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## **Monitoring the sedimentary carbon in an artificially disturbed deep-sea sedimentary environment**

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### **Abstract**

An area of 0.6 km<sup>2</sup> in the manganese nodule field of the Central Indian Basin was physically disturbed and sediments discharged in the near bottom waters to simulate seabed mining and study its impact on benthic ecosystem. An estimated 2-3 tonnes of sedimentary organic carbon (C<sub>org</sub>) was resuspended into the water column during a 9-day experiment. The majority of the sediment cores from within the disturbed area and areas towards the south showed a ~30% increase in C<sub>org</sub> content as well as an increase in carbon burial rates after disturbance, though with a reduction in carbon/phosphorus ratios. High specific surface area (SSA~25 m<sup>2</sup>g<sup>-1</sup>) and low C<sub>org</sub>/SSA ratios (mostly <0.5) are typical of deep-sea sediments. The increased C<sub>org</sub> values were probably due to the organic matter from dead biota and the migration and redeposition of fine-grained, organic-rich particles. Spatial distribution patterns of C<sub>org</sub> contents of cores taken before and after disturbance were used to infer the direction of plume migration and re-sedimentation. A positive relationship was observed between total and labile C<sub>org</sub> and macrobenthos density and total bacterial numbers prior to disturbance, whereas a negative relationship was seen after disturbance owing to drastic reduction in the density of macrofauna and bacteria. Overall decrease in labile organic matter, benthic biota and redistribution of organic matter suggest that the commercial mining of manganese nodules may have a significant immediate negative effect on the benthic ecosystem inducing changes in benthic community structure.

**Key words:** Organic carbon, phosphorus, specific surface area, macrobenthos, deep-sea sediments, disturbance experiment, Central Indian Basin

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## **Introduction**

Studies on deep-sea manganese nodules have increased considerably in recent decades because they are known to contain valuable metals such as Ni, Co, Cu which are already in short supply from rapidly depleting resources on land (Mero 1965; Glasby 1977; Rona 2003). The possibility of recovering these and other scarce metals such as Mo, V, Pb and Ti from manganese nodules has further enhanced the economic importance of mining the deep-sea nodule deposits (Cronan 1980, 2000). Although, unavailability of a commercial mining technology remains a limiting factor in exploiting these deposits (Glasby 2000), given their economic importance, several consortia and countries have initiated major programs for exploration of these mineral deposits that lie exposed on the deep seabed (below >4 km of water column).

However, before venturing into commercial mining of nodules, it is advisable to evaluate the potential impact of mining on the marine ecosystem. It has been estimated that, with every tonne of nodule recovered, 2.5-5.5 tonnes of sediment would be resuspended (Amos and Roels 1977), destroying the habitat of many sessile organisms (Thiel 1978) along the path of nodule collector as well as in the areas where the discharged sediments settle. This sediment could have deleterious effect on the food chain in the deep sea, as fine-grained sediment, pore water, near-bottom water and benthic organisms would all be stirred up near the seafloor (Morgan et.al., 1999; Thiel and Forschungsverbund Tiefsee-Umweltschutz, 2001). Sediment particles could then be transported for considerable distances by bottom currents and would settle far from the mined area with potential impact on benthic fauna because they are not adapted to complete burial (Ozturgut et al. 1978). Mining-induced resuspension and redeposition would heavily affect both suspension and surface deposit feeders (Jumars 1981).

Sediment redistribution from deep-sea mining may also alter the redox relationship between the sediment particles and dissolved phases, release porewater into the overlying water, and alter physico-chemical parameters such as pH, Eh and alkalinity (Nath et al. 2005). All these factors eventually affect the carbon turnover, remineralisation, decomposition and burial processes. These changes may have an adverse effect because the labile part of organic carbon in the sediment is an important food source for benthic fauna (Nath and Sharma 2000).

To evaluate these effects, environmental impact assessment studies on simulated nodule mining have been carried out by several groups in the Pacific Ocean (Foell et al. 1992; Trueblood 1994; Fukushima 1995; Tkatchenko et al. 1997). Similarly, the Indian Deep-Sea Environment

Experiment (INDEX) program was initiated in 1995 to create a disturbance on the seabed in the Central Indian Basin (CIB) and to monitor its effects on the benthic ecosystem (Sharma et al. 2000).

This study aims to understand the impact of benthic disturbance on the biogeochemical processes regulating carbon and phosphorus, as this is relevant to the evaluation of the effect of offshore commercial mining on benthic biogeochemistry and biota. In this study, emphasis is on carbon and phosphorus, since these elements are food sources of benthic biota. Carbon is the basic structural element of organic compounds such as carbohydrates, proteins, fats, vitamins etc. (Rüllkötter 2000). Phosphorus is one of the important biogenic elements and an essential nutrient in most ecosystems required for biological synthesis and energy transfer processes.

### ***Study area***

The Central Indian Basin (CIB) is an abyssal area bounded by the 90° E Ridge on the east, Central Indian Ridge to the west, and South East Indian Ridge to the south. To the north, it is open towards the Indian peninsula, and to the northwest it is bounded by Chagos-Laccadive Ridge. Terrigenous, siliceous and pelagic brown clay sediments are present in the basin (Rao and Nath 1988).

A test site of 3.5x5.4 km, which lies between 10°01' S and 75°59' E and 10°03' S, 76°02' E with a depth range of 5300m and 5400m was selected (Figure 1). The disturbance zone was 3 km x 0.2 km and was oriented NW-SE. It has an even topography, no rock outcrops, and uniform benthic conditions (Sharma and Nath 1997), which were the requirements for the experiment.

The total relief at this site is 20-40m, with low nodule abundance (<2kg/m<sup>2</sup>). The sediment type is siliceous ooze, consisting mainly of siliceous tests, clay minerals, such as smectite, illite, chlorite and kaolinite, as well as authigenic assemblages, such as Fe-rich smectites, phillipsites, other zeolites, and Fe-Mn oxides ((Rao and Nath 1988; Nath et al. 1992; Valsangkar et al. 1999).

### **Materials and methods**

The Indian Deep-sea Environment Experiment (INDEX) was conducted to simulate conditions similar to that of deep seabed mining of manganese nodules and to assess its potential impacts on the benthic environment. The experiment was conducted with a hydraulic device called the 'Deep-Sea Sediment Re-suspension System' (or 'Disturber'), which consisted of a metallic frame with base dimensions of 4.8 m x 2.4m and a stack 5 m high (Brockett and Richards 1994). A set of

hydraulic pumps near the base of the 'Disturber' were used for fluidizing and lifting sediment from the seafloor, and discharging them at a height of 5 m through the stack, as the Disturber moved on the seabed along a pre-determined track of 3000 m length and 200 m width (Fig.1). In all, 26 benthic disturbance tows were conducted in 9 days during the disturbance experiment. The total time of operation of the disturber was 47h and 30min, over a total distance of 88.3 km resuspending a total dry weight of sediment of 580 tonnes (Sharma et al. 2000).

Two cruises onboard RV *Yuzhmorgeologiya* were undertaken to conduct the disturbance and impact studies. The first cruise (INDEX 3A) in June-July 1997 concentrated on baseline studies on environment conditions prior to disturbance, whereas the second cruise (INDEX 3B) in August 1997 was undertaken to disturb the seafloor and to collect sediment samples immediately after the experiment to study the effects of the resuspended sediment plume on the characteristics of the near bottom and seabed areas.

The sediment samples were collected with a box core of dimensions 0.5x0.5x0.5 m. In order to achieve accurate positioning, transponder-based acoustic navigation was used. Sampling sites were selected in and around the disturbance track to represent the disturbance zone and in the area around the track. The top surface of the samples collected within the disturbance track visibly showed features of disturbance as compared to the samples collected outside the track. Fourteen sediment cores were collected before and after the benthic disturbance at the same locations (Figure 1). Out of these, 9 sediment cores (each for before and after disturbance) were sub-sampled at 2cm interval for geochemical analyses and stored in a refrigerator for the study.

Organic carbon was estimated using the wet oxidation method (El Wakeel and Riley 1957). The replicate analysis on the same day permitted us to determine the level of precision which varied between  $\pm 2\%$  and  $\pm 7\%$ , and was generally better than  $\pm 4\%$ . At times, the marine mud standard MAG-I of USGS was analysed to assess the analytical accuracy.

The method used for determination of phosphate in seawater (Koroleff and Grasshoff, 1983) is followed here. The sediment sample was oxidized with the help of a strong oxidizing agent (alkaline persulphate) by autoclaving in a closed condition. The organic forms of phosphate were finally oxidized to inorganic phosphate. After the digestion, ascorbic acid and mixed reagents were added to produce a phosphomolybdate complex and the absorbance was measured at 880 nm. The precision obtained from replicate analysis on each day was better than  $\pm 1\%$ . Potassium dihydrogen phosphate ( $\text{KH}_2\text{PO}_4$ ) was used for standardization of the analyses. The phosphate/phosphorus

measured here probably indicates the labile fraction (biogenic and organic phases) and not the fraction of phosphorus held in the mineral matrix given that the total P contents in the sediments using non-destructive methods such as XRF were found to be much higher in sediments from the Central Indian Basin (Nath et al. 1989).

For macrofaunal study, one-fourth of the box core was used for analysis. Sediment samples were sectioned at 0-2, 2-5, 5-10, 10-20 cm sections and preserved in neutralized 5% formalin-Rose Bengal solution prepared in filtered seawater. Each section was washed with filtered seawater and passed through sieve of 0.3 mm (300  $\mu$ ) mesh. Sieving was performed onboard the ship forty eight hours after collection. The contents left on the sieve were preserved in 10% buffered formalin containing Rose Bengal. Taxonomic identification and counting was carried out two months after the sieving in the shore laboratory.

Microbiological and biochemical techniques followed are as described in Raghukumar et.al., (2006). Aliquots from the formalin-fixed samples were sonicated (3\_30 s), diluted with sterile sea water, filtered over black polycarbonate nuclepore filters (0.22 mm pore size; Millipore, USA) and stained with an aqueous solution of acridine orange (0.01%; 3 min). Bacterial cells were counted from 10 to 20 microscope fields with an epifluorescence microscope (Olympus BX60, Japan). The final numbers were expressed as total counts per gram dry sediment (Hobbie et al., 1977). Sediments were analyzed for protein, carbohydrates and total lipids, the sum of which has been defined as the bulk LOM (Danovaro et al., 1993).

Redistribution of sediment was correlated with mean current data obtained from a current meter deployed at 5100 m water depth from September 95 to January 96 and April 96 to September 96 at a location near the study area.

## **Results and discussion**

### **Solid phase organic carbon, phosphate and C/P ratios**

The organic carbon ( $C_{org}$ ) and phosphate data are presented in Figure 2 and Table 1. The  $C_{org}$  content generally varied between 0.15 and 0.6% in the cores taken after disturbance. Post-disturbance changes included a surface enrichment of  $C_{org}$  with a gradual decrease with depth was noted in all but 3 cores with minor variations at subsurface levels (Figure 2). However, the lack of consistency in the downward trend of the  $C_{org}$  values and a narrow range of variability indicate low in situ degradation rates below the upper few centimeters of the sediment. The downcore profiles are

probably due to bioturbation, and are typical for Central Indian Basin sediments (Nath and Mudholkar 1989). The low  $C_{org}$  values determined here are typical of pelagic sediments as most of the degradable  $C_{org}$  is decomposed below a threshold sedimentation rate of between 1 and 4  $mm.yr^{-1}$  (Müller and Mangini 1980). The study area is characterized by very low sedimentation rates (Banakar et al. 1991; Borole 1993).

Among the sediments analysed, a major increase (>30%) in  $C_{org}$  contents was observed in sediments collected after disturbance. The sediments south of the disturbance area show the maximum change in average  $C_{org}$  content in surface sediments followed by sediments from the disturbed area and the area north of the disturbed area (Figure 3). When the downcore variation of  $C_{org}$  is concerned a distinct increase of  $C_{org}$  in the top sections was observed in cores collected after the disturbance (Figure 2). This may indicate a re-deposition of material transported during disturbance. A 3-way ANOVA (analysis of variance) showed that  $C_{org}$  content in two sampling stages, between cores and core depths was significantly different (Table 2). This is a clear indication of disturbance and associated changes.

Fine particles, which are susceptible to dispersion, often have organic carbon bound to them. The disturbance experiment must have suspended about 2.3 tonnes of organic carbon into the water column during the experiment (calculated from the total sediment suspended (580 tonnes) Sharma et al. 2000) and average  $C_{org}$  content of 0.4 %). The increase in  $C_{org}$  content could be either due to removal and redeposition of fine particles, and also from the accumulation of dead benthic biota.

The C/P ratios in all the areas decrease with depth after the disturbance reflecting the reduction of  $C_{org}$  in deeper sediment layers (Table 1). The ratios vary between 30:1 and 71:1 in the surface sediments, which are much lower than the marine planktonic ratio of 106:1 (Redfield et al. 1963). The oxidation of sedimentary organic matter is nearly complete in pelagic areas with low sedimentation rates resulting in low C/P residual organic material (Ingall and Van Capellan 1990). This residual organic matter may represent either refractory detrital organic compounds enriched in phosphorus compounds such as amino phosphoric acids or low C/P bacterial remains synthesized in situ (Ingall and Van Capellan, 1990) in addition to the progressive accumulation of metabolizable P-rich organic phases by microorganisms (Ingall and Jahnke 1994).

Sorption of phosphate on ferric oxyhydroxides is another possibility (e.g., Buffle et al. 1989). The Central Indian Basin sediments in general show a strong positive correlation between Fe and P

(Nath et al. 1989). In the disturbed zone, a positive correlation between C and P is observed prior to the disturbance but it reverses after disturbance (Figure 4).

Results of a 3-way nested ANOVA showed a highly significant difference in C/P ratios between pre- and post-disturbance sampling in different cores and core depths (Table 2). The data also suggests that the disturbance effects are minimum in the north and maximum in the south of disturbance area.

### **Organic carbon burial**

Ratios of sedimentary burial fluxes to corresponding annual average water column fluxes provide a measure of burial efficiency for any given organic component (Cowie and Hedges 1993) and also depend on the internal dynamics within the sediments. The potential organic carbon flux arriving at the sediment water interface ( $J_{cx=0}$  g C m<sup>-2</sup> yr<sup>-1</sup>) is estimated using the transfer equation of Berger and Herguera (1992) (Schenau et al. 2000).

$$J_{cx=0} = 2 PP^{0.5} \times (PP/100) \times (1/Z + 0.025) \quad (1)$$

where PP is the primary productivity rate (g C m<sup>-2</sup> yr<sup>-1</sup>), Z the water depth in units of 100m. Assuming an average primary productivity rate of 91.25 g C m<sup>-2</sup> yr<sup>-1</sup> and 81 g C m<sup>-2</sup> yr<sup>-1</sup> (Qasim 1977) for the Indian Ocean, the potential  $J_{cx=0}$  flux in the area amounts to 0.77 and 0.64 g C m<sup>-2</sup> yr<sup>-1</sup>.

The sediment accumulation rate is calculated using the formula

$$S_{acc} = S\rho(1-\Phi) \quad (2)$$

Where S is the linear sedimentation rate (cm yr<sup>-1</sup>), which is about 0.0002 cm yr<sup>-1</sup> in the Central Indian Basin (Banakar et al. 1991; Borole 1993),  $\rho$  is the dry bulk density calculated from wet bulk density and porosity ( $\Phi$ ) values.

The organic carbon burial for all the cores is calculated using the formula

$$\text{Organic carbon burial} = (C_{org} \%) * (S_{acc}) \quad (3)$$

It is seen that the organic carbon burial in all the sediment samples analyzed is about 1% of the total flux and that it decreases with increasing depth indicating degradation and reduction of organic matter with depth (Table 1). A carbon burial of 1% of that produced in surface waters is consistent with the previous estimates for the deep-sea areas (Suess 1980). Significantly, a reduction

in post-disturbance organic carbon burial rates is seen in two out of three cores in the disturbed area with a concomitant increase in burial rates in the south and east of the disturbance zone (Figure 5). This indicates a removal of fine particles rich in organic carbon from the disturbance zone and redeposition in the general direction of the then prevailing bottom currents. While the difference between C burial rates in the pre- and post-disturbance sediments was not statistically significant (Table 2), the difference was significant spatially as evidenced from variation in concentration.

### **Organic carbon degradation rates**

$C_{org}$  degradation is a complicated process and is controlled by biochemical components, oxygen levels in the water column and sediments, sedimentation rate and other factors. The gradient in  $C_{org}$  has been used to estimate organic carbon degradation rates in this study. The distribution of biogenic elements such as C can be described by simple first-order kinetics:

$$dC/dZ = -kC.$$

Integration of the above gives:

$$kZ = -\ln(C_0 - C),$$

where  $k$  is the rate constant in  $cm^{-1}$ ,  $C_0$  is the concentration of  $C_{org}$  undergoing decomposition at the top of the column and  $C$ , the remaining  $C_{org}$  at a given depth,  $Z$ , in  $cm$ . The dimension of the rate constant ( $cm^{-1}$ ) can be reciprocally displayed, as a function of time ( $yr^{-1}$ ) if one knows the sedimentation rate ( $cm\ yr^{-1}$ ).

The rate constants of decomposition of  $C_{org}$  calculated (sedimentation rates from areas, Borole 1993) by the above equation vary between  $1.91 \times 10^{-6}\ yr^{-1}$  and  $1.6 \times 10^{-5}\ yr^{-1}$  for the pre-disturbance cores and show a reduction after disturbance in cores from the disturbance zone and south of the disturbance zone. Lowered degradation rates may be due to increased burial rates of dead benthic organisms. The degradation values obtained here are consistent with the values obtained by Müller and Mangini (1980) for pelagic sediments.

### **Specific Surface Area and accumulation pattern**

Sedimentary organic matter is often strongly controlled by grain size (Bordoviskiy 1965; Hedges and Keil 1999) and persists mostly in association with mineral grains and not as distinct organic particles (Keil and Hedges 1993). The surface area (SA) of the sediment is the prime factor



in controlling sorption (Gibbs 1977) and the amount of the organic matter in marine sediments (Keil and Hedges 1993). On a temporal scale, the SSA did not differ significantly, but the difference was significant on spatial scale (Table 2).

The  $C_{org}/SSA$  found here (mostly  $<0.5$ , Table 1) are lower than that expected from monolayer coverage (Mayer et al. 1985) but comparable to other deep-sea regions (Hedges et al. 1999) probably due to the low sedimentation rates and higher bottom water oxygenation (BWO) conditions and the longer oxygen exposure time (OET). Higher  $C_{org}/SSA$  ratios after the disturbance also clearly indicate higher deposition rates during and after the disturbance (Parthiban 2000).

As a result of the disturbance, the SSA of the sediments must have decreased drastically and this could have led to additional coatings and increased adsorption of  $C_{org}$ . Disturbance as a result of offshore mining would lead to re-suspension/re-deposition as shown here and may alter the steady state conditions. Repeated “re-exposure” and burial of organic carbon may result in further biodegradation and non-availability to the benthic fauna.

### **Relation between sedimentary organic carbon, macrofauna and bacterial counts**

In view of the importance of sedimentary organic carbon as a food source and its role in influencing the structure and metabolism of the benthic communities (Smetacek 1984; Gage and Tyler 1992), the relation between organic carbon and the benthos was investigated. Generally, in the deep-sea benthic environment, polychaetes have been found to be dominant (Gage 1978; Parulekar et al. 1982). This trend is also observed in the present study. The polychaetes were the most abundant taxon of the macrofauna followed by nematodes prior to disturbance. The impact of disturbance was severe as the mean biomass of macrofauna drastically reduced by 52 % in the disturbed zone (Ingole et al. 2001). Normally, the benthic fauna have a positive correlation with sedimentary organic carbon. This was found to be true prior to disturbance where the macrofaunal population is positively correlated with sedimentary organic carbon and labile organic matter (Figure 6). After the disturbance a drastic reduction in the density of polychaetes was observed. The reduction in this fauna was presumably a result of overturning of the sediments, and mortality or the displacement of the organisms caused by the benthic disturber (Ingole et al. 2001).

Faunal reduction is similar to that observed during the German DISCOL (Disturbance and re-Colonization) program where the impact of ploughing was severe and the mean density of macrofauna reduced to 39% of the undisturbed values, which recovered to 82% in 6 months and 87% in 3 years due to availability of food material for the benthic organisms (Borowski and Thiel 1996).

Macrofauna were not evaluated immediately after the Japan Deep-sea Impact Experiment (JET), but the observations on megafauna showed that the deposit feeders were most sensitive due to the disturbance on their food environment as compared to suspension feeders (Fukushima et al. 2000). Also meiobenthos abundance and bacterial numbers were significantly less after the disturbance (Shirayama et al. 2001). Meiobenthos in the IOM (Inter Ocean Metal) experiment site also showed evidence of moderate disturbance, but their numbers were greatly enhanced subsequently as a result of phytodetritus input (Radziejewska et al. 2001).

The total bacterial counts reduced by 2-3 order of magnitude (from  $10^9$  to  $10^7$   $g^{-1}$  of dry sediment) in post disturbance samples (Raghukumar et al. 2001). Reduction of the benthos population might have been responsible for the increase in  $C_{org}$  levels immediately after the disturbance. Reduction in bacteria, macro- and meiobenthos may have curtailed the degradation of organic carbon temporarily.

The decrease in the total counts of bacteria could result from their release from sediment into the overlying water column after the disturbance. The environmental impact studies of JET in the Pacific Ocean also showed a similar decrease in bacterial abundance of sediment samples following the disturbance (Kaneko et al. 1995). The distinct decrease in bacterial abundance and bacterial carbon will therefore have an impact on meiobenthos, which are dependent on them for food and energy source.

### **Sediment migration induced by disturbance interpreted from sediment organic carbon data**

After disturbance, sediments in general showed an increase in organic carbon content, but were spatially variable. An increase (by 30%) in the average organic carbon content was observed in the disturbed zone and to the south (45%); but smaller changes were observed in the area to the north of the disturbance site (Figure 2). It appears that the condition of the surface sediment in the area to the north of disturbed zone remained stable after the disturbance, in comparison to the other two areas. This may be due to re-deposition of suspended sediments within the impact site and transportation of organic carbon-rich surface sediments to the south. Further, the distribution of organic carbon in surface sediments prior to disturbance (Figure 7) shows that the trend is gradual (from 0.28-0.4%) from NW to SE of the site. The  $C_{org}$  distribution after the disturbance shows a significant increase within the area with a significantly higher concentration (up to 0.64%) in the SW direction (Figure 7). This could be because of the fine sediment fraction, which predominantly hosts organic matter (Trask 1937) has been redeposited in the general direction of the prevailing bottom

currents (Fig. 7). The mean benthic current direction as computed for August (disturbance time) from the current meter data was  $201^\circ$  (Murthy V.S.N., Pers. Comm.) and the spatial distribution map of organic carbon has clearly shown an increase in this direction (Fig. 7), indicating the direction of resedimentation. A similar observation has been reported at the HEBBLE site where strong near-bottom currents ( $>25 \text{ cm.s}^{-1}$ ), which occur periodically at both the Mid site and Deep site, erode and remove reactive organic matter and presumably contribute to significant reductions in faunal abundances (Aller 1997). The size and biomass of organism therefore are reduced and epifauna eliminated.

Microfossil assemblages (radiolarians) in this study area have shown evidence of lateral migration as well as vertical mixing of the sediment within the sediment column in and around the disturbance zone (Gupta 2000). The higher occurrence of *Stylatractus Universus* species, which is an indicator of older sediment normally observed at deeper layers in the sediment column, was found to occur along with younger fauna, *Buccinosphaera invaginata*, in the surface sediments after disturbance (Gupta 2000). Evidence for redeposition also comes from sediment traps deployed 7m above the seafloor (Parthiban 2000). An increase in particle fluxes recorded by the DMS-8 moorings SW of the disturbed zone was  $\sim 0.5$  times that of the pre-disturbance flux. This was attributed to preferential movement of resuspended particles discharged by the disturber in the general direction of the prevailing currents in the study area.

## Conclusions

In contrast to the reduction of  $C_{\text{org}}$  observed in the Pacific sediments after the disturbance, we have observed an increase in  $C_{\text{org}}$  content of the sediments following the benthic disturbance experiment carried out in the Indian Ocean. However, the labile portion of the organic carbon, which is of nutritional value to the benthic biota was found to be reduced in sediments due to the disturbance. Although the disturbed area is small, increased  $C_{\text{org}}$  contents appear to have led to a reduction in the bottom water oxygenation conditions. Considering the volume of total sediment displaced, an average of about 0.25 tonne of  $C_{\text{org}}$  must have been resuspended every day. Repeated disturbance during a commercial mining activity, which might last for several years at a mine site (Nath and Sharma 2000), would increase the sediment turnover many fold and can be expected to create a great demand for oxygen and other oxidants in the water column.

The  $C_{\text{org}}$  burial fluxes were about 1% of the total production of organic carbon in the surface waters and in good agreement with previous estimates for the deep oceans. The lower values of

organic carbon normalized to surface area ( $C_{org}/SSA$ ) than expected from monolayer coverage and the lower C:P ratios than the Redfield ratios, indicate quiescent conditions, slow sedimentation and higher bottom water oxygenation before the disturbance. The  $C_{org}$  burial fluxes and the accumulation rates (indicated by  $C_{org}/SSA$  ratios) were higher for the sediments after disturbance. Increased burial of  $C_{org}$  during periods of low bottom water oxygenation would enhance the rate of P regeneration (Van Capellan and Ingall 1996; Ingall and Jahnke 1997) and may lead to a positive feedback to the marine productivity. A drastic reduction in macrobenthos was noted after the disturbance. The dead and injured benthic animals may therefore contribute to a temporary increase of food supply to the scavengers and non-swimming scavengers giving advantage to particular groups of animals to thrive which may lead to temporary imbalances in the benthic ecosystem (Shirayama, 1999; Ingole et.al., 2005).

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Table 1: C/P ratios, C<sub>org</sub> burial fluxes, specific surface area (SSA), and clay %

Depth (cm)	C/P (Pre-)	C/P (Post-)	C <sub>org</sub> Burial rate (Pre-) (x10 <sup>-1</sup> )	C <sub>org</sub> Burial rate (Post-) (x10 <sup>-1</sup> )	Clay (%) (Pre-)	Clay (%) (Post-)	SSA (m <sup>2</sup> g <sup>-1</sup> ) (Pre-)	SSA (m <sup>2</sup> g <sup>-1</sup> ) (Post-)	C <sub>org</sub> /SSA (Pre-)	C <sub>org</sub> /SSA (Post-)
<b>BC-8</b>	<b>North of the disturbed zone</b>									
0-2	58.70	59.88	0.17	0.16	47.10	42.36	29.23	26.43	0.14	0.18
2-4	53.73	65.06	0.12	0.18	46.33	35.66	28.77	22.48	0.13	0.24
4-6	52.17	56.00	0.09	0.05	41.71	42.1	26.05	26.28	0.14	0.16
6-8	58.33	58.44	0.14	0.11	47.10	35.13	29.23	22.17	0.14	0.2
8-10	37.68	48.72	0.09	0.10	54.03	41.51	33.32	25.93	0.08	0.15
<b>BC-12</b>										
0-2	38.46	54.12	0.05	0.07	51.13	-	31.61	-	0.09	-
2-4	53.95	55.42	0.10	0.08	44.32	42.09	27.59	26.27	0.15	0.18
4-6	35.00	56.06	0.07	0.09	48.21	49.95	29.88	30.91	0.09	0.12
6-8	30.43	38.89	0.07	0.07	49.6	42.39	30.7	26.45	0.07	0.11
8-10	29.17	42.11	0.09	0.10	53.35	49.03	32.92	30.37	0.06	0.11
<b>BC-2</b>	<b>Within the disturbed zone</b>									
0-2	29.46	42.53	0.13	0.13	12.35	38.66	8.73	24.25	0.44	0.15
2-4	44.58	32.18	0.13	0.10	30.71	39.98	19.56	25.03	0.19	0.11
4-6	45.12	31.58	0.16	0.12	35.74	42.12	22.53	26.29	0.16	0.11
6-8	40.51	33.33	0.12	0.12	34.63	41.32	21.87	25.82	0.15	0.12
8-10	47.42	27.72	0.26	0.16	34.57	44.31	21.84	27.58	0.21	0.10
<b>BC-3</b>										
0-2	56.94	61.63	0.10	0.12	38.9	39.25	24.39	24.60	0.17	0.22
2-4	53.85	67.47	0.13	0.09	41.65	39.46	26.01	24.72	0.16	0.23
4-6	48	52.13	0.12	0.08	52.66	45.77	32.51	28.44	0.11	0.17
6-8	33.61	47.57	0.17	0.02	51.17	45.61	31.63	28.35	0.13	0.17
8-10	36.71	1.08	0.12	0.003	41.04	46.56	25.65	28.91	0.11	0.004
<b>BC-5</b>										
0-2	36.55	67.52	0.05	0.08	42.98	43.77	26.80	27.26	0.10	0.19
2-4	51.43	65	0.12	0.13	44.35	40.00	27.61	25.04	0.13	0.21
4-6	36.11	65.88	0.08	0.18	47.38	46.97	29.39	29.15	0.09	0.19
6-8	25.37	54.05	0.05	0.24	45.24	40.79	28.13	25.51	0.06	0.16
8-10	30.56	47.14	0.09	0.11	43.46	46.12	27.08	28.65	0.08	0.12
<b>BC-7</b>	<b>South of the disturbed zone</b>									
0-2	44.16	58.39	0.09	0.11	45.74	42.34	28.43	26.42	0.12	0.16
2-4	34.09	57.14	0.06	0.11	37.87	40.13	23.78	25.12	0.13	0.18
4-6	30.12	56.52	0.07	0.07	46.66	40.81	28.97	25.52	0.09	0.15
6-8	27.17	56.94	0.09	0.14	44.93	41.08	27.95	25.68	0.09	0.16
8-10	25.93	42.11	0.07	0.01	44.04	42.06	27.42	26.26	0.08	0.12
<b>BC-14</b>										
0-2	45.61	60.44	0.20	0.20	34.94	42.85	22.05	26.72	0.18	0.21
2-4	44.71	60.87	0.09	0.10	35.61	23.58	22.45	15.35	0.17	0.36
4-6	37.08	55.68	0.08	0.16	50.2	34.93	31.06	22.05	0.11	0.22
6-8	35.63	59.34	0.10	0.18	47.47	41.82	29.45	26.11	0.11	0.21
8-10	36.71	38.71	0.15	0.11	45.91	43.0	28.53	26.81	0.10	0.13
<b>BC-4</b>	<b>West of disturbance zone</b>									
0-2	41.61	51.95	0.07	0.1	47.65	51.61	29.55	31.89	0.10	0.13
2-4	36.76	42.5	0.08	0.09	45.72	49.01	28.41	30.36	0.09	0.11
4-6	37.33	56.94	0.09	0.14	47.14	47.53	29.25	29.48	0.10	0.14
6-8	26.09	45.88	0.08	0.12	45.81	48.14	28.47	29.84	0.06	0.13
8-10	27.69	46.25	0.06	0.09	46.09	51.31	28.63	31.71	0.06	0.12
<b>BC-6</b>	<b>East of disturbance zone</b>									
0-2	52.63	67.92	0.13	0.22	41.22	37.05	25.76	23.30	0.16	0.23
2-4	64.06	51.76	0.14	0.15	42.36	34.41	26.43	21.74	0.16	0.20
4-6	49.40	53.66	0.14	0.13	41.47	35.06	25.91	22.13	0.16	0.20
6-8	43.84	52.70	0.09	0.09	42.8	41.87	26.69	26.14	0.12	0.15
8-10	30.26	38.10	0.06	0.05	42.87	43.01	26.73	26.82	0.09	0.12

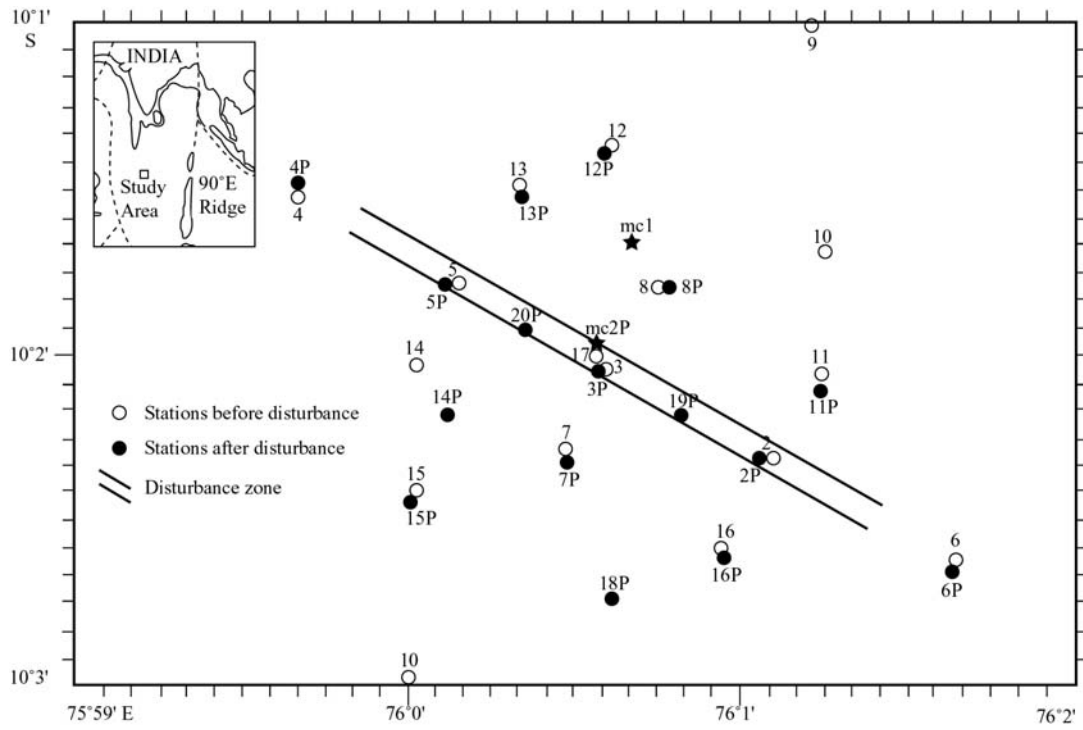
Table 2. A 3-way nested ANOVA to compare differences between 2 sampling stages, 9 cores and 45 depths. Degrees of freedom (DF) = n-1.

Source	DF	Org. carbon		C/P		C burial rate		CLAY		SSA	
		F	p	F	p	F	p	F	p	F	p
<b>Sampling stages</b>	1	68.56	<b>0.000</b>	26.39	<b>0.000</b>	0.39	0.535	2.94	0.095	1.88	0.179
<b>Cores</b>	8	4.40	<b>0.001</b>	2.71	<b>0.019</b>	3.80	<b>0.003</b>	10.36	<b>0.000</b>	2.47	<b>0.030</b>
<b>Core (Depths)</b>	44	3.26	<b>0.000</b>	2.93	<b>0.001</b>	1.87	<b>0.032</b>	1.94	<b>0.000</b>	1.21	0.289
<b>Sampling*Core</b>	8	5.04	<b>0.000</b>	4.50	<b>0.001</b>	2.84	<b>0.015</b>	5.79	<b>0.025</b>	2.58	<b>0.025</b>

Note: Numbers in bold denote significant difference.

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**Fig.1 (Nath et al.)**

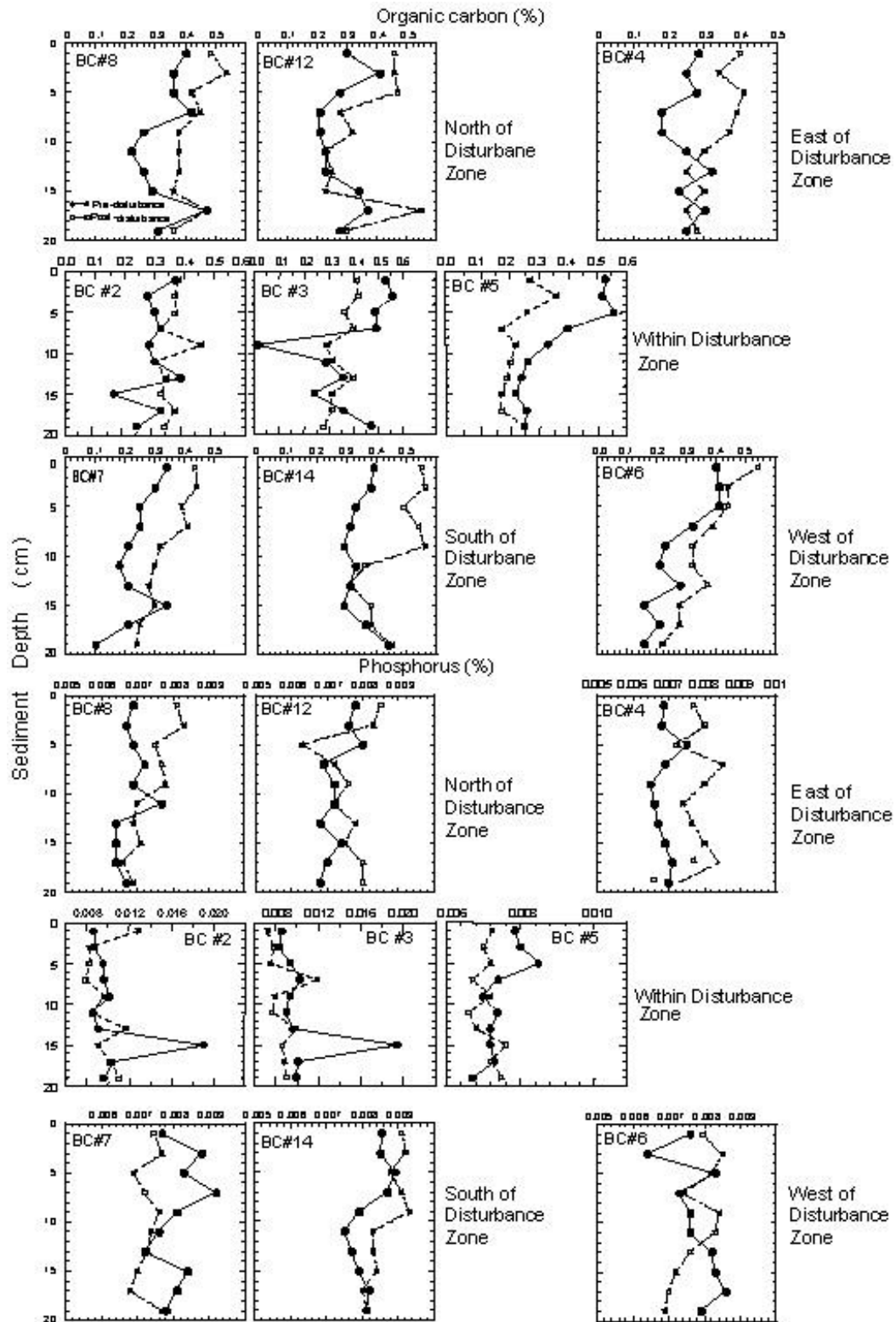
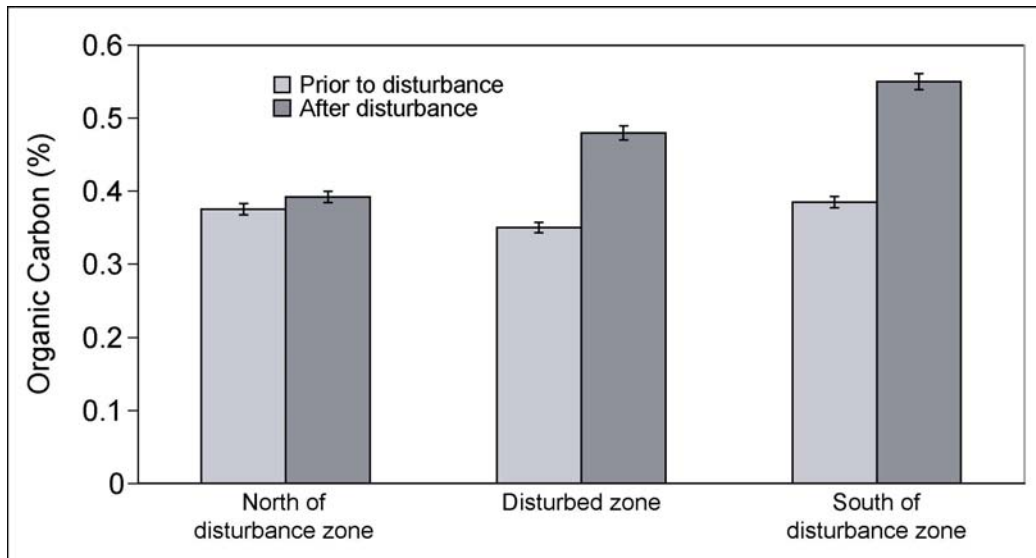
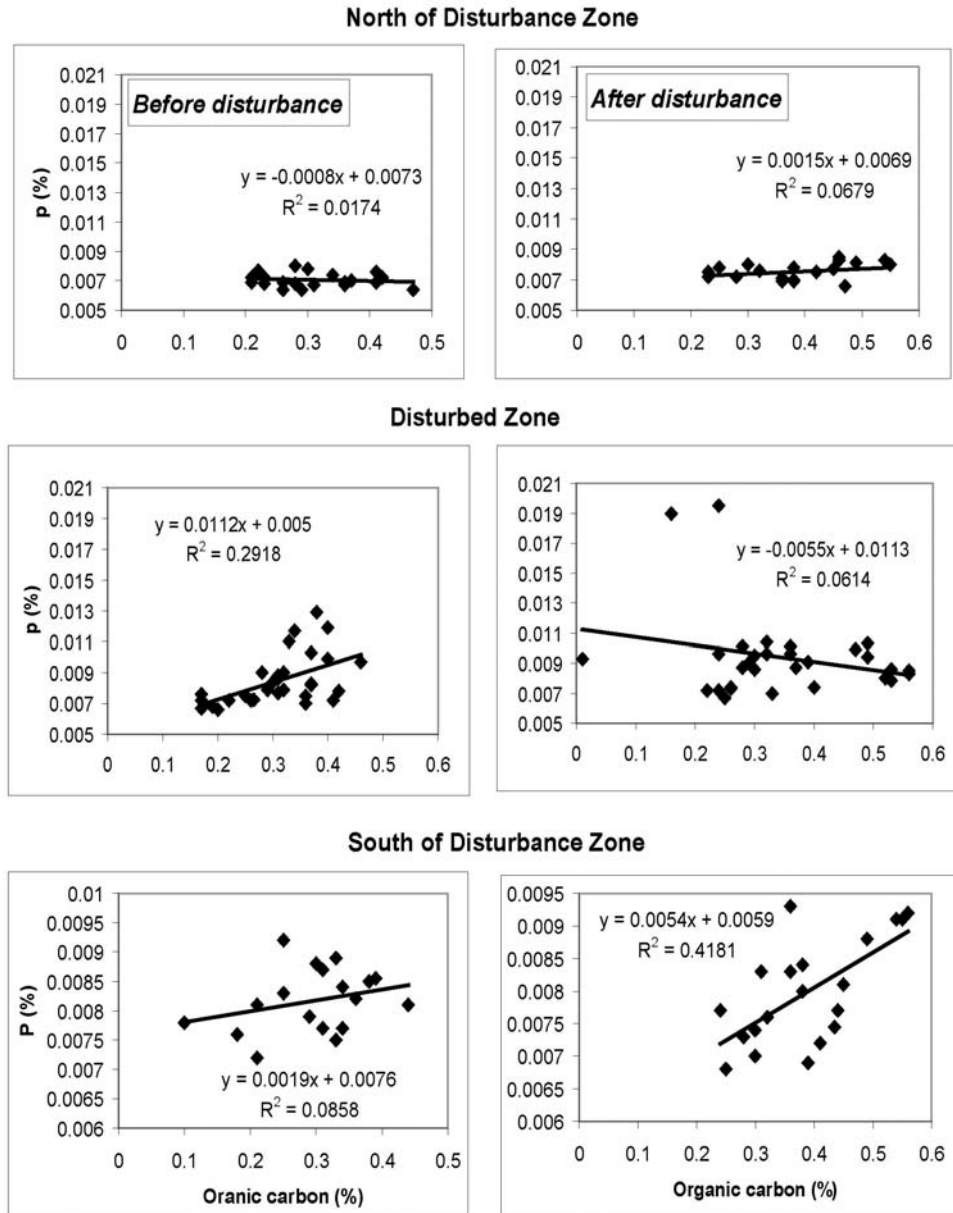


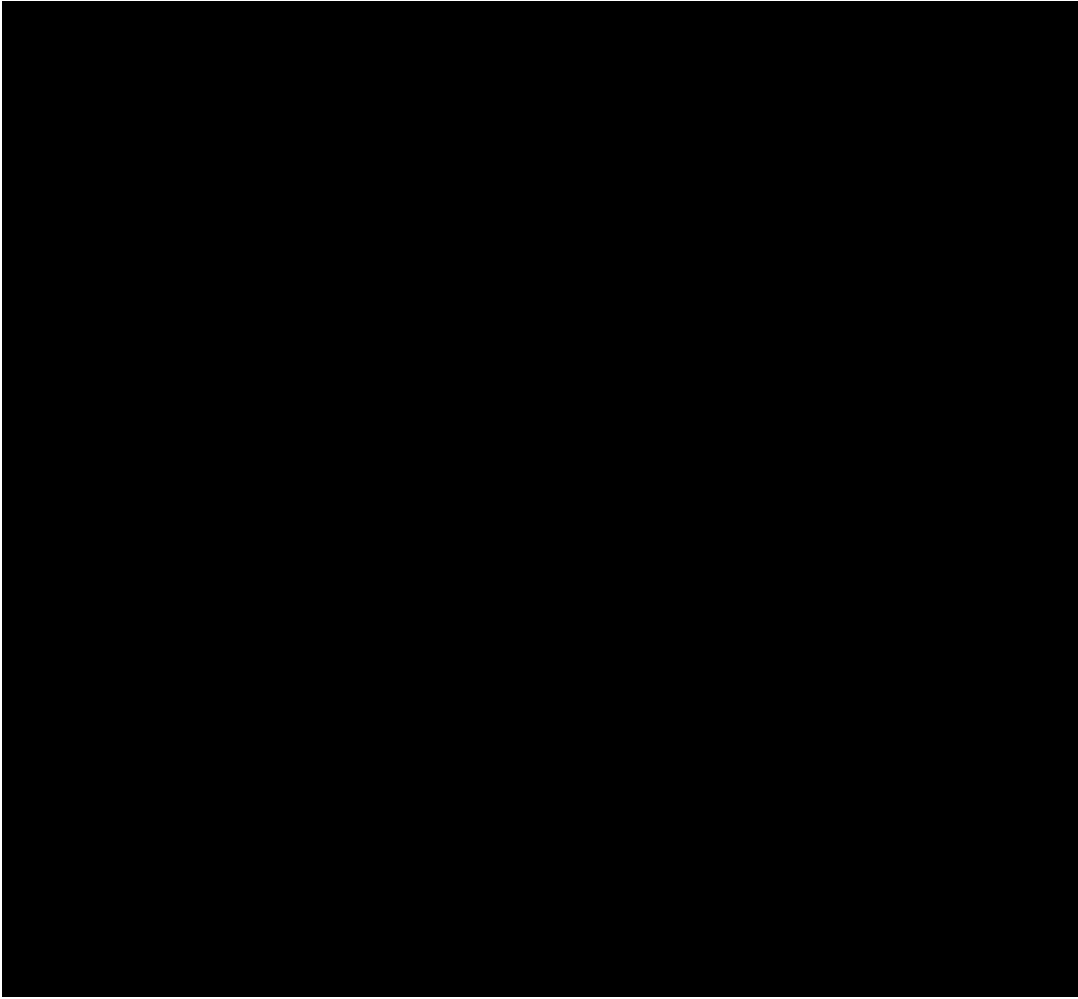
Fig. 2 (Nath et al.)



**Fig. 3 (Nath et al.)**



**Fig. 4 (Nath et al.)**



**Fig. 5** (Nath et al.)



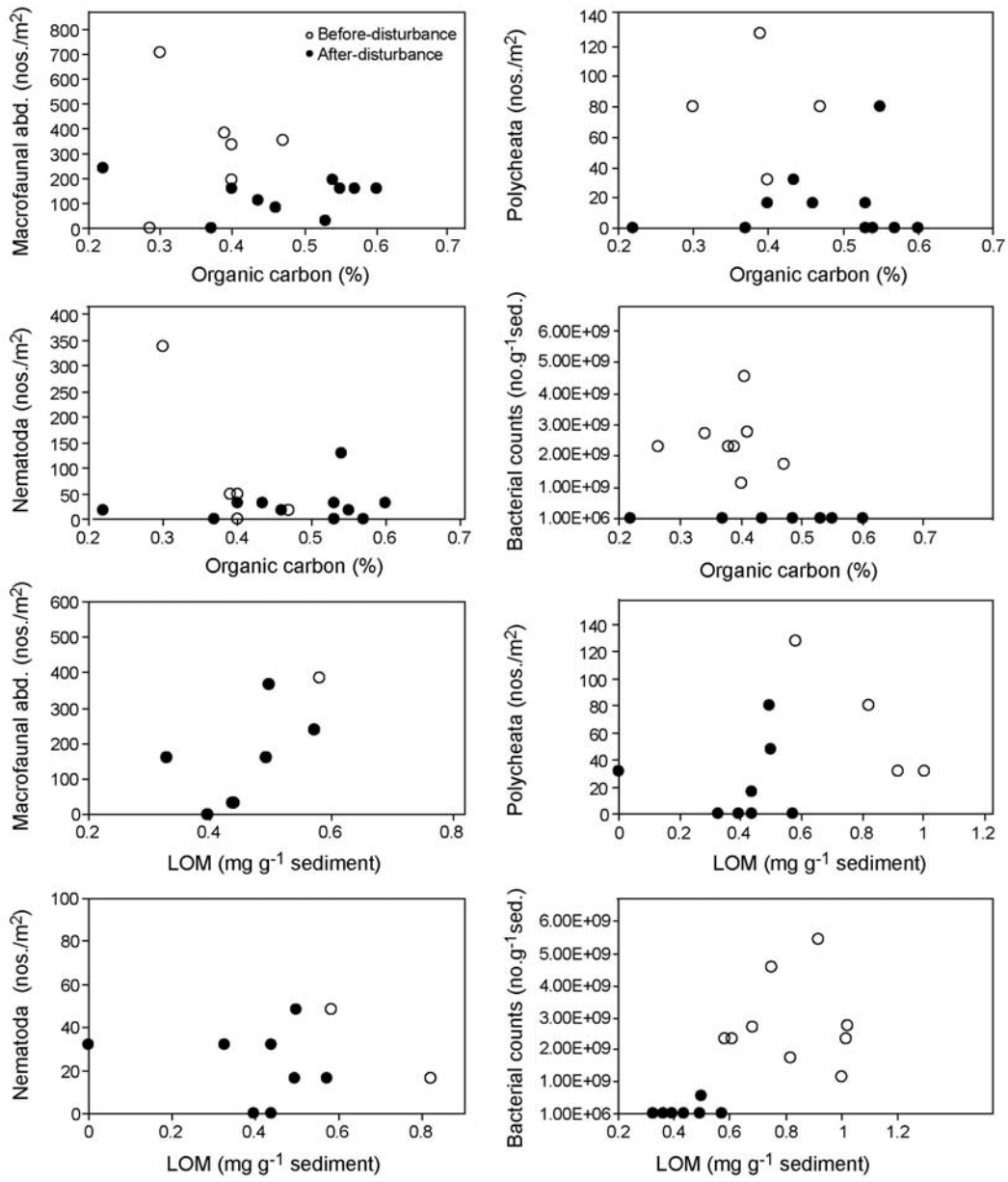
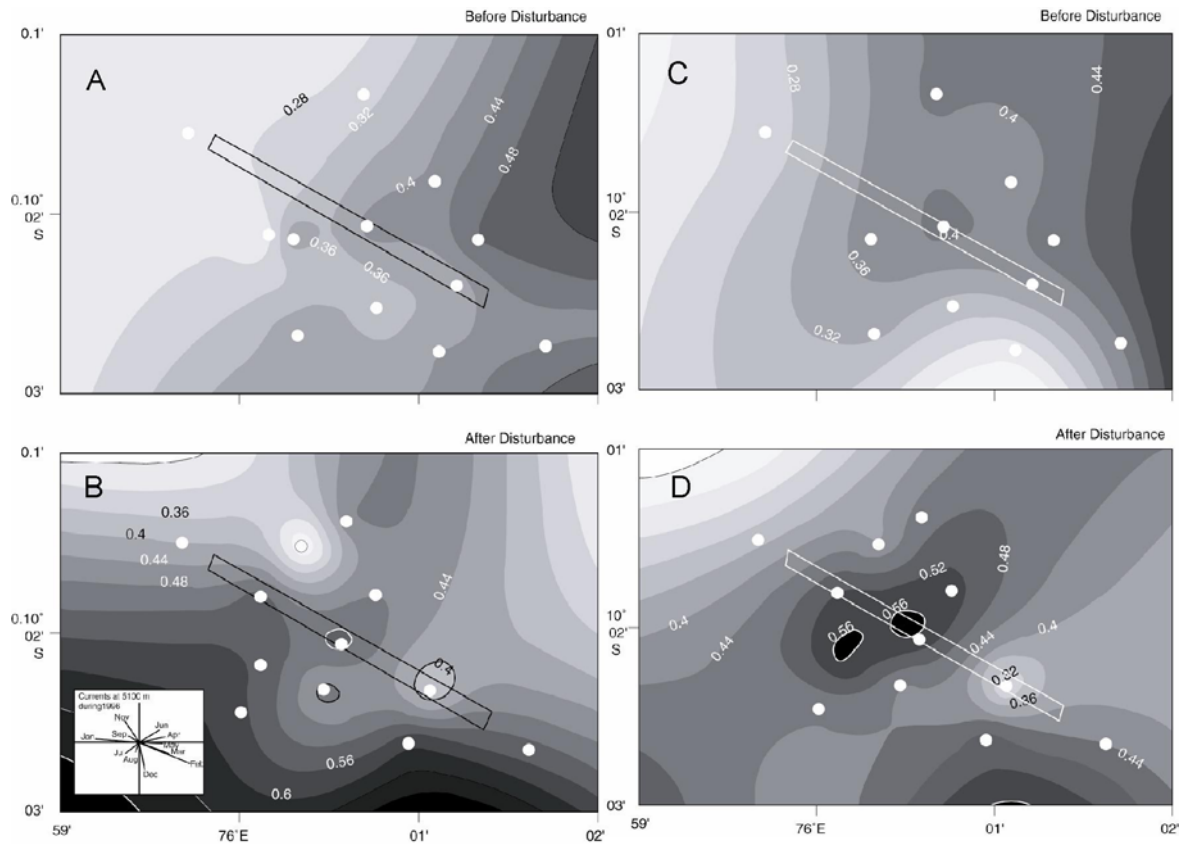


Fig. 6 (Nath et al.)



**Fig. 7 (Nath et al.)**