4:45	10.75
± uncertainty		Draw 6	19-Jan 10:30	16.50
Chamber Area (m^2)	0.073			

Original Data

Sample	Volume mL	Phosphate µM	Ammonia µM	Nitrite µM	Nitrate µM	N + N µM	Silica µM	Alkalinity µeq/L	Calculated TCO2 µM	Radon dpm/L	pH
Blue-1	130	1.91	0.66	0.01	0.05	0.06	12.13	2301	2070		8.07
Blue-2	130	2.20	1.74	0.02	0.14	0.16	16.88	2306	2086		8.05
Blue-3	130	2.37	2.34	0.03	0.19	0.22	19.75	2319	2113		8.02
Blue-4	300	2.54	3.10	0.04	0.24	0.28	23.13	2337	2141	18.2	8.00
Blue-5	300	2.91	4.08	0.04	0.34	0.38	28.75	2342	2164	22.2	7.95
Blue-6	300	3.23	5.58	0.07	0.55	0.62	35.50	2357	2201	31.6	7.90
Niskin		1.83	0.45	0.02	0.08	0.10	10.38	2310	2078		8.07
Uncertainty		±0.05	±0.08	±0.01	±0.05	±0.05	±0.50	±5	±6.0	±3.0	
Bottom Water		1.83	0.45	0.02	0.08	0.10	10.38	2301	2070	0.5	

y-Intercept	**1.9**	**0.7**	**0.01**	**0.0**	**0**	**12**	**2301**	**2069.0**
Source	Fit	Fit	Analysis	Analysis	Analysis	Fit	Fit	Fit
Error in Slope	0.0048	0.0130	0.0007	0.0034	0.0034	0.0652	0.3583	0.4556
Flux (unit/1000/m2/day)	**0.302**	**1.095**	**0.011**	**0.102**	**0.113**	**5.325**	**12.93**	**29.61**
Error in Flux	**±0.038**	**±0.131**	**±0.003**	**±0.016**	**±0.017**	**±0.640**	**±1.90**	**±3.68**

Seafloor biogeochemistry discussion

Oxygen fluxes

Oxygen uptake ranges from 15 to 100 mmol m^{-2} day^{-1}; however, most sites have oxygen uptake rates between 25 and 45 of these units (Table 15). These fluxes are comparable to but generally higher than oxygen fluxes measured elsewhere. For examples rates of oxygen consumption (in those same units reported here) were found to vary between 5-20 (San Franciso Bay); 5-20 (Adriatic Sea); 20-80 (Potomac River, USA) and 10-20 near a sewage outfall offshore Los Angeles. Oxygen fluxes measured in 'unimpacted' sediments of the continental shelf of eastern Australia (1.7-3.8) are more than an order of magnitude lower than those measured in Port Phillip Bay (Heggie et al., 1990). Collectively these data and the comparisons above indicate that Port Phillip Bay is clearly not an oligotrophic environment as was thought prior to this work.

Two chambers were deployed, in Corio Bay, on the same day, and within metres of each other. Although the chamber paddle stir-rate varied by a factor of 5, the rate of oxygen uptake within these chambers is identical. The significance of this result will be discussed further in the section describing transport processes.

The rate of oxygen consumption within a benthic chamber generally decreases with time, consistent with the premise that oxygen uptake will be first order with respect to oxygen concentration. However, at Site 37, where the lowest oxygen flux was observed, first-order effects appear to be negligible and the oxygen uptake rate is constant.

Oxygen data from the chamber reflect the net oxygen flux, the sum of production and consumption. Thus the values reported as oxygen uptake indicate net oxygen consumption at all sites. At sites 8 and 6, near the Werribee Treatment Complex, the net oxygen consumption within the chamber becomes negligible near the end of the

incubation. This occurs before the chamber is completely depleted in oxygen; at Station 8 there is still 140 μM present. The abrupt change in the trend of oxygen consumption at Station 8 suggests an input of oxygen to the chamber, possibly through benthic photosynthesis. However, the sample draw times did not capture this event. At Station 6, the concentration of oxygen within the chamber decreases to about 30 μM at hour 16, but increases slightly towards the end of the incubation. At the time of draw 6, the oxygen profile shows a slight increase in O_2 and corresponding with this increase is a decrease in chamber CO_2. This is compelling evidence for benthic photosynthesis.

The oxygen electrode data from station 22 is enigmatic. At least 4 zones can be identified where the slope of the oxygen electrode chamber data changes. The Cs spike data indicates that the chamber was not compromised by leakage (at least during draws 4, 5, and 6). Treatment of this data includes the calculation of both average and maximum uptake rates. The spacing of sample collection and the generally small changes in nutrient and radon concentrations do not permit a more quantitative treatment of this data. Again, the data suggest that benthic photosynthesis is occurring at this site.

Nutrient Fluxes/Diagenetic Stoichiometry

Phosphate, ammonia, nitrite plus nitrate, carbon dioxide and dissolved silica are released from the sediments and added to the water column of the Bay (Tables 15 and 16). Of the nitrogen species measured, ammonium is the dominant nitrogen species recycled.

The remineralisation of organic matter within the sediments of Port Phillip Bay can be viewed using models describing diagenesis in other marine sediments. One common assumption is that the organic matter undergoing remineralisation is composed of C, N and P in a fixed ratio, approximately 106:16:1 (this is known as Redfield's Ratio and is considered representative of marine organic matter). A plot of the oxygen flux versus

the inorganic nitrogen flux is shown in Figure 12. In this figure N+N is the arithmetic sum of nitrate + nitrite, and TIN is total inorganic nitrogen or nitrate+nitrite + ammonia. The 'Redfield' line indicates the amounts of inorganic nitrogen produced for a range of measured oxygen fluxes, assuming Redfield stoichiometry. Figure 12 shows that the amount of nitrate+nitrite measured in the chambers is significantly less than that predicted to be produced from the ammonification and nitrification reactions (ie oxygen/nitrate+nitrite is predicted to be about 7:1). When the ammonia flux is included in this comparison, all data still are considerably lower than predicted, except at Site 16 (Hobsons Bay), where the ammonia produced results from interfacial sulphate reduction (see below). These results suggest that the 'missing nitrate' is being consumed by denitrification in the interfacial sediments; that is, nitrate which is produced during the nitrification reaction is being converted to N_2 during the anaerobic oxidation of organic matter by the denitrifying bacteria. Another plot (Fig. 13) of phosphate vs. total N indicates that these two species are not being released according to the Redfield ratio; there is much less nitrogen apparently escaping the sediments than predicted from the phosphate flux. It is not likely that this difference results only from an unusual N:P ratio in the material undergoing diagenesis. Our interpretation of these data is that significant denitrification is occurring within the sediments.

The relationship between oxygen and carbon fluxes is another measure of diagenetic stoichiometry. If oxygen is only consumed by the oxidation of carbon in organic matter, the ratio of oxygen flux to carbon flux will equal 1.0. If oxygen is also used to convert all of the ammonia released from the organic matter to nitrate, this ratio can increase up to 1.3. The measured TCO_2 flux may include CO_2 produced by $CaCO_3$ dissolution. If we assume that all of the alkalinity flux is due to the dissolution of $CaCO_3$ and subtract its contribution to the CO_2 flux, the relationship between oxygen uptake and CO_2 release corresponding to carbon oxidation shows a very systematic trend (Fig. 14). All the data, except two points, lie between the trend of oxygen/CO_2

flux ratio = 1.0-1.3. Two points fall significantly off the trend established by the other data. At Site 16 there is more CO_2 produced than can be accounted for by oxygen consumption, and at Site 6 there is far more oxygen consumed than CO_2 produced. The situation at Site 16 can be explained by the contribution of sulfate reduction to carbon oxidation. If the flux of alkalinity at this station is assumed to all come from sulfate reduction, then roughly half the carbon oxidised at this site is oxidised by sulfate and the other half by oxygen. In this case the ammonium flux is in general balance with the Redfield ratio, ie. measured ratio 86:11 is approximately = 106:16. The situation at Site 6 calls for a more unusual scenario. There must be a sink for oxygen that does not produce CO_2. The oxidation of reduced metals may be that sink. It is possible that during certain times of the year reduction of sulfate to sulfide results in the precipitation of metal sulphides such as iron sulfide. It is also possible that by means of bioturbation, physical mixing and the deeper penetration of oxygen into the sediments, these metals may periodically get oxidised, and as such account for the higher rates of oxygen consumption off the Werribee Treatment Complex (Fig.14). Such cycling has been proposed for the sediments within San Francisco Bay (Hammond et al., 1985). Reduced metals may also be reaching the zone of oxygen penetration if significant advection of groundwater occurs in this region.

Table 15. Summary of oxygen, alkalinity, total CO2 and radon fluxes ± 1 s.d.

Site	Oxygen	Alkalinity	Total CO2	Radon
8	27 ± 5	11 ± 3	29 ± 5	27 ± 5
8*	38 ± 6	18 ± 3	35 ± 6	688 ± 60
6	102 ± 15	24 ± 5	58 ± 7	555 ± 90
3-Y	30 ± 5	8 ± 2	32 ± 5	226 ± 20
3-B	30 ± 5	4 ± 2	27 ± 5	23 ± 3
11	29 ± 5	12 ± 2	31 ± 4	201 ±15
13	25 ± 4	16 ± 3	30 ± 5	455 ± 20
22 (ave)	15 ± 3	13 ± 5	20 ± 6	75 ± 10
22 (max)	29 ± 6	38 ± 14	50 ± 16	—
37	19 ± 3	7 ± 2	18 ± 3	220 ± 20
14	39 ± 6	17 ± 3	36 ± 5	460 ± 40
16	47 ± 7	44 ± 11	86 ± 15	603 ± 50
19	27±4	13 ± 2	30 ± 4	672 ± 60

Table 16. Summary of Nutrient Fluxes ± 1 s.d.

Site	Phosphate	Ammonia	Nitrite	Nitrate	N + N	Total Nitrogen	Silica
8	0.14 ± 0.02	1.1 ± 0.1	0.03 ± 0.01	0.24 ± 0.03	0.28 ± 0.04	1.4	2.0 ± 0.3
8*	0.26 ± 0.03	1.6 ± 0.2	0.03 ± 0.01	0.09 ± 0.02	0.12 ± 0.02	1.7	4.1 ± 0.5
6	0.27 ± 0.05	0.7 ± 0.4	0.03 ± 0.01	0.05 ± 0.02	0.08 ± 0.03	0.8	5.1 ± 0.7
3-Y	0.17 ± 0.03	0.61± 0.09	0.01 ± 0.01	0.01 ± 0.01	0.02 ± 0.01	0.6	2.5 ± 0.4
3-B	0.04± 0.01	0.18 ± 0.03	0.01 ± 0.01	–0.01 ± 0.01	0.00 ± 0.01	0.2	1.6 ± 0.3
11	0.08 ± 0.02	0.10 ±0.04	0.01 ± 0.01	0.01 ± 0.01	0.02 ± 0.01	0.1	1.9 ± 0.3
13	0.14 ± 0.03	0.11 ± 0.03	0	0.06 ± 0.02	0.06 ± 0.02	0.2	2.8 ± 0.4
22 (ave)	0.020 ± 0.015	0.01 ± 0.02	0	0	0	<0.1	0.5 ± 0.2
22 (max)	0.048 ± 0.045	0.05 ± 0.07	0	0	0	<0.1	1.3 ± 0.5
37	0.09 ± 0.02	0.34 ± 0.05	0.02 ± 0.01	0.04 ± 0.02	0.06 ± 0.02	0.4	2.7 ± 0.4
14	0.30 ± 0.05	1.4 ± 0.2	0.02 ± 0.01	0.26 ± 0.06	0.36 ± 0.08	1.8	6.1 ± 0.8
16	1.1 ± 0.2	11 ± 1	0.16 ± 0.02	0.05 ± 0.02	0.20 ± 0.03	11	13.0 ± 1.7
19	0.30 ± 0.04	1.1 ± 0.1	0.01 ± 0.01	0.10 ± 0.02	0.11 ± 0.02	1.3	5.3 ± 0.6

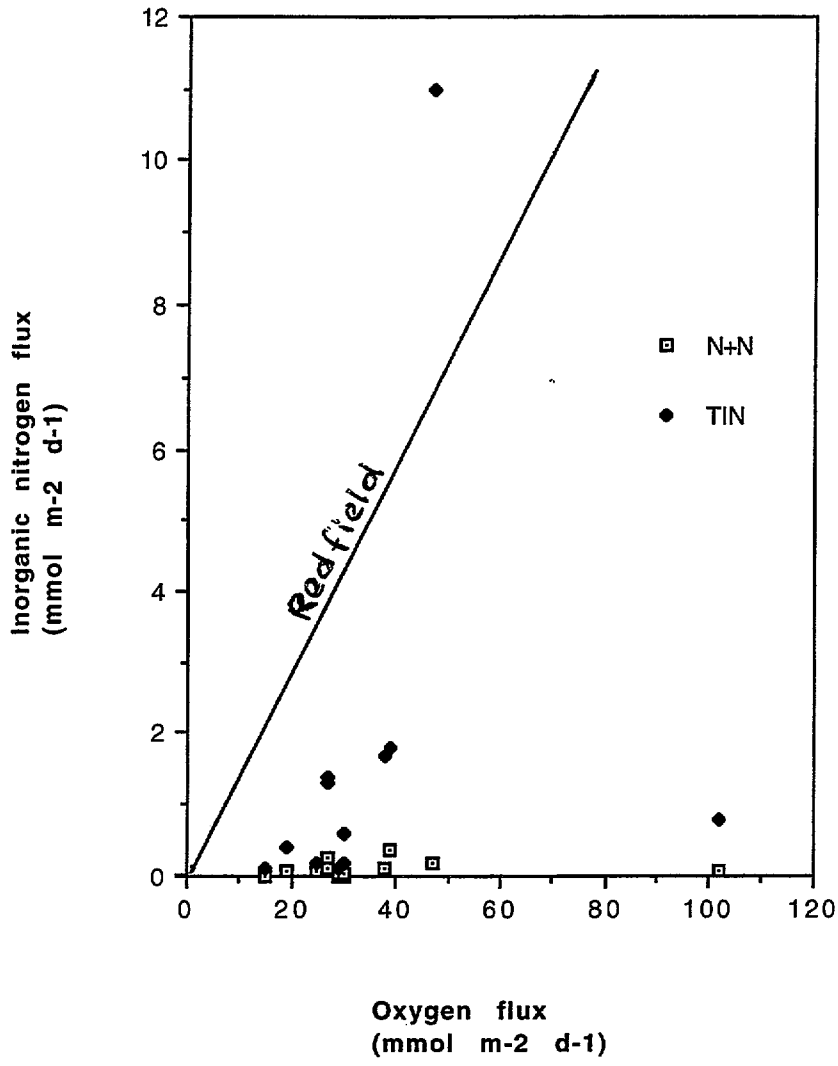

Figure 12. Flux of N+N (nitrate plus nitrite; open squares) and TIN (nitrite+nitrate+ammonia; closed diamonds) versus oxygen flux.

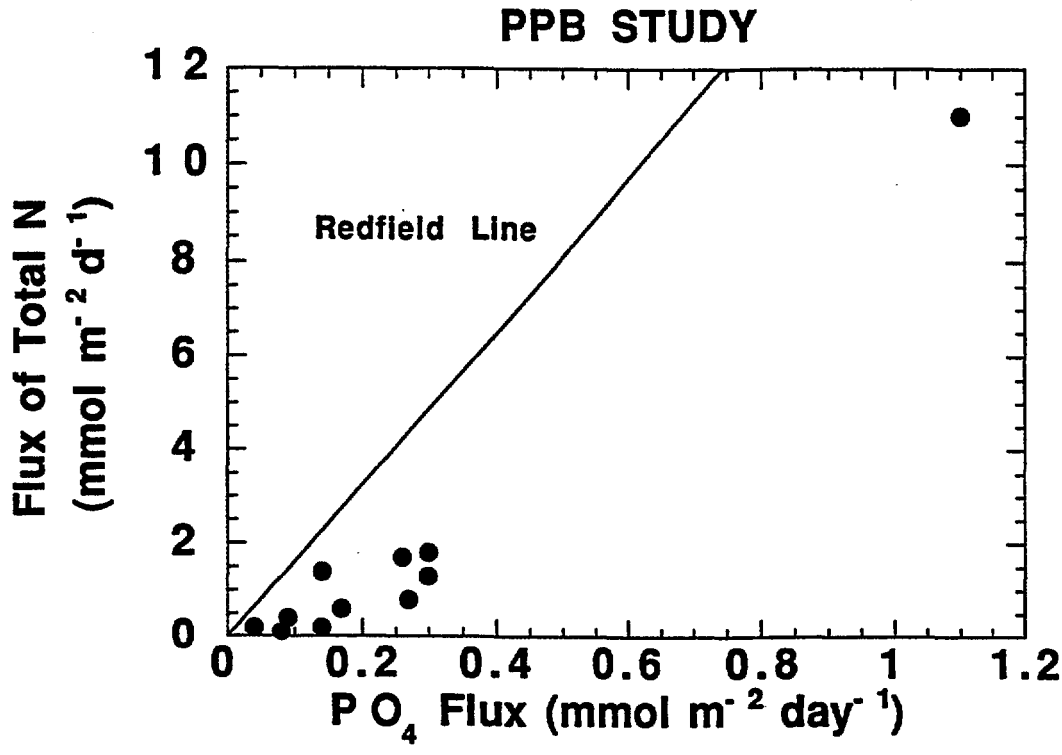

Figure 13. Flux of total measured N versus phosphate flux. The line depicts the predicted Redfield ratio stoichiometry. All of the points fall to the right of this line, indicating that the diagenesis of organic matter favours the release of phosphate over nitrogen.

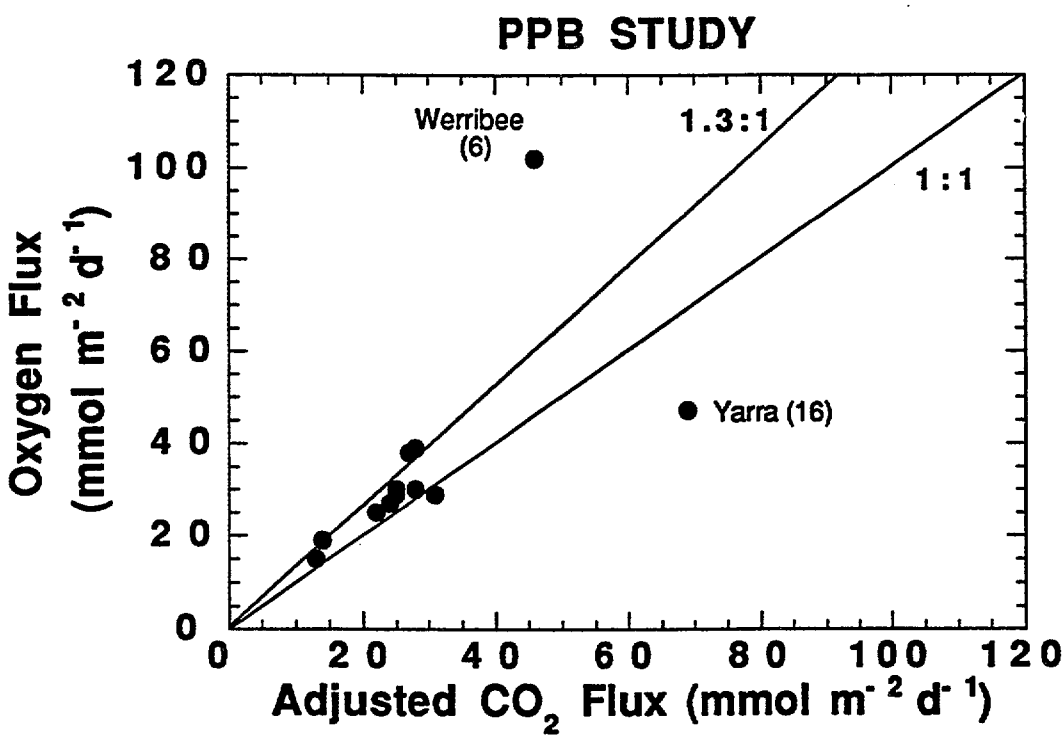

Figure 14. Oxygen flux versus carbon dioxide flux adjusted for carbonate dissolution. All but two of the data points lie between the lines defining a ratio of oxygen uptake:carbon release of 1.0-1.3. Sites 6 and 16 fall considerably off this trend, as is explained in the text.

Transport Processes in Sediments

The mechanism of solute exchange across the sediment-water interface in Port Phillip Bay is under investigation via several different avenues. Pore water profiles have been measured and continue to be measured as part of the ongoing study being conducted by the Marine Science Laboratories. Using natural (radon-222) and artificial (Cs) tracers, the relative importances of irrigation-induced advective exchange as well as diffusive exchange in these sediments was made.

Radon.

Radon-222 is produced in the sediments from the decay of its parent, radium-226, and accumulates in pore waters. The production of radon in sediments produces a strong concentration gradient between the pore water and overlying water. Because radon is a non-reactive element, the rate of radon transport across the sediment-water interface can be modelled assuming transport is diffusive, using an equation describing radon diffusion and decay. This simple diffusion-decay model (Berelson et al., 1987c) was used to predict the diffusive flux of radon from sediments in Port Phillip Bay.

Sediment samples from several locations were incubated in glass jars for a period of 15-16 days in order to measure the radium concentration within bay sediments. Based on these measurements, the diffusive flux of radon was calculated using the equation from Berelson et al. (1987c):

$$J = [D_S/\lambda]^{1/2} \times P_O$$

where J is the flux of radon, D_S is the diffusivity of radon through the sediments, l is the decay constant for radon ($l = 0.25$ day^{-1}; $t_{1/2} = 3.8$ days), and P_o is the measured radium activity of bay sediments in dpm/cm^3 of wet sediment. This calculation assumes that the source of radon production in sediments is constant down-core. The

results of these calculations are summarised in Table 17.

The diffusive flux of radon, predicted by the radium measurements and the equation above, varies between 27 and 114 atoms m^{-2} sec^{-1}. One site (Site 15) in Hobsons Bay had a diffusive flux of 114 atoms m^{-2} sec^{-1}. This flux is higher than all other diffusive fluxes, probably as a result of a different sediment type containing a higher abundance of terrigenous sediment which accumulates in the outer reaches of the Yarra River estuary. All other diffusive fluxes from Port Phillip Bay sediments fell within a relatively narrow range between 27 and 49 atoms m^{-2} sec^{-1}. The measured chamber fluxes varied between 27 and 688 atoms m^{-2} sec^{-1}, with most samples varying between 201 and 688 atoms m^{-2} sec^{-1}. At Site 8 (near Werribee Treatment Complex), Site 3-B (Corio Bay) and Site 22 (Central Zone of Port Phillip Bay), the diffusive flux and the measured chamber flux are comparable indicating measured chamber fluxes result predominantly from diffusive processes. At most sites, chamber fluxes exceeded diffusive fluxes, a result which can only be explained by irrigation of sediments, probably by benthic organisms. Large fluxes of radon can be explained if sediment pore water, which is very concentrated in radon, is being exported from depth and advected into the chamber. The measured chamber fluxes at Sites 3-B and 3-Y differ by an order of magnitude (23-226 atoms m^{-2} sec^{-1}), an observation which suggests patchiness in transport processes, notably irrigation activity. Similarly, at Site 8 (Werribee Treatment Complex), which was occupied on two separate occasions, radon flux varied between 27 and 425 atoms m^{-2} sec^{-1}, again indicating patchiness in irrigation.

A further test of the relationship between radon flux and irrigation can been seen in the plot of radon flux versus silica flux (Fig. 15). Because the source strength of production for both of these species is below a few cm's in the sediment column, they will more likely be affected by irrigation processes than will oxygen, which will be predominantly diffusion controlled. Silica and radon, which are in very low concentrations in the overlying water, can be greatly enriched in sediment pore water,

up to several hundred times bottom water concentrations. Thus, silica and radon fluxes will generally show the influence of irrigation more than will oxygen fluxes. The trend in Figure 15 clearly shows a correlation between silica fluxes and radon fluxes.

Cesium

During all benthic chamber deployments, a known volume of a solution of cesium chloride of known concentration is added to the chamber. There are two reasons for this: (i) the addition of a known volume of a known concentration is used to determine the volume of the seawater trapped beneath the benthic chamber and this is essential to accurately determine benthic fluxes and (ii) under certain conditions cesium may be used as a tracer and indicator of benthic transport processes.

At Sites 8, 11, 13 and 22 cesium was added toward the mid-point of the deployment, while at all other sites cesium was added near the beginning of the experiment, just before sample 2 was withdrawn. The change in cesium concentration with time was determined for all sites. A simple model can be used to explain the change in Cs concentration with time within a benthic flux chamber. Assuming cesium behaves conservatively, the transport of cesium from the overlying waters (enriched in cesium by the injection of spike) into the interstitial waters (naturally low cesium concentration), will occur by molecular diffusion or irrigation. In the scenario below we combine irrigation and diffusion processes and use the measured rate of change of cesium in the benthic chambers to calculate a transport coefficient or apparent diffusion coefficient. The equation describing Cs flux out of the chamber water and into the sediments is described below:

$$F_{(Cs)} = Da\,[Cs_{(bw)} - Cs_{(pw)}]/Z$$

where $F_{(Cs)}$ = the measured cesium flux out of the chamber

Da = the apparent mixing coefficient

$Cs_{(bw)}$ = the concentration of enriched cesium in the benthic chamber

$Cs_{(pw)}$= the concentration of cesium in pore waters

Z = the thickness of the benthic diffusive boundary layer

For $Cs_{(bw)} >> Cs_{(pw)}$ the equation reduces to

$$F_{(Cs)} = Da\ [Cs_{(bw)}]/Z \quad \text{and}$$

$$Da = F_{(Cs)}\ Z/Cs_{(bw)}$$

This equation was solved assuming that Z = 400 μm, based on the calibration between stirring rate and boundary layer thickness conducted by Berelson et al. (1990b), for all deployments except Station 3-Y (for which the stirring rate was 1 RPM corresponding to a diffusive boundary layer thickness of 800μm). The flux was determined from the initial change in Cs concentration after the injection although we also calculated the average change in Cs over the duration of the incubation (Table 18). Da was determined from the equation above and is shown plotted versus radon flux in Figure 16. If the loss of Cs from the chamber is related to the rate of pore water advective exchange, we would expect a positive relationship between Da and radon flux, as is shown in Fig. 16. Some scatter in this plot is undoubtedly due to the assumption that Z is constant for all chambers; nonetheless, the general correlation between Cs uptake and radon flux, totally independent parameters, adds additional evidence of the importance of irrigational advective transport between the sediment pore water and overlying water, especially at Sites 8*, 6, 13, 14, 16 and 19.

The calculated apparent mixing coefficients varied between 28 and 138 x 10^{-6} cm^2 sec^{-1}. In most cases the apparent mixing coefficient calculated from the two-point gradient method is higher than that calculated from the linear regression fit to all data, the range of the calculated coefficients reflects both the analytical uncertainties of cesium measurements (+/- 5%) and the assumptions of the model. Although Cs is not a perfectly conservative tracer, the molecular diffusivity determined by Buchholtz

(1987) is approximately $1x10^{-7}$ cm^2 sec^{-1}. Thus the apparent diffusivities we see exceed the molecular diffusivity, further confirming the existence of non-diffusive transport.

Diffusive Boundary Layer, Wave Pumping and Benthic Fluxes

The experiment we conducted in Corio Bay with paddle stir rate sheds some important insight into the nature of transport processes in these sediments. Chamber 3-Y was located within a few meters of chamber 3-B; chamber 3-Y was stirred at 1 RPM and chamber 3-B at 5 RPM. The diffusive boundary layer created by these two stir rates should vary by about a factor of 2. The only explanation for larger radon, silica, alkalinity and ammonium fluxes into chamber 3-Y is the importance of non-diffusive transport. This also implies that there is some source of alkalinity and ammonium deeper within the sediments; this source is undoubtedly sulfate reduction. The chamber that was stirred more rapidly had lower fluxes in everything except oxygen; the CO_2 fluxes were comparable. Oxygen uptake may be diffusion controlled and still not show much relationship to diffusive boundary layer if (1) oxygen uptake occurs deep (>1 mm) within the sediments, (2) oxygen uptake occurs primarily within burrows and irrigation structures, or (3) the effective diffusive boundary layer in both chambers was the same due to differences in the topography within the area captured by the chamber. Chris Burke (Univ. Tasmania) will be measuring oxygen profiles and the depth of oxygen penetration within these sediments as another portion of the overall study; thereby addressing item (1). We do not have the data to establish whether factors (2) or (3) are operating but conclude that diffusive boundary layer thickness is not a critical parameter in the control of benthic fluxes and nutrient exchange in Port Phillip Bay.

The transmittal of wave energy to the seafloor has been suggested as a means of mixing pore waters and enhancing benthic exchange. This process would be predicted to be more important or prevalent in coarse-grained, permeable sands. The data from

the Cs injections (Table 18) indicate that the apparent mixing coefficients at the most sandy site (Site 22) were comparable to coefficients calculated at the other sites. The highest apparent mixing coefficients were calculated at those sites which appeared to contain the higher proportions of fine grained material, those sediments which in fact would dampen wave induced turbulence to the surficial pore waters. The highest mixing coefficients were calculated for sites off Werribee (Site 6) and also in the deep-water site (Site 13) in the central zone of Port Phillip Bay, and both of these sites had abundant benthic animal activity present (Table 2).

Fluxes in atoms/m2/sec

Station ID	Diffusive Flux from Sediments	Measured Flux from Chamber
8	39	27
8*	39	688
6	27	555
1	37	
3-Y	36	226
3-B	36	23
11		201
13	39	455
22		75
37		220
14		460
15	114	
16	49	603
19	40	672

Table 17. Summary of Radon Fluxes from PPB

Table 18 Summary of calculated apparent mixing coefficients in sediments from cesium data.

Site	Cesium flux (ppm.cm/hr)	Cs concentration in chamber (ppm)	Apparent mixing coefficient 1 10^{-6} cm^2sec^{-1}
Site 8	-15.2 - 10.9	30.3	56-40
Site 8*	-15.2 - 19.3	27.2	62-79
Site 6	-20.7 - 30.9	29.5	78-116
Site 3Y	-14.8 - 13.7	34.9	94-88
Site 3B	-15.6 - 23.7	38.9	44-68
Site 11	-12.7 - 11.3	31.7	44-40
Site 13	-18.8 - 29.4	23.7	88-138
Site 22	-21.5 - 15.8	38.3	62-46
Site 37	-8.5 - 16.7	32.9	28-57
Site 14	-13.4 - 13.5	25.7	58-58
Site 16	-13.7 - 11.1	25.7	59-48
Site 19	-12.6 - 16.6	30.3	46-61

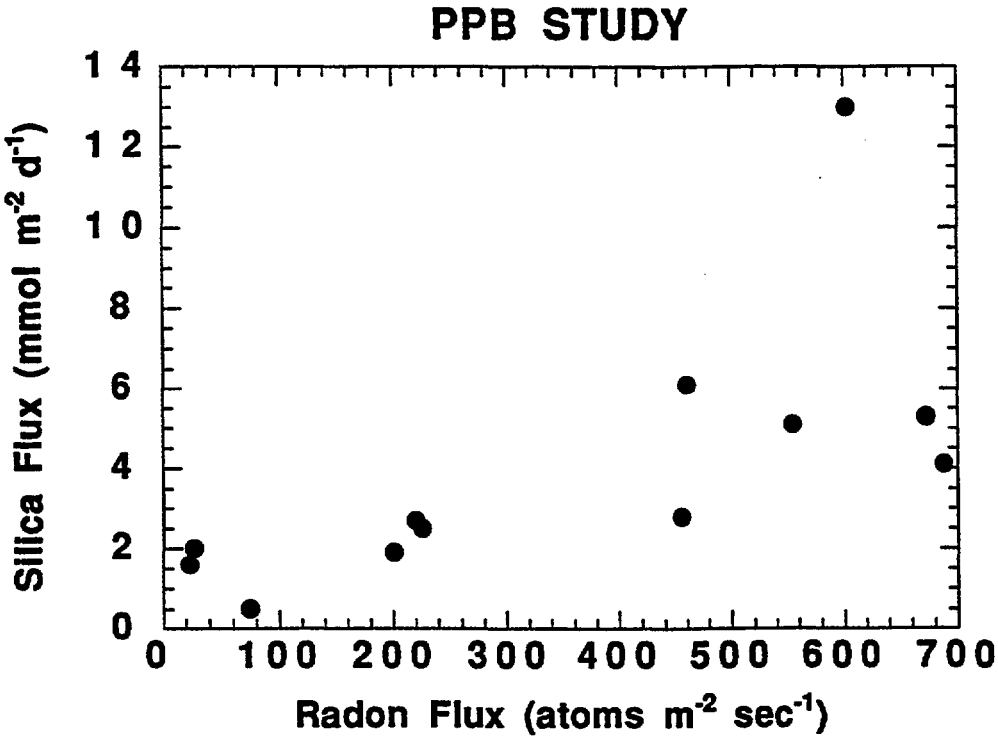

Figure 15. Silica flux versus radon flux.

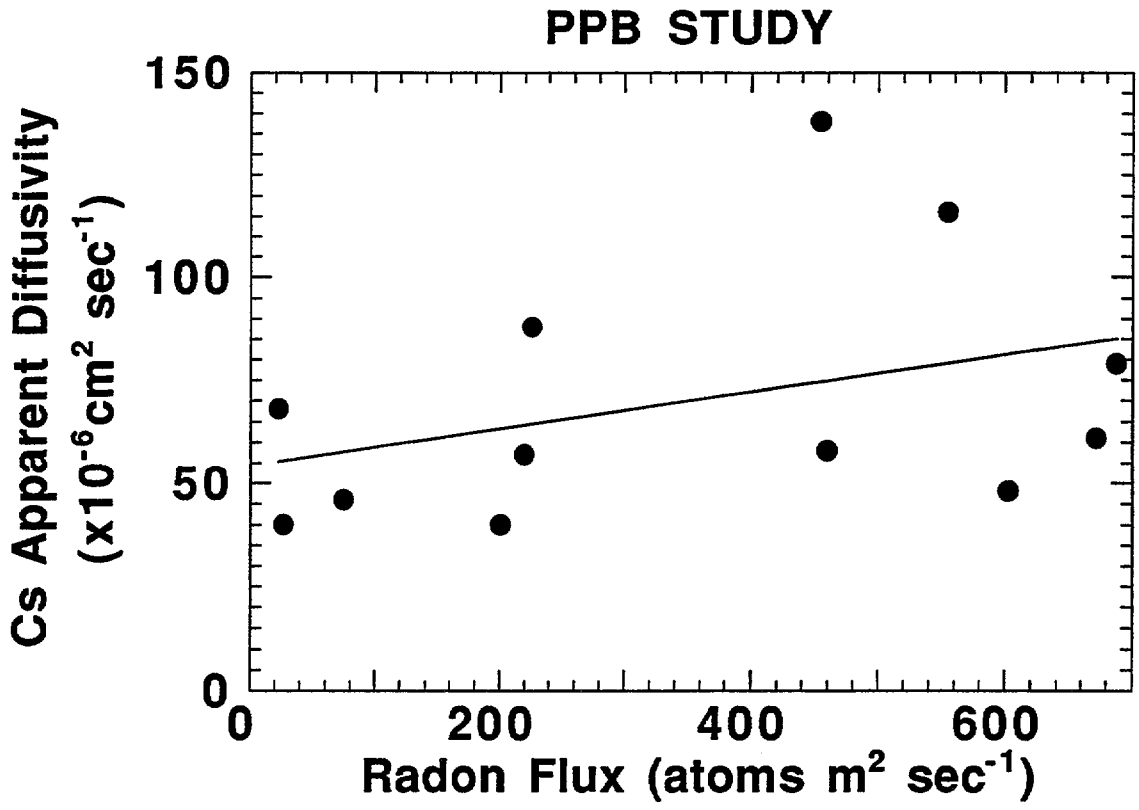

Figure 16. The apparent diffusivity of Cs versus radon flux.

Summary

1. Benthic fluxes of oxygen, phosphate, ammonia, nitrate, nitrite, silica, alkalinity, TCO_2 and radon were measured using benthic incubation chambers from 10 sites in Port Phillip Bay (Table 19).

2. The sediments of Port Phillip Bay are a net sink for oxygen. Benthic photosynthesis occurs at some of the shallower sites, but respiration dominates during both night and day. Further measurements with dark and light chambers should add some detail to this conclusion but we do not think it will change the overall finding.

3. The premise that marine organic matter is undergoing diagenesis on the sea floor of Port Phillip Bay is consistent with the fluxes and conclusions drawn from this study. The benthic fluxes of oxygen measured in Port Phillip Bay are generally higher than those measured in nearshore environments elsewhere, and are more than an order of magnitude higher than oxygen fluxes measured in 'unimpacted' sediments of the east Australian continental margin. These data indicate that Port Phillip Bay is not an oligotrophic environment as was thought prior to this survey. Oxygen accounts for most of the carbon oxidation, sulfate reduction is of secondary importance except at Site 16 in Hobsons Bay. It is likely that some sulfate reduction is occurring at many more sites but does not contribute more than 20-30% of the total carbon oxidised.

4. There is a conversion of organic nitrogen to inorganic nitrogen which is further converted to either N_2O or N_2 by nitrate reduction. This loss of utilisable N may make Port Phillip Bay nitrogen limited regarding primary productivity.

5. Phosphate is also not recycled as efficiently as carbon; phosphate is being retained within the sediments, probably by reaction with iron. However, at the Yarra River site 16, more phosphate is released than can be accounted for by carbon diagenesis. Hence, there is likely to be some adsorbed or mineral phosphate being released to the overlying water at this site.

6. Silica and radon release are closely related to the extent of irrigation. However, again in Hobsons Bay (Site 16), the silica flux exceeds the amount predicted based on the radon flux. One explanation may be that increased silica productivity in this region of the Bay enhances the diagenesis of biogenic silica.

8. The benthic fluxes of nutrients measured here must now be compared to other nutrient inputs into the bay, and the relative importances of these various fluxes in controlling the seawater inventories of nutrients assessed. In this way the major processes controlling the seawater nutrient concentrations can be identified.

9. The fluxes of radon into a benthic chamber are enhanced, in almost all sites, over the production and diffusive escape of radon from bay sediments. This is clear evidence that irrigation transport is important in this system. However, irrigation does not affect the transport of oxygen as much as it affects the transport of silica and radon. It will also enhance the transport of alkalinity and CO_2, especially if significant sulfate reduction is occurring.

10. The occurrence and extent of irrigation can be patchy. Nine of the 12 chamber deployments showed significant irrigation transport of sediment pore waters.

11. This survey has identified that the denitrification process and irrigation of the sediments controll (in part) the nutrient concentrations in the overlying water. As such these processes may be important controls on primary production and the 'health' of the bay. Additional work on the environmental conditions which support and sustain these processes is recommended.

Table 19. Summary of all Chamber Fluxes

Site	Oxygen	Phosphate	Ammonia	Nitrite	Nitrate	N + N	Total N	Silica	Alkalinity	Total CO2	Radon
8	-27	0.14	1.1	0.03	0.24	0.28	1.4	2.0	11	29	27
8*	-38	0.26	1.6	0.03	0.09	0.12	1.7	4.1	18	35	688
6	-102	0.27	0.72	0.03	0.05	0.08	0.8	5.1	24	58	555
3-Y	-30	0.17	0.61	0.01	0.01	0.02	0.6	2.5	8	32	226
3-B	-30	0.04	0.18	0.01	–0.01	0	0.2	1.6	4	27	23
11	-29	0.08	0.1	0.01	0.01	0.02	0.1	1.9	12	31	201
13	-25	0.14	0.11	0	0.06	0.06	0.2	2.8	16	30	455
22 (ave)	-15	0.02	0.01	0	0	0	<0.1	0.5	13	20	75
22 (max)	-29	0.05	0.05	0	0	0	<0.1	1.3	38	50	—
37	-19	0.09	0.34	0.02	0.04	0.06	0.4	2.7	7	18	220
14	-39	0.3	1.4	0.02	0.26	0.36	1.8	6.1	17	36	460
16	-47	1.1	11	0.16	0.05	0.2	11	13.0	44	86	603
19	-27	0.3	1.1	0.01	0.1	0.11	1.3	5.3	13	30	672

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