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The Partitioning of Organic Carbon Cycle in Coastal Sediments of Kwangyang Bay

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Biogeochemical cycling of organic carbon is quantitatively partitioned in terms of 1) flux to the ocean bottom, 2) benthic utilization at or near the sediment-water interface, 3) remineralization and 4) burial within sediments, by making an independent determination for each component process from a single coastal site in Kwangyang Bay. The partitioning suggests that the benthic utilization at or near the sediment-water interface is the major mode of organic carbon cycling at the site. The benthic utilization takes 61.8% (441.6 $gCm^{-2}yr^{-1}$) of the total near-bottom organic carbon flux, 714.6 $gCm^{-2}yr^{-1}$, and far exceeds the remineralization of organic carbon within the sediments which amounts only to 6% (41.24 $gCm^{-2}yr^{-1}$) of the total near-bottom flux. The residence time is about 1.6 years for the sedimentary metabolic organic carbon in the upper 45 cm. The dominant partitioning of the benthic utilization in the carbon budget suggests that most of labile organic carbons are consumed at or near the sediment-water interface and are left over to the sediment column by significantly diminished amounts.

INTRODUCTION

Biogeochemical cycling of organic carbon has been quantified by partitioning the processes involved in the cycling (Reimers and Suess, 1983; Martens and Klump, 1984; Berelson *et al.*, 1987; Smith, 1987; McNichol *et al.*, 1988; Rowe *et al.*, 1988; Berelson *et al.*, 1990; Martens *et al.*, 1992). The processes include organic carbon flux to the ocean bottom, decomposition and burial of organic carbon in sediments. The decomposition of sedimentary organic carbon has been further partitioned (Reimers and Suess, 1983; Smith, 1987): benthic utilization at or near the sediment-water interface and remineralization within sediments. With these partitionings a mass balance may be set up to establish an organic carbon budget: the organic carbon flux to the ocean bottom (C_{in}) being equal to the sum of the benthic utilization ($C_{benthic}$), the remineralization (C_{remin}) and the burial (C_{burial}) of organic carbon. Though each component in the mass balance can be determined independently (either by direct measurement or by indirect diagenetic modeling), no study is available that has secured independent estimates for all those partitionings.

In the previous attempts at least one component among all partitionings has been dependently calculated from the mass balance of:

$$C_{in} = C_{benthic} + C_{remin} + C_{burial} \tag{1}$$

For instances, Martens and Klump (1984) do not have an independent measurement of C_{in} for which a value of primary productivity was substituted; despite their emphasis on the importance of benthic utilization in the organic carbon cycling, Reimers and Suess (1983) dependently calculated $C_{benthic}$ from the mass balance equation, Eq. (1), after substituting the independently determined values for C_{in}, C_{remin} and C_{burial}. In these dependent approaches, the potential uncertainties of all the known components are accumulated and contributed to the last unknown component during the simple calculation. Since there are inherent uncertainties even with an independent determination for each partitioning process (e.g. Jorgensen, 1978; Cobler and Dymond, 1980; Klump and Martens, 1981; Murray and Kuivila, 1990), any dependent determinations for the processes would make the uncertainties even greater, potentially leading to sham results.

Here, we have obtained the independent determinations for the all four partitioning processes from a station located in the eastern margin of Kwangyang Bay. C_{in} is determined by sediment trap mooring; $C_{benthic}$ by benthic chamber deployment that has allowed an *in situ* carbon flux measurement. C_{remin} is determined interactively by applying both a kinetic decay model to the sedimentary organic carbon contents and a steady-state diagenesis model to the pore water total CO_2 (ΣCO_2) concentrations. C_{burial} is determined from the kinetic decay model. Those determinations have allowed us to have genuine, quantitative assessment of the importance of each component process in the organic carbon cycling.

METHODS

Gravity coring, deployments of a sediment trap and a benthic chamber were performed at the site chosen for this study in July of 1994, the warmest summer over the last decade (Fig. 1). A 45 cm long, 9 cm wide gravity core was retrieved from the site. The sediment trap was moored 2 m above the sea floor for 17 hours in the water depth of 12 m at the site. The cone-shaped trap has a baffled mouth (12 cm radius) with the aspect ratio of 6. A stainless collector bottle is screw-attached to the trap end. The trapped sample in the bottle was freeze-dried and analyzed for organic carbon content using Carlo Erba NA 1500 following the method of Verardo *et al.* (1990).

Assisted with SCUBA diving, the benthic chamber (40 cm W×40 cm L×35 cm H) was deployed on the sea floor. A tiny hole (0.5 cm diameter) in the center of the chamber lid kept the pressure inside the chamber equal to that of the outside, and maintained the height of the bottom water trapped in the chamber at 20 cm. An arm of Tygon hose was attached to the side of the chamber for water sampling in approximately 4 hr interval. A set of four 50 mL syringes was used for each sampling by a SCUBA diver. Collected water samples were analyzed for dissolved oxygen, ammonia, and ΣCO_2 by the methods described in Grasshoff *et al.* (1983) and Parsons *et al.* (1984).

Pore waters were extracted from 2.5 cm interval down to the first 15 cm sediment depth and 5 cm interval in the remainder depth by pressure filtration of nitrogen gas through 0.45 mm membrane filter at in situ temperature. Ammonia and nitrate+nitrite were analyzed by the methods of Grasshoff *et al.* (1983). Organic carbon contents of the squeezed sediment cakes left after pore water extraction were determined using Carlo Erba NA 1500 analyzer by the method of Verardo *et al.* (1990). Porosities and bulk densities were measured from wet weights and weight loss after oven drying at 80°C (Curtis, 1971).

RESULTS

From the deployment of the sediment trap near

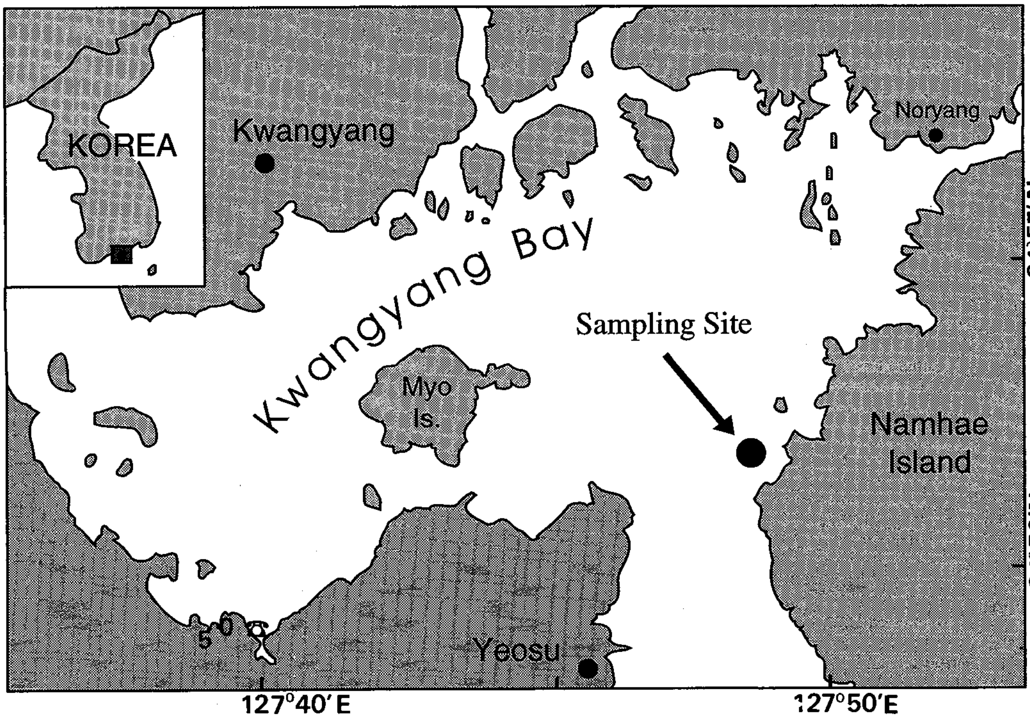

Fig. 1. A location map for the study site (34°51.8'N, 127°48.8'E) marked in solid circle in Kwangyang Bay.

Table 1. Chemistry data of the benthic chamber

BENTHIC CHAMBER			
Elapsed time (hr)	Dissolved Oxygen (mg/L)	Ammonia (μM)	ΣCO_2 (μM)
0.00	6.78	0.22	2.32
2.17	6.73	1.46	2.43
4.17	5.88	1.12	2.46
5.58	4.83	3.08	2.48
19.83	4.24	13.30	2.65
22.16	3.00	44.23	2.92

the sea floor, organic carbon flux to the floor was determined as 714.6 $gCm^{-2}yr^{-1}$ with its content of 1.22%. This organic carbon flux is two to three orders of magnitude greater than the fluxes near the bottom at the VERTEX sediment trap stations in the deep North Pacific (Martin *et al.*, 1987; Murray and Kuivila, 1990), and nine times less than the average flux in Shihwa Lake (Hong *et al.*, 1996). Rapid increases in both ΣCO_2 and nutrients within the chamber water with time are consistent with the decrease in dissolved oxygen (Fig. 2 and Table 1), indicating benthic utilization of organic carbon at or near the sediment-water interface. $C_{benthic}$, representing benthic utilization at or near the sediment-water interface, was measured to be 441.6 $gCm^{-2}yr^{-1}$ from the rate of change in ΣCO_2 within the benthic chamber (Fig. 2).

The results of the pore water and sediment analyses are listed in Table 2. Silty mud sediments, found at and around the study site, are characterized

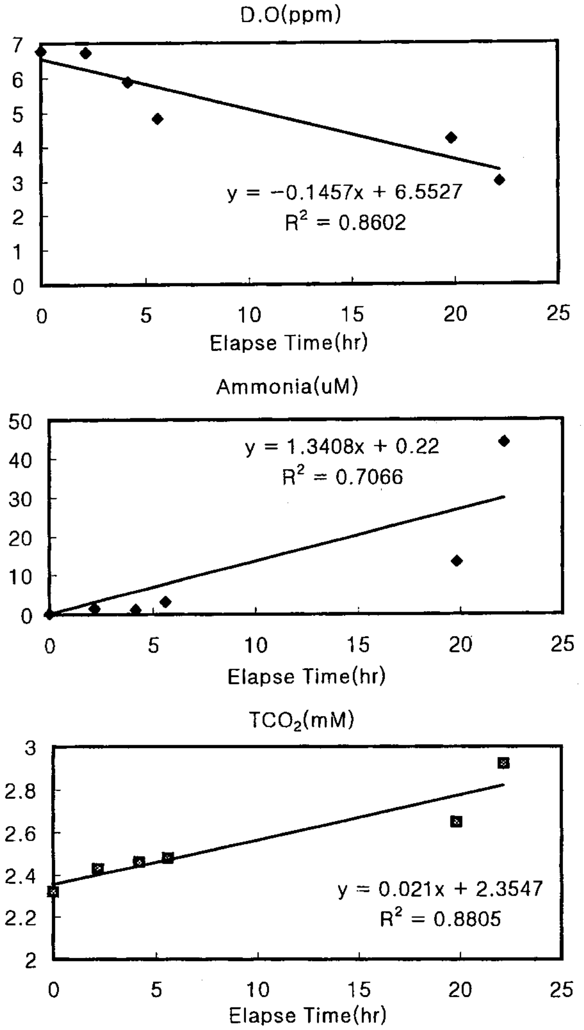

Fig. 2. Changes in concentrations of dissolved oxygen, ammonia and ΣCO_2 with time within the benthic chamber deployed on the sea floor of the eastern margin of Kwangyang Bay. No SCUBA diving during the night time after the chamber deployment has resulted in the missing data points in the middle of x-axis.

Table 2. Sedimentary organic carbon and porewater chemistry data

SEDIMENT		PORE WATER		
Depth (cm)	Organic Carbon (%)	ΣCO_2 (mM)	Ammonia (μM)	$NO_3^- + NO_2^-$ (μM)
2.5	0.83	4.24	-	-
5.0	-	-	280.92	6.74
7.5	0.79	-	219.42	3.88
10.0	-	-	221.62	2.39
12.5	0.77	8.38	200.22	2.69
15.0	-	9.43	232.97	2.54
20.0	0.77	7.67	242.60	3.00
25.0	0.76	9.60	289.63	2.39
30.0	0.76	7.91	320.30	2.27
35.0	0.73	8.85	366.30	2.39
40.0	0.68	8.28	478.10	2.39
45.0	0.74	9.65	-	-

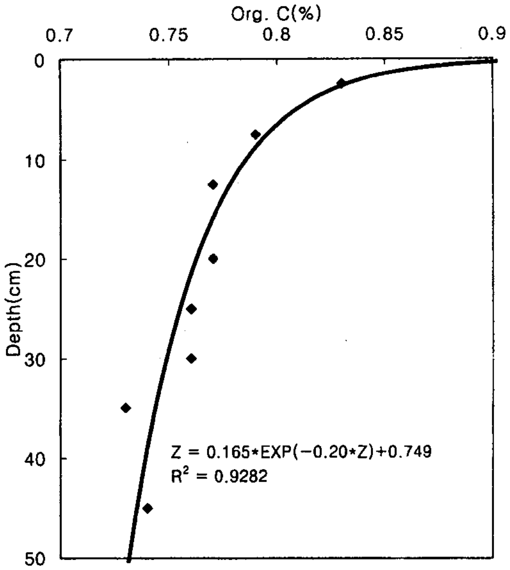

Fig. 3. Distribution of sedimentary total organic carbon contents with depth. The solid line represents a computer fit of Eq. (9) to the data above 50 cm, yielding its equation in the form of C(z) = 0.165 exp(-0.2z) + 0.749.

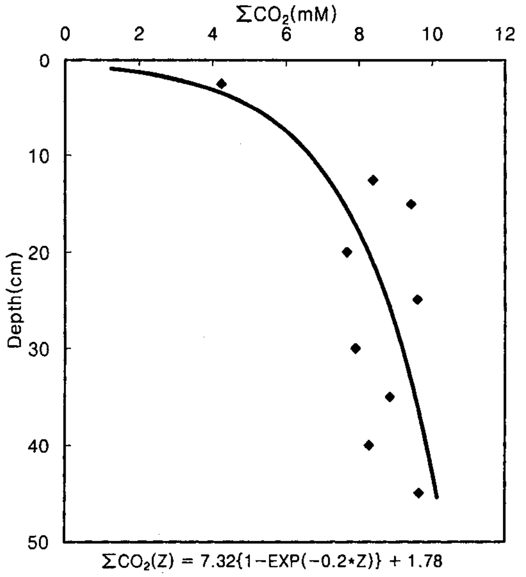

Fig. 4. Distribution of pore water ΣCO_2 with depth. The solid line represents a computer fit of Eq. (17) to the data above 50 cm, yielding its equation in the form of $\Sigma CO_2(z) = 7.32\ \{1\text{-}\exp(-0.2z)\} + 1.78$.

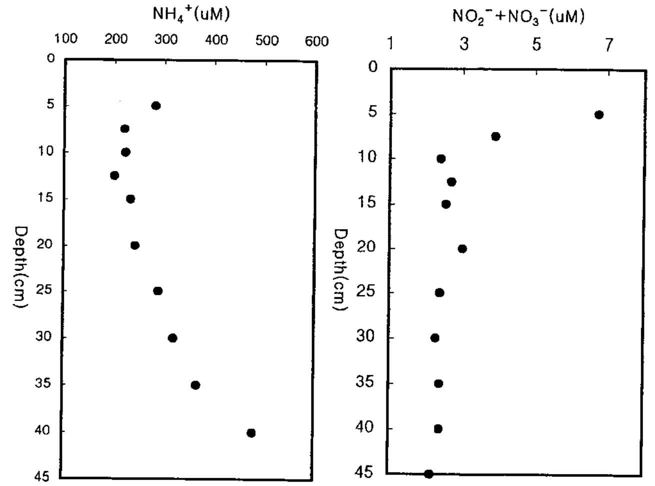

Fig. 5. Downcore distributions of pore water ammonia and nitrate+nitrite.

by low macrofaunal abundance and lack of sediment mixing. Sedimentary organic carbon decreases continuously with depth (Fig. 3). Constant background level of organic carbon at depth is convincingly observed at the top 35-45 cm. Pore water ΣCO_2 increases with depth (Fig. 4) in response to the downcore decrease in the sedimentary organic carbon content (Fig. 3). The depth gradients of both pore water ΣCO_2 and organic carbon, however, are not notably large. Pore water ammonia increase with depth, but again its gradient is not large (Fig. 5). Rapid decrease in the pore water nitrate+nitrite indicates ongoing process of denitrification in the sediments (Fig. 5). Sediment color does not clearly reveal redox boundary. However, the profiles of porewater ammonia and nitrate show that the boundary appears to develop over the subsurface depth zone between 5 cm and 10 cm.

DISCUSSIONS

Sedimentary organic carbon modeling

The organic carbon degradation rate constants have been derived through diagenesis modelings (Berner, 1980; Grundmanis and Murray, 1982; Emerson *et al.*, 1985; Emerson and Hedges, 1988; and many others). Berner (1980) assumes that the decomposition of metabolic organic carbon follow first order kinetics according to the reaction given below:

$$dG/dt = -kG \qquad (2)$$

where G is the content of metabolic organic carbon at any depth z, and k is a first order rate constant. The total derivative may have the following mathematical representation for sedimentary diagenesis of metabolic organic matter:

$$dG/dt = \delta G/\delta t + (\delta z/\delta t)\,(\delta G/\delta z) \qquad (3)$$

where $\delta z/\delta t$ can be replaced by sedimentation rate, ω. Under the assumption of steady state diagenesis of metabolic organic carbon, the term $\delta G/\delta t$ is equal to zero, and Eq. (3) becomes:

$$dG/dt = \omega\delta G/\delta z \qquad (4)$$

Relating Eqs. (2) and (4) gives the steady state diagenetic equation which employs first order decomposition of metabolic organic carbon in sediments:

$$-\omega\delta G/\delta z - kG = 0 \qquad (5)$$

Potential sediment mixing was not considered in this equation as there were no apparent signs of mixing. Metabolic organic carbon runs out at great depth so that $G = 0$ at $z = \infty$. At the sediment-water interface, i.e. $z = 0$, metabolic organic carbon is set to be G_0. With these boundary conditions the appropriate solution of Eq. (5) is:

$$G(z) = G_0 \exp(-\beta z) \qquad (6)$$
$$\text{where } \beta = k/\omega \qquad (7)$$

Since the data we have are not metabolic organic carbon contents but total organic carbon contents which may include non-metabolic organic carbon, Eq. (6) needs to be operationally modified. Assuming that non-metabolic organic carbon is constant at any depth, the following relations will hold:

$$C(z) = G(z) + C_\infty, \text{ and } C_o = G_o + C_\infty \qquad (8)$$

where C(z) is the total organic carbon content at any depth, C_o the total organic carbon content at z=0, and C_∞ the content of non-metabolic organic carbon at $z=\infty$. Substituting Eqs. (8) into Eq. (6):

$$C(z) = (C_o - C_\infty) \exp(-\beta z) + C_\infty \qquad (9)$$

Curve fitting of Eq. (9) to the profile of sedimentary total organic carbon gives the following solution with C_o=0.914% and C_∞=0.749% (Fig. 3):

$$C(z)=0.165 \exp(-0.2z) + 0.749 \qquad (10)$$

The difference between C_o and C_∞ corresponds, according to Eqs. (8), to G_o=0.165% which is equivalent to the sedimentary organic carbon remineralized. Using the difference, the remineralization of sedimentary organic carbon (C_{remin}) can be determined as follows (Martens and Klump, 1984):

$$C_{remin} = \omega\, \rho\, (1 - \phi)\, (C_o - C_\infty) = \omega\, \rho\, (1 - \phi)\, G_o \qquad (11)$$

where ω is the sedimentation rate, ρ the sediment density, and ϕ the porosity. Though the G_o in Eq. (10) is obtained in weight percent, the G_o in Eq. (11) has to be supplied in the unit of weight fraction. Table 3 summarizes values of ω and C_{remin} obtained from Eq. (11).

The burial of organic carbon (C_{burial}) may be obtained from the non-metabolic organic carbon, C_∞:

$$C_{burial} = \omega\, \rho\, (1 - \phi)\, C_\infty \qquad (12)$$

Table 3 also lists C_{burial} values corresponding to the varying sedimentation rates.

Pore water ΣCO₂ modeling

Remineralization of sedimentary organic carbon is reflected in ΣCO_2 dissolved in pore water. The increase in the pore water ΣCO_2 with depth is a mirror image of the decrease in sedimentary organic carbon with depth (Figs. 3 and 4). Because of this coupling C_{remin} can be determined from a diagenetic modeling of the pore water ΣCO_2, an alternative to the organic carbon modeling in the previous section. Pore water ΣCO_2 may be explained by a steady-state diagenetic model:

Table 3. Organic carbon remineralization rate (C_{remin}) and burial rate (C_{burial}) at varying sedimentation rate. The C_{remin} and C_{burial} are determined from Eqs. (11) and (12), respectively, both of which are derived from the first order kinetic decay model for sedimentary organic carbon, Eq. (9). Parameter values used for the determinations are ρ=2.78 gcm^{-3}, ϕ=0.7, C_o=0.914%, C_∞=0.749%, and $G_o=C_o-C_\infty$=0.165%

ω ($cmyr^{-1}$)	C_{remin} ($gCm^{-2}yr^{-1}$)	C_{burial} ($gCm^{-2}yr^{-1}$)
1.0	13.761	62.4666
2.0	27.522	124.9332
3.0	41.283	187.3998
4.0	55.044	249.8664
5.0	68.805	312.3330
6.0	82.566	374.7996
7.0	96.327	437.2662
8.0	110.088	499.7328
10.0	137.610	624.6660

$$D\delta^2\Sigma CO_2/\delta z^2 - \omega\delta\Sigma CO_2/\delta z + \Gamma k G = 0 \qquad (13)$$

where ΣCO_2 is in millimolar concentration, D is the diffusion coefficient of ΣCO_2 which is assumed to be the average value for the coefficients of CO_2, carbonate and bicarbonate ions in pore water in cm^2yr^{-1}. A mixing coefficient for D is not considered, because no noticeable signs of bioturbation were observed (Han, 1994). Γ is the factor which converts the metabolic organic carbon content from the unit of weight fraction to that of millimolar carbon concentration, i.e. it is in $mmolL^{-1}$:

$$\Gamma = 10^6\rho\, ((1 - \phi)/\phi)/12 \qquad (14)$$

With the boundary conditions of $\Sigma CO_2 = \Sigma CO_2^0$ at z=0 and $\Sigma CO_2=\Sigma CO_2^\infty$ at $z=\infty$, the solution of Eq. (13) becomes:

$$\Sigma CO_2(z) = \{\Gamma G_o/(\beta(D/\omega)+1)\}\, \{1-\exp(-\beta z)\} + \Sigma CO_2^0 \qquad (15)$$

At $z=\infty$, Eq. (15) becomes $\Sigma CO_2^\infty=\{\Gamma G_o/(\beta(D/\omega)+1)\}+\Sigma CO_2^0$. This relation is rewritten:

$$\Sigma CO_2^\infty - \Sigma CO_2^0 = \{\Gamma G_o/(\beta(D/\omega)+1)\} \qquad (16)$$

Substituting Eq. (16) into Eq. (15) for G_o, the solution Eq. (15) can be rewritten:

$$\Sigma CO_2(z) = (\Sigma CO_2^\infty - \Sigma CO_2^0)\, \{1-\exp(-\beta z)\} + \Sigma CO_2^0 \qquad (17)$$

Curve fitting of Eq. (17) to the profile of pore water ΣCO_2 gives the following solution (Fig. 4):

$$\Sigma CO_2(z) = 7.32\{1-\exp(-0.2z)\} + 1.78 \qquad (18)$$

Eq. (18) shows that $\Sigma CO_2^\infty - \Sigma CO_2^0$ = 7.32 mM and ΣCO_2^0 = 1.78 mM. G_o which was derived from the previous organic carbon modeling can be alternatively derived by rearranging Eq. (16):

$$G_o = \{(\beta(D/\omega)+1)/\Gamma\}\ \{\Sigma CO_2^{\infty} - \Sigma CO_2^{0}\} \qquad (19)$$

These two G_os, the one from sedimentary organic carbon modeling (Eq. (8)) and the other from pore water ΣCO_2 modeling (Eq. (19)), should be consistent with each other. Substituting G_o in Eq. (11) by Eq. (19):

$$C_{remin} = \omega\ \rho\ (1 - \phi)\ \{(\beta(D/\omega)+1)/\Gamma\}\ \{\Sigma CO_2^{\infty} - \Sigma CO_2^{0}\} \qquad (20)$$

The C_{remin} in Eq. (20) should be compatible with the C_{remin} in Eq. (11) which is obtained from the sedimentary organic carbon model. This compatibility would validate our modeling approaches.

Table 4 summarizes, at varying sedimentation rates, values of G_o and C_{remin} that are obtained from Eqs. (19) and (20), respectively. Since the sedimentary organic carbon modeling of Eq. (10) has determined G_o to be 0.165%, the pore water ΣCO_2 modeling should also generate a similar G_o value. For this to be met, a sedimentation rate capable of generating a G_o value similar to 0.165% has to be selected from Table 4. The sedimentation rate satisfying this restriction is determined to be around 3.0 cmyr^{-1}. The values of G_o and C_{remin} corresponding to this sedimentation rate in Table 4 are compatible with those in Table 3 at the same sedimentation rate. These compatibilities of sedimentation rate, G_o, and C_{remin} support the credibility of the two modelings. Though a directly measured sedimentation rate is not available at the site, the model-derived rate of 3.0 cmyr^{-1} is within the range of 1.0 to 7.4 cmyr^{-1} reported from Kwangyang Bay (RCOID, 1991). The sedimentation rate of 3 cmyr^{-1} is roughly two to three orders of magnitude greater than those from the VERTEX sediment trap stations in the deep North Pacific (Murray and Kuivila, 1990). This proportionality is also consistent with the two to three orders of magnitude greater particulate flux at our site than the fluxes at the VERTEX sediment trap stations (Martin *et al.*, 1987), again supporting the reliability of our sedimentation rate derived from the two diagenesis modelings. A direct measurement of sedimentation rate is, however, still anticipated for a fine-tuning of the two models employed in this study.

Table 4. Organic carbon remineralization rate (C_{remin}) at varying sedimentation rate. The rate C_{remin} is determined from Eq. (20) which is derived from the steady-state diagenesis model for porewater ΣCO_2, Eq. (13). Parameter values used for the determinations are ρ=2.78 gcm^{-3}, ϕ=0.7, ΣCO_2^{∞}-ΣCO_2^{0}=7.32 mmolL^{-1}, β=0.2 cm^{-1}, Γ=9.9×10^{4} mmolL^{-1} and D=9.8×10^{-6} cm^{2}sec^{-1}. Corresponding to the varying sedimentation rate, G_o is estimated from Eq. (19) which is also derived from the porewater ΣCO_2 model

ω (cmyr^{-1})	G_o %	C_{remin} gCm^{-2}yr^{-1}
1.0	0.4670	38.9479
2.0	0.2372	39.5646
3.0	0.1606	40.1812
4.0	0.1223	40.7979
5.0	0.0993	41.4145
6.0	0.0840	42.0312
7.0	0.0705	42.6478
8.0	0.0648	43.2645
10.0	0.0534	44.4970

Sensitivity testing for the two models

It is obvious from Eq. (11) that C_{remin} is directly proportional to ω and G_o, making C_{remin} sensitive to the changes in ω and G_o. Referring to Eq. (20), C_{remin} is also sensitive to a change in ΣCO_2^{∞} - ΣCO_2^{0}. Uncertainties for the parameters of k, ω, D and ΣCO_2^{∞} - ΣCO_2^{0} could generate consequent errors in G_o and C_{remin}. Therefore, fine tunings for these parameters need to be performed with the solution equations of the organic carbon and pore water ΣCO_2 models.

Uncertainties of G_o and ΣCO_2^{∞} - ΣCO_2^{0} are simultaneously deduced. At the values of ω=3 cmyr^{-1}, D= 9.8×10^{-6} cm^{2}sec^{-1}, G_o=0.165%, β=0.2 cm^{-1} and Γ= 9.9×10^{4} mmolL^{-1}, the ΣCO_2^{∞}-ΣCO_2^{0} is estimated to be 7.52 mM from Eq. (19). At the same values of ω and D, the values of G_o and ΣCO_2^{00}-ΣCO_2^{0} are 0.161% and 7.32 mM, respectively (Table 4). Therefore, G_o and ΣCO_2^{∞}-ΣCO_2^{0} would be in the ranges of 0.161 to 0.165% and 7.32 to 7.52 mM, respectively, at the fixed values of ω=3 cmyr^{-1} and D=9.8×10^{-6} cm^{2}sec^{-1}. Consequent to these ranges of G_o and ΣCO_2^{∞}-ΣCO_2^{0}, the C_{remin} would correspondingly be in the range of 40.18 to 42.30 gCm^{-2}yr^{-1}.

Since a direct measurement of the sedimentation rate is not available at the study site, any uncertainty in the rate would be at best suggested from Eq. (20) by substituting those uncertainties for G_o, ΣCO_2^{∞}-ΣCO_2^{0} and C_{remin} obtained above. If ΣCO_2^{∞}-ΣCO_2^{0}, G_o and C_{remin} could have any values within their ranges, ω would be in the range of 2.92 cmyr^{-1} (at ΣCO_2^{∞}-ΣCO_2^{0}=7.32 mM, G_o=0.165% and C_{remin}= 40.18 gCm^{-2}yr^{-1}) to 3.07 cmyr^{-1} (at ΣCO_2^{∞}-ΣCO_2^{0}= 7.52 mM, G_o=0.161% and C_{remin}=42.30 gCm^{-2}yr^{-1}).

Interrelationship between ΣCO_2^{∞}-ΣCO_2^{0} and G_o as represented in Eq. (19) allows us to refine uncertainties for diffusion coefficient D (Fig. 6). Since the β in Eq. (7) has been determined to be 0.2, the range of k corresponding to that of ω (2.92-3.07

$cmyr^{-1}$) is from 0.584 to 0.614 yr^{-1}, respectively. A similar linear relationship between k and ω was also documented (Toth and Lerman, 1977; Muller and Mangini, 1980). With these ranges of k and ω, the G_o in Eq. (19) can be regarded as being dependent only on D and ΣCO_2^{∞}-ΣCO_2^0, enabling the generation of Fig. 6. Fig. 6 shows that, at a constant value of G_o, a larger value of ΣCO_2^{∞}-ΣCO_2^0 is predicted either at a lower D or at a lower ω, and vice versa. The reason for these inverse relationships is because low molecular diffusion or low advection should result in a large difference between ΣCO_2^{∞} and ΣCO_2^0 in pore waters. The projections of the ranges of ΣCO_2^{∞} -ΣCO_2^0 and G_o onto the x-y plane have yielded the slashed rectangle in Fig. 6. Any value of D that allows a line to pass through the rectangle would be accepted for an appropriate diffusion coefficient. The minimum and the maximum values of D satisfying this condition are estimated to be 8.7×10^{-6} cm^2sec^{-1} and 9.9×10^{-6} cm^2sec^{-1}, respectively. The diffusion coefficient for CO_2 is at least a factor of one or one-and-half higher than those for bicarbonate and carbonate ions (Broecker and Peng, 1982). Therefore, the range for D appears to be reasonable.

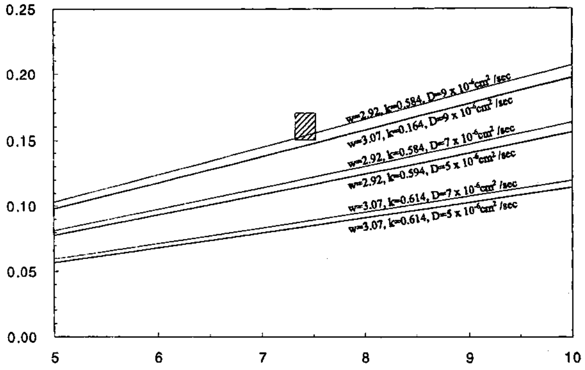

Fig. 6. A graphical presentation for the sensitivity test for the diagenesis model as represented by Eq. (19). The series of lines generated from Eq. (19) illustrate relationships between ΣCO_2^{∞}-ΣCO_2^0 and G_o at varying parameter values for ω, k, and D. To comply with the fine tuned ranges of ΣCO_2^{∞}-ΣCO_2^0 (7.32-7.52 mM), G_o (0.161-0.165%) and ω (2.92 to 3.07 $cmyr^{-1}$), a line must pass through the hatched rectangle which is constructed by the intersections of the ranges of ΣCO_2^{∞}-ΣCO_2^0 and G_o. The lines bounding the rectangle have yielded the minimum and the maximum values of D at 8.7×10^{-6} and 9.9×10^{-6} cm^2sec^{-1}, respectively.

Organic carbon budget

Table 5 summarizes the magnitudes of the partitions in the biogeochemical cycling of organic carbon at the site in Kwangyang Bay. Any attempt for the independent quantifications of all the partitioning processes in the mass balance equation, Eq. (1), could be a wild approach in that potential uncertainities in the quantification often could not satisfy the equation. The partition values in Table 5 do satisfy the mass balance equation in the first order: the summation of $C_{benthic}$ + C_{remin} + C_{burial} explains C_{in} by up to 94 percent. The remaining 6 percent may be due to the uncertainties from the measurements of C_{in} and $C_{benthic}$ as well as the diagenesis modelings. Considering inherent uncertainties in the determination of each process, the first order satisfaction of the mass balance supports the validities of the measurements of particulate carbon flux and benthic flux of dissolved carbon as well as the diagenesis modelings. These independent quantifications are advantageous over the previous attempts in which at least one partitioning process was indirectly (passively) calculated from the mass balance equation. The previous attempts never fail to satisfy the mass balance but are very likely to carry large errors (Reimers and Suess, 1983).

Of the total organic carbon flux to the sediments more than 60% is utilized at or near the sediment-water interface, and 26% is buried in the sediments (Table 5). Interestingly, only about 6% of the total flux of organic carbon is remineralized within the sediments, suggesting that the benthic utilization of organic carbon at or near the sediment-water interface is the major mode of organic carbon recycling at the site. High bottom water temperature in the warm summer during the field work may intensify the benthic utilization. Summation of the $C_{benthic}$ and C_{remin} readily shows that almost 68% of the total organic carbon reaching the sea floor is recycled back to the overlying water column, supporting the

Table 5. Partitioning of organic carbon fluxes at the site in Kwangyang Bay. The lower and the upper range values respond to sedimentation rates of 2.92 $cmyr^{-1}$ and 3.07 $cmyr^{-1}$, respectively

$C_{benthic}$ ($gCm^{-2}yr^{-1}$)	C_{remin} ($gCm^{-2}yr^{-1}$)	C_{burial} ($gCm^{-2}yr^{-1}$)	C_{in} ($gCm^{-2}yr^{-1}$)	$C_{benthic}/C_{in}$ (%)	C_{remin}/C_{in} (%)	C_{burial}/C_{in} (%)
441.6	40.18-42.30	187.4-188.4	714.6	61.8	5.6-5.9	26.2-26.4

argument by Zeitschel (1980) that benthic regeneration of nutrients is as equally important as the riverborn input of nutrients in the coastal ecosystems.

Since our data, used for the determinations of the organic carbon budget, were obtained during summer, the budget should not be regarded as an annual average one. It may be acceptable only for a summer time. However, the partitionings of C_{remin} and C_{burial} may not show a considerable seasonal change, because those are derived from within the sediments. The C_{in} and $C_{benthic}$ are likely to show a certain seasonal change in their partitionings in the organic carbon cycle. Seasonal measurements of C_{in} and $C_{benthic}$ would provide an annual average budget for the organic carbon cycling in the area.

Residence time of organic carbon

The reciprocal of the k is equivalent to the residence time of organic carbon in the upper 40 cm of the sediments affected by the organic carbon modeling. At the values of $\beta=0.2$ cm^{-1} and $\omega=3$ cmyr^{-1}, k is equal to 0.6 yr^{-1}, and thus the residence time becomes 1.6 years. This residence time is the mean life for the organic carbon in the upper 45 cm sediments at the site since the k is obtained from the best fitting of the kinetic decay model to the organic carbon distribution over that depth range. For comparison, the residence time similarly determined was on the average 250 years in the western equatorial Pacific (Grundmanis and Murray, 1982), 12, 000 years in the central North Pacific (Murray and Kuivila, 1990), and 0.25 years in an organic-rich coastal station (Klump, 1980).

The high taking of the partitioning of $C_{benthic}$ and the low taking of C_{remin} in the budget (Table 5) explain the relatively long residence time for the metabolic organic carbon at the site sediments in Kwangyang Bay. Most of the easily metabolic organic carbon is remineralized and recycled back to the overlying water at the sediment-water interface, and greatly diminished portion of the easily metabolic organic carbon with relatively large amount of 'not-easily' metabolic organic carbon is likely to be deposited and remineralized, resulting in the long residence time relative to other coastal areas (Crill and Martens, 1983; Martens and Klump, 1984). Moderate increases in both pore water ammonia and ΣCO_2, despite their samplings in the warm summer, also suggest the relatively long residence time at the site.

CONCLUSIONS

The independent determinations of all the partitioning processes in the biogeochemcial cycle of organic carbon have provided a reliable carbon budget at a single coastal station in Kwangyang Bay. Of the total organic carbon flux to the sea floor approximately 62% and 6% are utilized at or near the sediment-water interface and remineralized within the sediments, respectively. These partitionings suggest that the benthic flux is much more important than the remineralization for the carbon cycling at the site. However, they should not be extended to an annual time frame since the data were obtained only during summer. Though not easy, acquisition of a complete seasonal data and subsequent determinations for the annual partitionings are left for the future study. First order satisfaction of the carbon budget equation by the independent determinants proves our approach advantageous over the existing 'partially independent' approaches. To obtain a credible carbon budget, therefore, it is desirable to simultaneously undertake sediment trap mooring and benthic chamber deployment together with sediment coring.

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