Implications of post-disturbance studies on the grain size of the sediments from the Central Indian Basin

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Indian Deep-Sea Environment Experiment (INDEX) was conducted by simulating benthic disturbance and resuspension of the sediments in 3 km × 200 m narrow strip at 5300 m water depth in the Central Indian Basin (CIB). Using the conventional coring methods, pre- and post-disturbance data have been compared to predict the probable direction of the plume movement on the seabed. Studies on 84 sub-sections of 10 box cores show that the disturbance at places was effective up to 25 cm depth. Post-disturbed samples collected from the pre-disturbed locations show an increase of 10 to 27% silt and clay, and indicate that they were the major component of the plume. It has been shown that for such studies the silt and clay can be used as effective indicators of the plume movement. The studies revealed that the plume has migrated at least up to 2 km in the south-west direction and 1 km south of the disturbed zone (DZ). Increase in the surface clay content is ascribed to mixing of the sediments from deeper sections due to the benthic disturbance.

THE Indian polymetallic nodule programme (PMN) executed in the Central Indian Basin (CIB) has been one of the major R&D efforts of the National Institute of Oceanography (NIO) Goa, in the past 20 years. Under this programme in 1987, India acquired the exclusive rights over 150,000-km^2 area in the CIB from the International Seabed Authority. One of the anticipated effects of mining deep-sea polymetallic nodules is disturbing the top few centimetres of sediments on the sea-floor. Uplifting of such bulk quantity of nodules from the seabed would create a large sediment plume that would migrate in the direction of currents and affect the water column, benthic community and marine ecosystem. Many authors[1–9] have discussed environmental problems due to seabed mining. Assuming 8 kg/m^2 abundance of nodules in the CIB, the deep-sea mining is expected to disturb about 504×10^7 m^3 of sediments per year over 600 km^2 area, at the mining rate of 3 million tonnes of nodules per year[10].

A long-term Environmental Impact Assessment (EIA) study in the CIB has been initiated at NIO since 1996 and in the first phase, baseline studies in reference and test areas were carried out[11–13]. During the second phase (1997), Indian Deep-Sea Environment Experiment (INDEX) was conducted in the test area ‘A’. Pre- and post-disturbance box-core sampling was carried out at the same locations in and around the area, using acoustic navigation system.

Here, pre- and post-disturbance data on grain size of 10 sediment cores are presented. Results obtained are discussed and interpreted to understand the composition of the plume and its direction of movement. It has been shown that studies on grain size can help (a) to understand the depth up to which the disturbance was effective, (b) to determine the direction in which the benthic plume can migrate, and (c) to calculate the distance travelled by the plume after the disturbance.

Using acoustic navigation system, 10 box cores (BC) were taken during cruises YMG-3A (May 1997) and YMG-3B (July 1997) with Russian *R/V Yuzhmorgeologiya* (Figure 1*a*). Water depth, topography, bathymetry and sediment thickness were considered for selecting the sampling locations[11,12,14]. The INDEX was performed using hydraulic equipment called ‘the disturber’ (Figure 1*b*). During the experiment, the sediments were fluidized and resuspended 5 m above the seabed. The disturber unit was operated for 9 days, covering 26 tracks (NW–SE) in 200 m × 3 km strip in the test area ‘A’ along 88.3 km^2 distance at an average water depth of 5300 m. It was estimated that 6023 m^3 sediments were resuspended, consisting 580 tonnes of dry sediments[15]. Pre- and post-disturbance sampling was carried out before and immediately after the experiment, in order to record the changes due to benthic disturbance.

Pre- and post-disturbance comparative studies were carried out on sub-sections as follows; (a) three cores (BC-02, 03 and 05) in the disturbed zone (DZ); (b) two cores, including BC-04 at north-west and BC-06 at south-east ends of the disturbed zone; (c) three cores (BC-08, 12 and 13) north of the disturbed zone; and (d) two cores (BC-07 and 14) south of the disturbed zone. Acrylic liner was used to sub-sample the sediments in the box core. Each core was sub-sampled at 2-cm interval down to 10-cm and then at 5-cm intervals for the remaining length. All the samples were desalinated by repeated washing with Barnstead RO-pure water and oven dried at 70°C. The sand contents were determined after wet-sieving through a 62 μm sieve, and silt (63 to 2 μm) and clay (< 2 μm) were determined by the standard pipette analysis[16].

It was found that 88% (106 sections out of 120) of the pre-disturbance samples were clayey silt. Among the remaining (12%), there was one silt sample (0 to 2 cm) out of nine sections at station BC-02, and two sections (4 to 6, 6 to 8 cm) of silty clay out of eight at BC-03 in DZ. North of DZ, there were 2 sections of silty clay (8 to 10, 15 to 20 cm) out of nine at BC-08, six sections (0 to 2, 4 to 6, 6 to 8, 8 to 10, 10 to 15, 15 to 20 cm) of silty clay out of eight at BC-12, and two sections (2 to 4, 8 to 10 cm) of silty clay out of nine at BC-13. South

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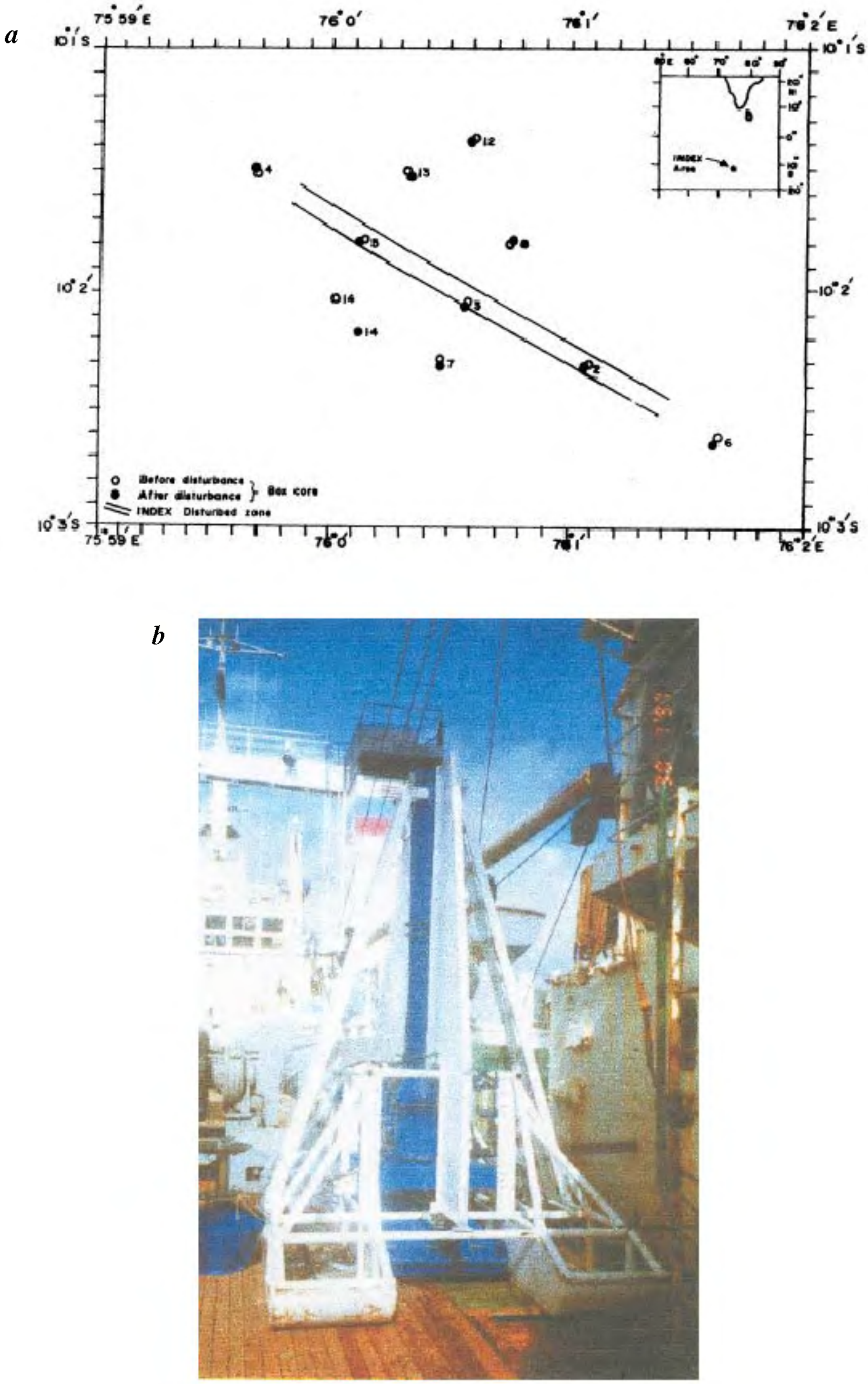

Figure 1. *a*, Selected sample locations in INDEX area for comparative studies. O, Box core samples before the disturbance; ●, box core samples after the disturbance; \\\\, INDEX area of disturbance. *b*, Hydraulic equipment (benthic disturber) used to fluidize and resuspension of the sediments at 5300 m depth in the CIB.

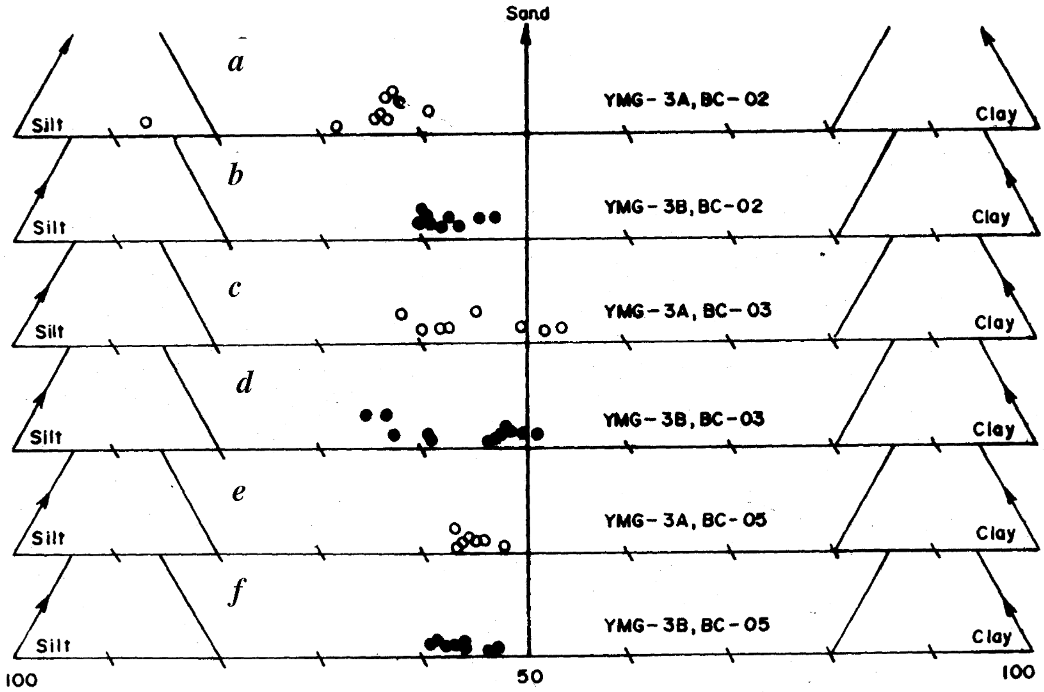

Figure 2. Distribution of sand–silt–clay in DZ (*a*, *c*, *e*) before disturbance (open circles, YMG-3 A); and (*b*, *d*, *f*) after disturbance (filled circles, YMG-3 B).

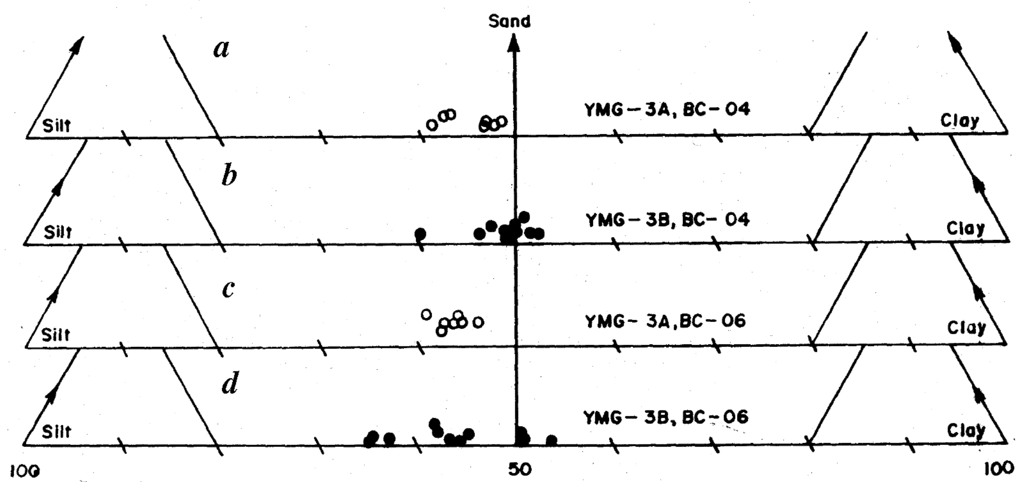

Figure 3. Distribution of sand–silt–clay in EDZ (*a*, *c*) before disturbance and (*b*, *d*) after disturbance. Symbols as in Figure 2.

of DZ, there was one section (4 to 6 cm) of silty clay out of eight at BC-14.

In the distributed zone (DZ) after the disturbance, the surface sediment (0 to 2 cm) texture at BC-02 changed from silt to clayey silt (Figure 2*a*, *b*). There were minor changes at BC-03, in which two sections (4 to 6, 6 to 8 cm) changed from silty clay to clayey silt, whereas sediments from 15 to 20 cm depth changed from clayey silt to silty clay (Figure 2*c*, *d*). No textural change up to 25-cm depth was observed at BC-05 in the disturbed zone (Figure 2*e*,*f*).

At the NW end of DZ (BC-04), the surface sediment texture (0 to 2 cm) along with those of deeper sections (8 to 10, 35 to 37 cm) changed from clayey silt to silty clay (Figure 3*a*, *b*). At the SE end of DZ (BC-06), the surface sediment texture remained unchanged, but the deeper sections (20 to 25, 30 to 40 cm) changed from clayey silt to silty clay (Figure 3*c*, *d*).

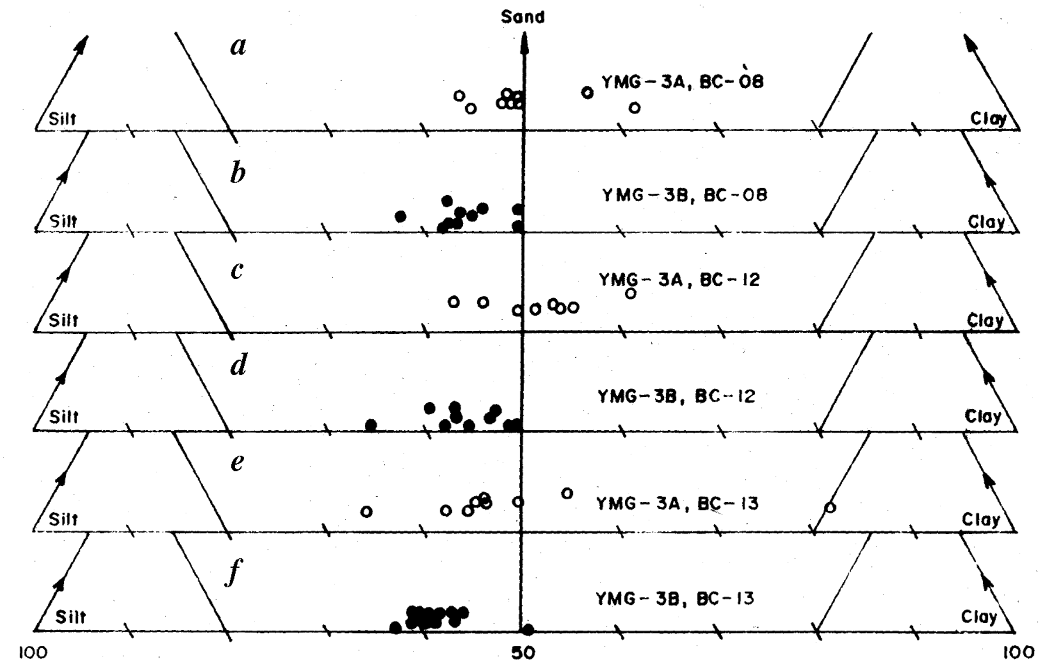

Figure 4. Distribution of sand–silt–clay in NDZ (*a*, *c*, *e*) before disturbance and (*b*, *d*, *f*) after disturbance. Symbols as in Figure 2.

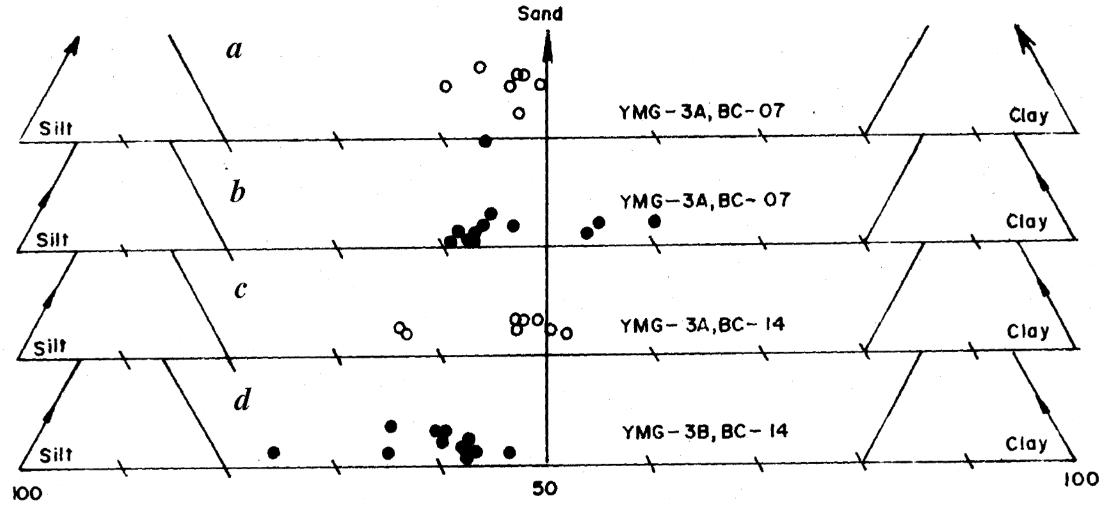

Figure 5. Distribution of sand–silt–clay in SDZ (*a*, *c*) before disturbance and (*b*, *d*) after disturbance. Symbols as in Figure 2.

North of DZ (NDZ) except at one location (BC-13), where one section (0 to 2 cm) out of nine changed from silty clay to clayey silt (Figure 4*e*, *f*), the surface texture did not change at other two locations (BC-08 and 12). At deeper levels, two sub-sections (8 to 10, 15 to 20 cm) out of nine at BC-08 changed (22%) to clayey silt (Figure 4*a*, *b*), and four out of eight clayey silt samples (6 to 20 cm) changed (50%) to clayey silt (Figure 4*e*,*f*) at BC-13.

South of DZ (SDZ), at BC-07, no change was observed up to 30 cm and sub-sections from 30 to 45 cm depths changed from clayey silt to silty clay (Figure 5*a*, *b*). At BC-14, two samples (4 to 6, 10 to 15 cm) changed from silty clay to clayey silt (Figure 5*c*, *d*).

A reduction in sand percentage was observed in DZ after the disturbance from surface to downcore to 30 cm at BC-02, whereas BC-03 shows an increase in sand content (Figure 6). At BC-05, minor increase is seen for the sediment down to 8-cm depth, followed by a decrease in sand content down to 20 cm.

Pre- and post-disturbance trends at EDZ are similar down to 20-cm depth with a minor increase up to 6 cm depth and reduction from 25 to 30 cm at NW end (BC-04). At the SE end (BC-06), the post-disturbance trend follows that of the pre-disturbance with minor increase (0.9 to 2.5%) in sand percentages throughout the depth of the core (Figure 6).

North of DZ, the sand content in the sediment down to 15 cm depth at BC-08 is decreased. The sand content varied between 3 and 4.5% in pre-disturbed and 0.6–1.7% in post-disturbed samples (Figure 6). Similarly, at BC-12 the sand variation is between 2.6 and 3% in pre-disturbed samples with a reduction throughout the core (Figure 6) to 0.4–1.1% in post-disturbed. Reduction in sand up to 20-cm depth is also seen at BC-13 (Figure 6). Compared to the deeper samples, the 3% change at surface level is more pronounced.

South of DZ reduction in sand content at two locations is similar to that in NDZ. At BC-07, the sand content reduces down to 10-cm depth, to 0.6–1.9% in post-disturbed from 2.6 to 6.6% in pre-disturbed ones. Surprisingly, a peak is observed at 10 to 15 cm where sand increased to 7.8% (Figure 6). In contrast to BC-07, both pre- and post-disturbance trends at BC-14 are similar. A small peak is observed at 6 to 8 cm depth, but overall sand variations are reduced from 7.4 to 7.7% in pre-disturbed and 1 to 2.4% in the post-disturbed ones (Figure 6).

Silt is reduced at BC-02 after the disturbance (Figure 7). Reduction is more pronounced (25%) at the surface (0 to 2 cm) and less (9%) down to 10-cm depths at BC-02. At BC-03, 6% increase is observed for the sediments down to 8-cm depth (Figure 7) whereas at BC-05, the increase is 4 to 5% with initial decrease of 1% at the surface.

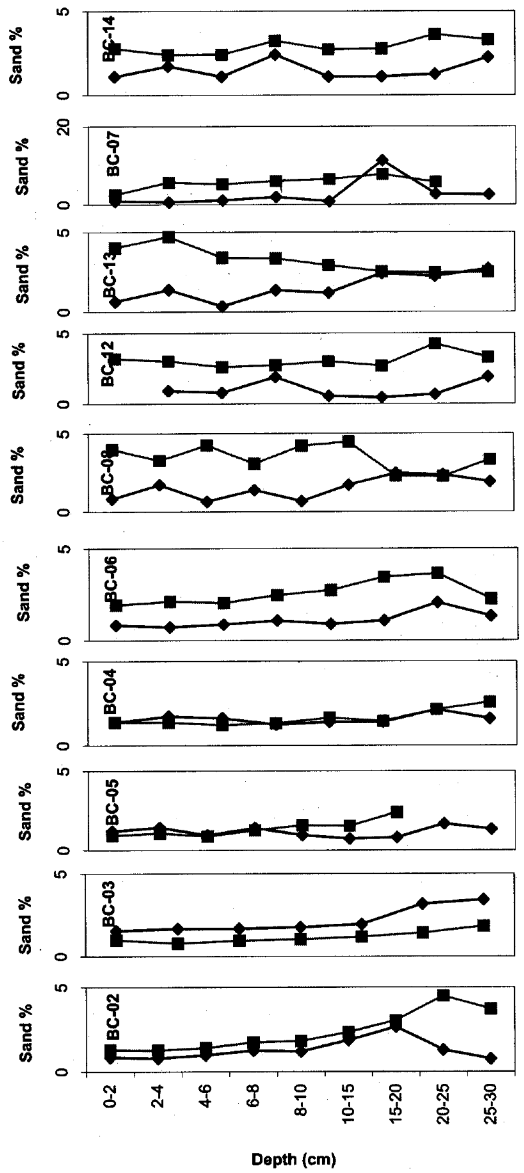

Figure 6. Variation of sand with depth in DZ. ■, pre-disturbance; ◆, post-disturbance.

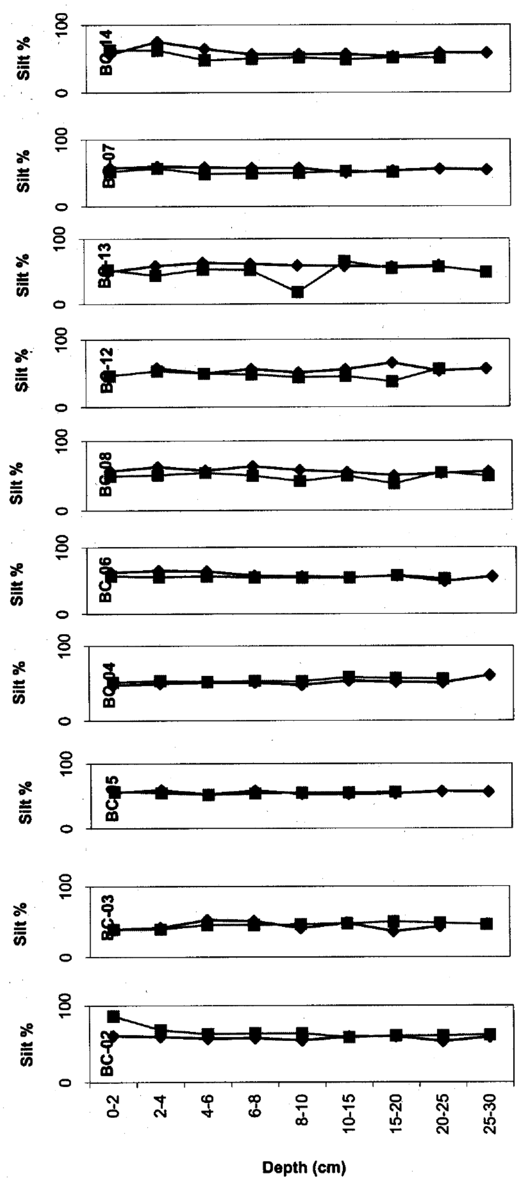

Figure 7. Variation of silt with depth. Symbols as in Figure 6.

Post-disturbance trend of silt in the sediments at BC-04 in the NW end follows that of the pre-disturbed ones with minor decrease of 4% down to 8 cm depth (Figure 7). At SE end (BC-06), noticeable increase (5 to 9%) is observed for the surface samples down to 6-cm depth (Figure 7). For the remaining downcore samples, both pre- and post-disturbance trends are similar.

North of DZ after the disturbance, the silt content increased by 8 to 13% at the surface (0 to 4 cm) of BC-08 (Figure 7) and 4% at BC-12 (Figure 7). The silt was reduced by 10 to 15% for 0 to 8-cm depth at BC-13 in the north of the disturbed zone (Figure 7). The post-disturbance trend of silt follows that for the pre-disturbed one down to 30 cm at BC-12, BC-08 and BC-13, except for minor differences.

In south of DZ, increase in the silt content is similar to that observed for the samples in NDZ and the trend in the post-disturbed samples follows that of the pre-disturbed ones (Figure 7). At BC-07, there is 6 to 10% increase in silt down to 6 cm depth, 8% up to 10-cm depth, and 2% up to 20-cm depth. At BC-14, similar trend of increase in silt content with depth is observed.

Compared with the pre-disturbed samples in DZ, the post-disturbed samples at BC-02 have 6 to 9% higher clay content from 2 to 10 cm depths, and 8 to 11% higher content from 20 to 30 cm depth (Figure 8). The surface sediment (0 to 2 cm) shows an increase of 27% clay after the disturbance. At BC-03, pre- and post-disturbance clay contents are similar in the top 2-cm, but post-disturbance contents are 3 to 7% lower at 4 to 10 cm depth, and 5 to 12% down to 25-cm depth at BC-03 (Figure 8). Similarly, at BC-05 the clay content decreases down to 8-cm depth (Figure 8), and both pre- and post-disturbed trends are similar for the remaining depth. The clay content at BC-05, decreases (by 2 to 4%) up to 8-cm depth and later increases by 3% down to 20-cm depth.

Both pre- and post-disturbed trends at BC-04 and BC-06 are similar at EDZ. Comparatively, the clay content at the surface (0 to 2 cm) increases slightly by 3 to 4% at BC-04 in NW end of DZ (Figure 8) and decreases by 4 to 8% at BC-06 towards the SE end (Figure 8).

North of DZ noticeable changes occurred in the clay content of surface samples (0 to 4 cm) at BC-08, BC-12 and BC-13 (Figure 8). Surface clay (0 to 4 cm) decreased by 5 to 10% at BC-08 and 2% at BC-12, but increased by 6% for 0 to 2 cm depth sediments at BC-13.

South of DZ, in contrast to NDZ, the surface samples (0 to 2 cm) show increase in clay content at BC-14. At BC-07, the clay is decreased by 6% at the surface (0 to 2 cm), but increased by 2% for 2 to 4 cm sample (Figure 8). Highest increase of 8% for the surface sediments (0 to 2 cm) is observed at BC-14 (Figure 8).

Textural changes in the sediment after the disturbance at seabed locations clearly show that the grain size was modified according to the quantity of resuspended sediments received at these locations. Post-disturbance textural changes were observed in the disturbed zone at BC-02 where silt in the surface sediment (0 to 2 cm) changed to clayey silt (11%), whereas the surface texture at BC-03 and BC-05 did not change significantly after the disturbance, indicating that the maximum re-deposition was in the direction of movement of the disturber. Deposition of fine fractions (clays) at BC-04 suggests that the plume with clay particles moved from the disturbed zone towards a westerly direction. However, downcore variations of sand, silt and clay indicate differential movement of particular grain sizes.

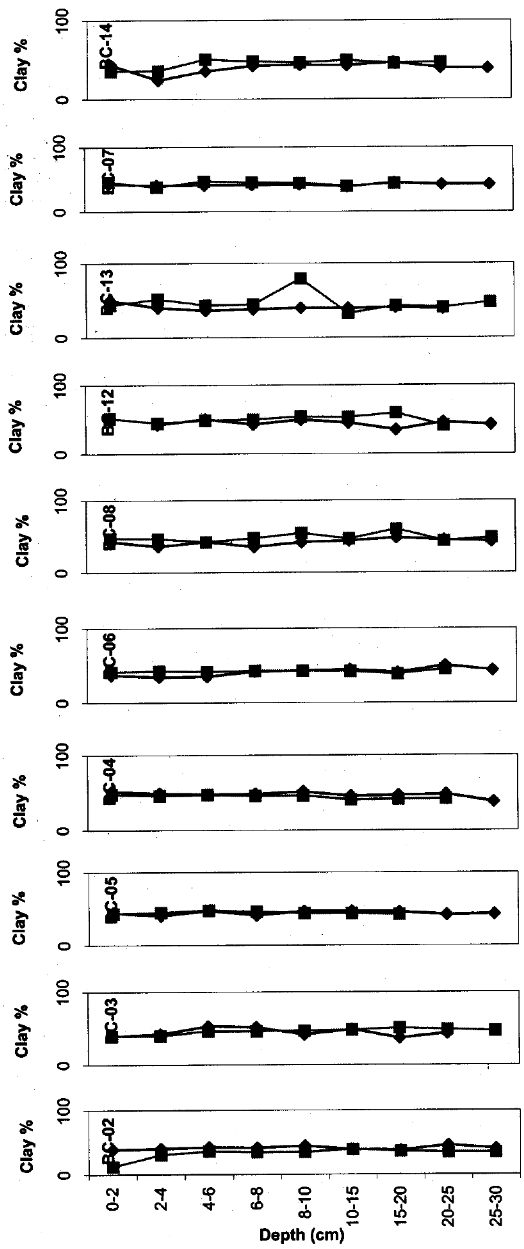

Figure 8. Variation of clay with depth. Symbols as in Figure 6.

In the pre-disturbed samples, the sand percentage increased with depth from 1.4 to 4.5% at BC-02; 1.5 to 3.5% at BC-03, and ~1.0 to 2.5% at BC-05. The post-disturbed samples have lower sand content and follow a similar trend up to 20 cm depth at BC-02 and BC-03. At BC-05, little increase (1 to 1.5%) is seen up to 8-cm depth. Although the increase is minor, it could be attributed either to mixing of sediments from the depth or the removal and deposition to a nearby area due to disturbance. Therefore, it can be inferred that the disturbance in the DZ was effective up to 20 cm. At the ends of DZ, negligible increase (~1%) in the surface sand towards SE end (BC-06), and no change in sand content at BC-04 towards NW end of the DZ, clearly show no movement of sand in either direction. Similarly, the sand might not have moved in the direction north and south of DZ as revealed from the sand percentages in the surface sediments of BC-08, BC-12 and BC-13 in the north, and BC-07 and BC-14 in the south. Therefore, the sand movement due to disturbance was only within the DZ, and the sand was re-deposited at the same locations after the disturbance. It is thus clear that the plume was devoid of sand particles. Pre- and post-disturbed sections from the study area up to 10 cm

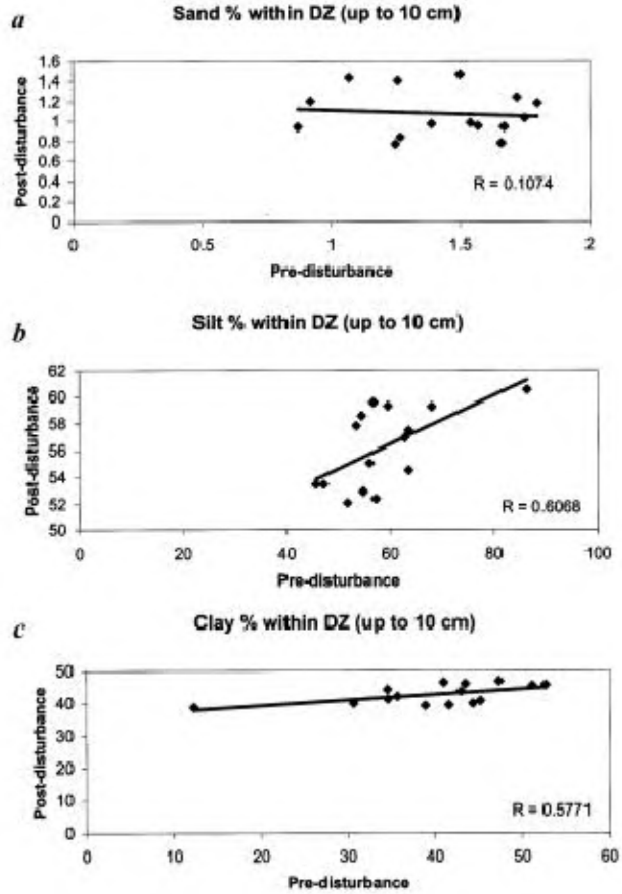

Figure 9. Correlation of pre- and post-disturbed (*a*) sand %; (*b*) silt %, and (*c*) clay %, within DZ.

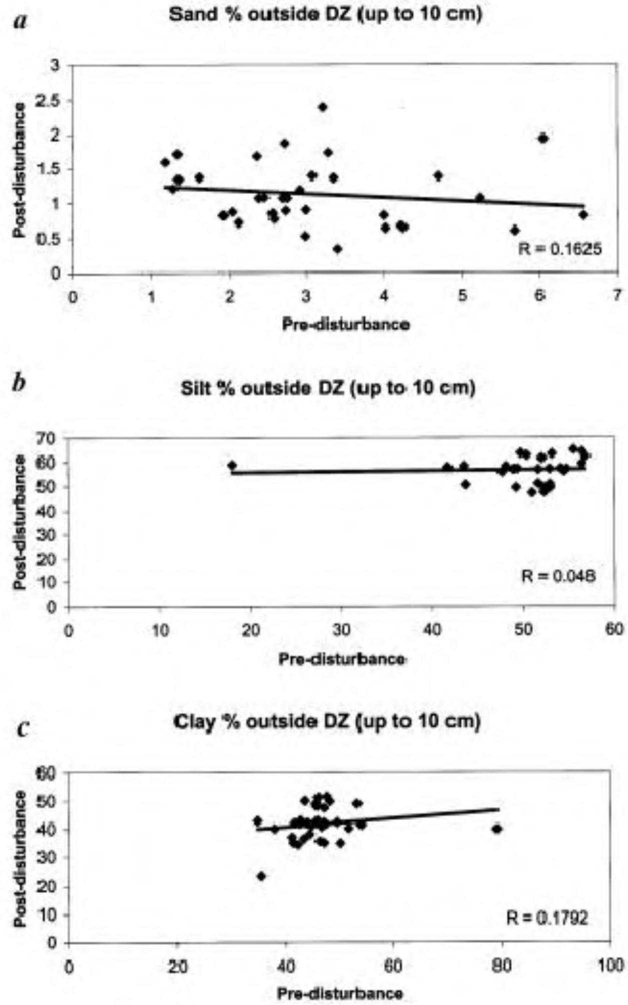

Figure 10. Correlation of pre- and post-disturbed (*a*) sand %, (*b*) silt %, and (*c*) clay %, outside DZ.

depth do not show good correlation within (Figure 9 *a*) and outside (Figure 10 *a*) the disturbed zone mainly because the sediments have very low sand content and so 'sand' cannot be considered as an effective indicator of disturbance or plume migration.

Overall decrease in silt (9 to 25%) from surface to 10-cm depth at BC-02, 3 to 8% increase down to 8-cm depth at BC-03 and 4% increase down to 8-cm depth at BC-05 illustrates the movement and deposition of silt from BC-02 towards BC-05 in the DZ. It is further inferred that the silt, after the disturbance, moved from BC-02 towards the NE direction. However, the silt might not have moved away from the NW end of the DZ, as there is no increase in silt at BC-04. But 8% increase in silt at BC-06 at the SE end of DZ clearly shows that some silt was forced out of DZ in the SE direction. North of DZ, there is 8% increase in silt at the surface (0 to 2 cm) of BC-08 and 4% at BC-12 (2 to 4 cm depth). South of DZ, there is 6% increase in silt at the surface (0 to 2 cm) of BC-07 and BC-14. This reveals that the silt from BC-02 was moved to the north and south of the DZ.

From the above discussion it is clear that the major fraction in the plume comprised of silt and not sand. This observation is further supported by the presence of 'clayey silt' sediments in the rosette sampler collected at three locations during INDEX experiment of disturbance along DZ (Figure 11). Therefore, it can be concluded that the major portion of the plume comprising silt migrated, dispersed and resettled within 245° to 310° direction (Figure 12). Pre- and post-disturbed sections have a weak correlation outside the disturbance zone ($R = 0.048$; Figure 10 *b*), whereas they are strongly correlated within the disturbed zone ($R = 0.6068$, $N = 15$, 99% confidence; Figure 9 *b*). The strong correlation within DZ indicates re-deposition of silt particles in the DZ, and the weak correlation outside the DZ points towards movement and resettlement of silt at a few places outside the DZ.

Significant increase in surface clay was observed at BC-02 in DZ, BC-04 at NW of DZ, BC-13 at NDZ and BC-14 at SDZ. At BC-02, the increase is 27% at the surface and to an extent of 9% for 2 to 10 cm depths. This increase is attributed to addition of clay from the nearby locations (BC-03 and BC-05). This is further supported by the fact that the clay content at BC-05 and BC-03 is reduced. It is therefore visualized that the clay fractions from BC-05 and BC-03 travelled about 2 km in suspension in the SE direction in DZ and settled at BC-02. Hence, it appears that after the disturbance, the movement of clay was within the DZ from NW to SE direction, which was also the direction of the disturber. About 3 to 4% increase in clay content down to 4-cm depth at BC-04 further suggests that some clay might have moved to the NW from BC-05. Similarly, 6% increase in clay at the surface (0 to 2 cm) at BC-13 and 8% at BC-14 suggests that the movement of clays was not restricted within DZ, but also towards NDZ and SDZ. The clay movement was thus similar to the silt (Figure 12) and strongly supports the fact that the major plume movements were within 180° to 300° direction. Pre- and post-disturbed samples have very good correlation ($R = 0.5771$, $N = 34$, 98% confidence; Figure 9 *c*) within the DZ, and weak correlation ($R = 0.1792$; Figure 10 *c*) outside the DZ. This correlation is similar to that of silt and suggests that although the major portion

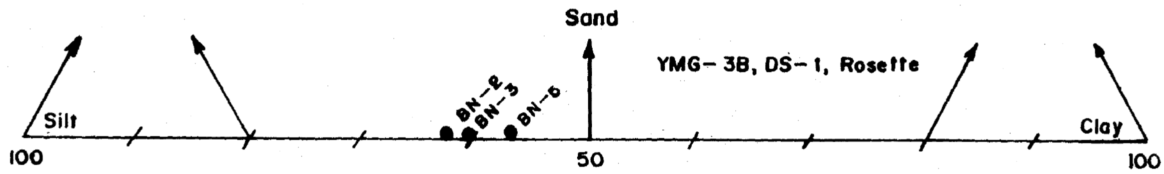

Figure 11. Distribution of sand–silt–clay in rosette sampler collected at three locations (BN-2, 3 and 5) during INDEX disturbance cruise (YMG-3B).

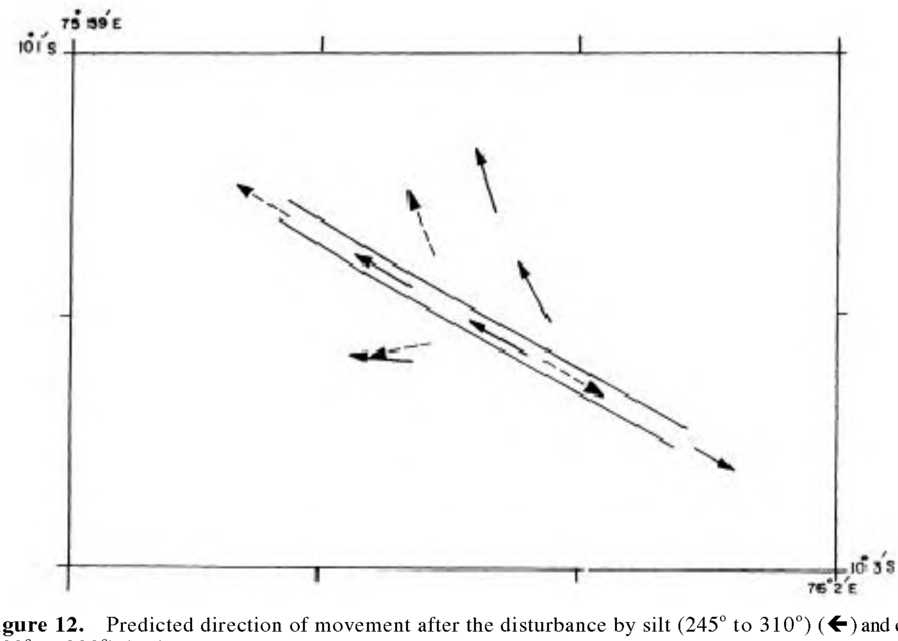

Figure 12. Predicted direction of movement after the disturbance by silt (245° to 310°) (🡐) and clay (230° to 300°) (←···).

of the clay has been redeposited within the DZ, some part of clay comprising the plume resettled outside the disturbed zone.

Grain-size analyses of the pelagic sediments have provided useful information for predicting and determining the direction of plume movement in the INDEX area. The INDEX experiment in the CIB showed that the sediment disturbance and resedimentation produced significant changes in sediment texture, silt and clay content whereas sand remained almost unaffected with little variations. These variations in the sand–silt–clay content of pre- and post-disturbed samples have been effectively used to interpret the direction of sediment plume.

The post-disturbance studies on the grain size of the sediments from EIA area in the CIB show that the disturbance was effective up to 20 cm depth. There is (i) overall increase in silt at most (7) locations; (ii) increase in clay at few (4) locations similar to those of silt; and (iii) increase in silt at certain (6) locations similar to those of clay. From the pre- and post-disturbance comparative studies, the general direction of plume is interpreted to be within 180° and 300° (Figure 12). This agrees with the average direction of currents for this period reported to be 201° (with 1.3 cm/s velocity) obtained by deploying the current meters above the seabed during baseline studies in the area[17]. Correlation between pre- and post-disturbed samples shows that silt and clay fractions can be used as indicators of sediment movement, as these particles are relatively smaller and lighter than sand particles.

The experiment showed that the fine particles in the sediments (fine silt and clay) remain in suspension for longer time leading to resedimentation within and around the disturbed zone, DZ whereas the larger particles (sand) settle immediately after the disturbance. These studies have relevance where generation of voluminous sediment plume will be the major outcome of deep-seabed mining of the polymetallic nodules in future. The changes in the characteristics of the sediments due to the disturbance may also result in changes in density of macro- and meio-faunal abundance[18] as well as bacteriological and biochemical processes[19] leading to changes in ecology of the benthic environment. Similar effects may result from the large-scale nodule mining, the intensity of which may vary depending upon the quantity and altitude of discharge of sediments in the water column.

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