

## Geochemical and biological recovery of the disturbed seafloor in polymetallic nodule fields of the Clipperton-Clarion Fracture Zone (CCFZ) at 5,000-m depth

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### Abstract

Environmental data were obtained on the nodule fields of the Clipperton-Clarion Fracture Zone at 5,000-m depth in June 2004 during the Nodinaut cruise. The long-term effects of physical disturbance made by a dredge 26 yr ago on the sediment were investigated. We focused our study on its track, which is still visible on the bottom. The first major consequence of the passage of this equipment was to remove 4 cm ± 0.5 cm of superficial sediment. The physical and chemical properties of this disturbed sediment sampled in the track did not change significantly over time and has not shown any recovery since the disturbance. However, an exception was observed for depth variations of manganese concentration in the sediment, which were similar in the track to those in the surrounding undisturbed sediment and can be explained by the diffusion over time of oxygen from the sea water. On the other hand, the biological activity measured in the track with the respirometer RAP2 carried by the submersible *Nautilie* did not differ from the unperturbed site, which suggests that the benthic fauna has completely recovered, as have nutrient fluxes at the water–sediment interface.

Human activities in the deep sea are expected to cause disturbances to the abyssal benthic ecosystem. Future mineral mining in the Pacific Ocean will affect the sediment properties and the deep fauna (Jumars 1981; Thiel 2001). The assessment of damage from mining requires contributions from many fields of oceanographic research, but for evaluation of the potential impact, the prime task is to collect information about the natural state of the deep-sea environment and faunal distribution before any mining activity. This baseline study is essential for describing the structure of the benthic community (composition, diversity, density, and distribution) and also for evaluation of the environmental factors that affect its spatial distribution. These data must be obtained if protection of the deep-marine environment is to be ensured. Although a number of environmental studies have been conducted in the nodule areas, important ecologic aspects of these abyssal habitats remain very poorly understood. In the framework of the contract for nodule exploration in the Clarion-Clipperton Fracture Zone (CCFZ) concluded between the French authorities and the International Seabed Authority (ISA), Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) conducted the Nodinaut cruise to obtain environmental reference data in the French claim areas.

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Manganese-nodule fields of CCFZ and their sedimentary environment have been studied by IFREMER between 1970 and 1988 in terms of geomorphology, sedimentary geology, and geotechnical character (see review in Cochoinat et al. 1992). During this previous French nodule-research project, pictures and videos of the seafloor provided observations of old mining tracks made by the American consortium OMCO in 1978. One of these tracks, 26 yr old, was a target of study during the Nodinaut cruise; the intent was to compare the surface sediments inside and outside the track. The specific goal of the present paper is to compare the functioning of the ecosystems of the disturbed and undisturbed sediments in the East Sta. of CCFZ at 5,000-m depth, through measurement of their oxygen and nutrient fluxes at the water–sediment interface.

### Study site

The area of investigation is located on the NIXO zone in the Clarion-Clipperton Fracture Zone (CCFZ), in a manganese-nodule field at 14°02'N and 130°07'W (Fig. 1a). It was at 5,000-m depth and below the carbonate-compensation depth (CCD). The general topography of the NIXO zone includes several hills between 100 and 300 m high, usually oriented north–south and spaced from 5 to 10 km apart. Between the hills, nodules were present in about 90% of the area. Zones without nodules were usually found at the bottom of thalwegs.

The dark-brown surface sediments were fine-grained silicate oozes. The clay fraction (<2 μm) accounted for 85% of sediment dry weight and was quite homogeneous at the scale of the study area. Clay minerals were dominated by smectite and illite. The biogenic fraction of the sediment was dominated by siliceous taxa (radiolarians and diatoms). Radiolarian species allowed dating of the superficial

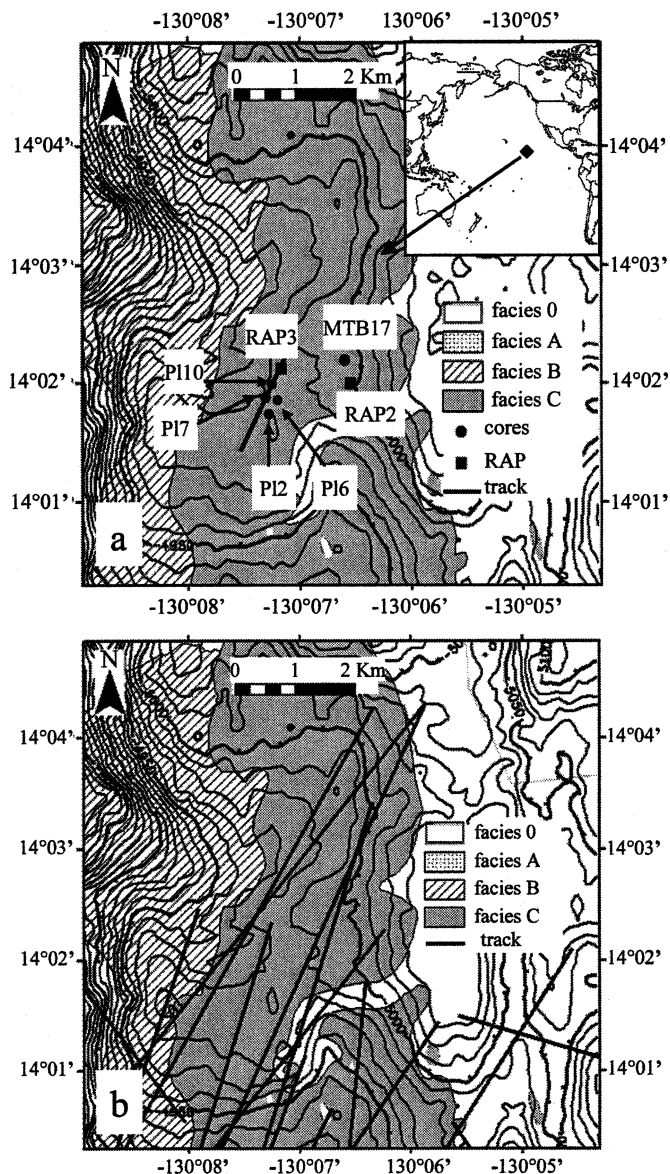


Fig. 1. (a) Map of study area and sample positions. (b) Location of observed tracks (solid lines) during NIXO program.

sediments of the area. The sediments were characterized by a mix of Tertiary (Oligocene, Miocene, and Pliocene) and Quaternary species. The mix indicated a possible reworking of superficial sediments, but J. L. Reys (pers. comm.) observed that a homogeneous sedimentary phase has settled in an extremely regular way for more than 400,000 yr in the NIXO area. Locally, the sedimentation rate is controlled by the deep currents. It reaches 5 mm  $10^{-3}$  yr on the flat bottom and can be near zero on the slopes swept by the currents.

Nodules in the NIXO area differed in size, shape, extent of burial, and density, so several different nodules facies could be determined. The presence of large, mamillate nodules on the bottom, which covered about 40% of the sediment at our station, characterizes facies C. Other facies can be found in the NIXO area: facies 0 corresponds to

sediment without nodules, and facies B describes sediment with small and spherical nodules (Fig. 1a).

During the NIXO program, more than 10 tracks were observed in the 60-km<sup>2</sup> area oriented more or less north-south (Fig. 1b). They are 2.5-m wide and can be over 10-km long. We found no information on the design of the dredge used by the OMCO consortium during the exploration cruise in 1978, but detailed observation of the track during several *Nautille* dives found no nodules on its surface, which indicated the great efficiency of this tool. The dredge left the sediment very flat and smooth, without lumps. The tracks were bordered by sediment accumulations 15-cm high. The superficial sediment was the same color as the surrounding sediment, and some bioturbation structures were evident.

### Material and methods

**Sediment**—Sediment was sampled with two different corers at two stations (Table 1), facies C and track (Fig. 1a). A multicorer collected sediment in 10-cm diameter, 30-cm long Plexiglas tubes. It was used once on facies C. Tube corers of 6.5-cm diameter and 20-cm length were lowered very slowly into the sediment by the submersible *Nautille* to avoid disturbance as facies C (two cores) and the track (two cores) were sampled.

Total core length was between 15 and 32 cm. Cores were immediately taken to a cold room at 4°C on board ship just after recovery. The sediment of each core was sectioned into 0.5-cm slices down to 5 cm, followed by 1-cm slices from 5 to 10 cm, and finally 2-cm slices below 10-cm depth. In total, 275 sediment samples were obtained. Each slice was divided into two parts. One part of the slice was dried on board ship at 60°C over night. The chemical composition of the sediment was analyzed by wavelength dispersive X-ray fluorescence spectrometry (Siemens). The routine major elements were measured on samples prepared as glass discs. Calibration curves were established by use of a set of international reference materials (El Maghraoui et al. 1998). Data were not rectified by NaCl dilution. The other part of the slice was packed in a preweighed plastic bag and frozen. At the laboratory, slices of wet sediment in each bag were weighed, and then were freeze-dried and weighed again to calculate the water content of samples. Total sulfur, nitrogen, and carbon were determined in duplicate by a Leco CNS-2000 autoanalyzer. Total organic-carbon concentration was measured by a Leco WR12 elemental analyzer after removal of carbonates with a 2 N HCl solution. Inorganic-carbon content was calculated by difference.

**The benthic lander**—The autonomous “Respiromètre Autonome Grande Profondeur” (RAP2) benthic lander (Fig. 2a) was deployed twice on the manganese-nodule field (Fig. 1a). The first moorings were made with the RAP2 used as a free vehicle at the facies C station. The second deployment of the RAP2 was made with the submersible *Nautille* used to position the frame exactly on the track (Fig. 2b). Incubation periods were 50 and 47 h, respectively, for the two deployments. Mean current speed, measured

Table 1. Number, position, and depth of the cores.

Station	N° Core	Position	Depth (m)
Facies C	MTB 17	N14°02.202 W130°06.603	4,975
Facies C-pl 2	1594-02-CT5	N14°01.963 W130°07.353	4,972
Facies C-pl 6	1598-06-CT9	N14°02.004 W130°07.339	4,971
Track pl 7	1599-07-CT7	N14°02.068 W130°07.204	4,978
Track pl 10	1602-10-CT5	N14°02.126 W130°07.174	4,980

with the Aanderaa RCM 11 current meter positioned on the top of the respirometer, was weak ( $4.1 \text{ cm s}^{-1}$ ) during the two deployments, with a maximum speed of  $12 \text{ cm s}^{-1}$ . The current did not perturb the work of the respirometer on the bottom or its transport by the submersible.

The principle of the RAP 2 is to isolate and incubate a known volume of seawater in contact with a predetermined sediment-surface area. Variations in the concentrations of several chemical elements can be measured on seawater samples isolated within the measurement chambers, directly by specific probes, or both (Tengberg et al. 2005).

The RAP 2 is an autonomous lander with a tubular aluminium frame. It measures 3-m long, 2.5-m wide, and 2-m high and weighs 2,000 kg in air with its two ballasts of 150 kg each. The lander is composed of an upper part with syntactic buoyant foam, a parachute to reduce descent velocity, a current meter (RCM11 Aanderaa), two acoustic releases, and surface-positioning systems (flasher, radio, and Argos beacons) and a lower part with the modules for the water sampling and the electronics and battery housings. The sampling module consists of a motor-driven central tray to which three cylindrical (30 cm in diameter and 24 cm in height) PVC benthic chambers, open at both ends, are fixed. Electrically operated lids on the top of each chamber seal the upper, open ends when the chambers have been pushed into the sediment and, thus, isolate a known volume. A rectangular ( $9 \times 7 \text{ cm}$ ) stirring paddle fixed beneath the lid and driven by an electric motor mounted on the lid ensures that the water in the chamber remains well mixed. Stirring was preset to a speed of  $7 \text{ rotations min}^{-1}$  (rpm). In this configuration, water velocities are  $\leq 1.5 \text{ cm s}^{-1}$  in the chambers, and complete mixing of the enclosed water is attained in 10 minutes. Reaction rates and chemical fluxes at the water-sediment interface are controlled by the thickness of the diffusive boundary layer (DBL), which depends on water circulation close to the bottom. The stirrer mechanism of the chamber must have the ability to reproduce the natural DBL. By use of the "Alabaster" method (Tengberg et al. 2005), an average DBL thickness of  $680 \pm 170 \mu\text{m}$  was measured in the chamber. Similar values have previously been measured at deep-sea environments (Santschi et al. 1991).

Three sampling cells, positioned within the chambers, enable water subsample collection (100 mL) at predetermined intervals for later calculation of fluxes. The cells were constructed with an internal glass lining because glass is impermeable to oxygen. The upper and lower plates that seal the cells are made of PVDF (polyvinylidene fluoride) plastic. The position of the cells inside the chamber and

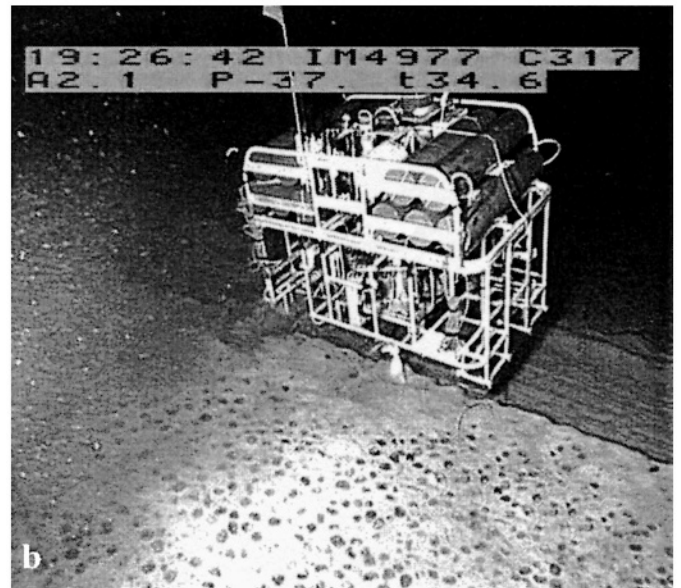
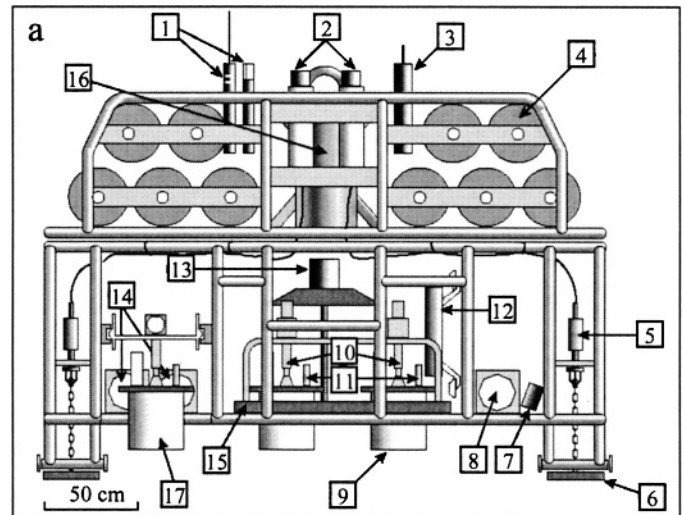


Fig. 2. (a) Scheme of the respirometer RAP2. 1: flasher and radio beacon, 2: acoustic releases, 3: current meter, 4: syntactic buoyant foam, 5: ballast release, 6: ballast, 7: video camera, 8: battery for the camera, 9: measurement chamber, 10: motor to close the lid, 11: stirrer, 12: Niskin bottle, 13: main motor, 14: battery and electronics housings, 15: platform, 16: parachute housing, 17: external chamber (not used). (b): Respirometer RAP2 on the track of the dredge.

Table 2. Elemental composition (%) of the surface-sediment facies C.

Porosity	Org C	N	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	CaO	MgO	TiO <sub>2</sub>	K <sub>2</sub> O	SO <sub>4</sub>	Ba
0.93	0.48	0.11	47.4	12.05	5.74	0.51	1.21	3.52	0.58	2.40	1.16	0.38

their closure mechanism preclude any suction of water into the chamber.

All the electric motors are of the stepper type, housed in oil-filled, pressure-compensated containers isolated from the ambient environment. Their electronic components are located in a central container.

After the lander is launched from the ship, the deployment of a 3-m diameter parachute is triggered by a hydrostatic release at a predetermined depth, which reduces the descent velocity of the lander from 1 m s<sup>-1</sup> to 0.5 m s<sup>-1</sup> before the lander reaches the bottom. A plastic shield fixed between the ballasts and the benthic chambers reduces the effect of the bow wave on landing.

The central motor starts after a stabilization period of a few hours on the bottom and inserts the three chambers simultaneously into the sediment up to a predetermined depth of 9 cm ± 1 cm. This depth is monitored by a video camera. The chamber's exact volume is calculated from the dilution of a known volume of NaF solution injected when the lids close. The surrounding seawater is obtained by a 1-liter Niskin bottle mounted on the chassis at the time of closure of the lids. This sample contains the water at the initial concentration of solutes. The incubation starts at this moment. The water within the chambers is mixed by the stirring paddle. The three sampling cells in each chamber enable collection of subsamples at predetermined intervals during the incubation. At the end of the experiment, the central tray moves back to the initial position and, thus, withdraws the three chambers from the sediment. An acoustic command releases the two ballasts, and the positively buoyant floats (100 kg) raise the lander to the sea surface.

Immediately after lander recovery, the Niskin bottles and the sampling cells are removed from the chambers. The water samples are then collected by gravity flow directly in various vials. Two methods were used to measure O<sub>2</sub> consumption under the chambers of the respirometer. The first method was Winkler titration, which is the reference method always performed in the laboratory. Oxygen content was analyzed in 10-mL water samples from cells and Niskin Bottles by use of the modified Winkler method (Carritt and Carpenter 1966). The endpoint is detected by potentiometry with combined platinum electrodes (Metrohm). The standard error of the measurements is 2 μmol L<sup>-1</sup>. The second method was the new electrochemical sensor optode (Aanderaa), which was positioned under each chamber to measure O<sub>2</sub> consumption with a better temporal resolution. The principal attributes of this probe are its accuracy and long-term stability; it is not stirring sensitive (no oxygen consumption) and is little and predictably affected by pressure (Tengberg et al. 2006). Silicate, phosphate, and nitrate were measured in a Chem-lab autoanalyzer by application of the methods described by Strickland and Parsons (1972). Coefficients of variations in the measurements were 2.5%. For each water sample,

constituent concentrations were measured in duplicate aliquots.

## Results and discussion

*Sediment composition of facies C*—Water content decreases from 82% (porosity = 0.93) at the surface to 68% (porosity = 0.85) at the transition zone at 8-cm depth and, below this zone, it remains stable within the next 30 cm (Table 2; Fig. 3). This profile is an exact copy of the compilations of water-content data obtained on the equatorial Pacific (Jahnke et al. 1986) or on the Jet site (Harada and Shibamoto 1997). Sediment is rich in deep-sea water, particularly under the CCD depth, because of the fast dissolution of calcareous skeletons in the surface sediment and the relative increase in swelling-clay minerals.

Organic-carbon content equals 0.48% of dry sediment at the surface (Fig. 3). This value is similar to the results obtained under the CCD in the Central Pacific by Weber et al. (2000). Siliceous skeletons of radiolarian, along with additional organic substances, and fecal pellets are the main sources of organic carbon in the sediment. Curiously, the organic-carbon concentration did not vary from the surface down to 3 cm in facies C. The organic-carbon profile of surface sediment at the Jet site at a 5,150-m depth showed the same homogeneous thickness of 3 cm (Harada and Shibamoto 1997). This observation could be the result of a complete homogenization of this sediment layer by the benthic organisms. Given the very low density of benthos in this area, this explanation is not realistic. Conversely, the weak activity of the benthos could have as a consequence a very weak bioturbation intensity and, thus, permit the conservation of the carbon accumulated in the sediment. Jahnke et al. (1986) observed in the deep equatorial Pacific

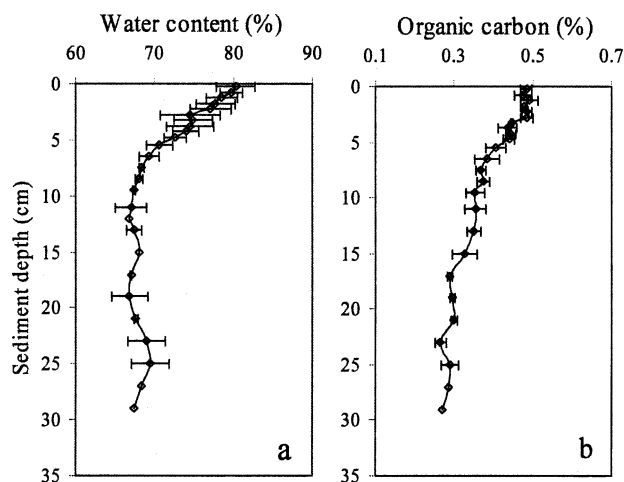


Fig. 3. Profiles of (a) water content and (b) organic carbon in the sediment of facies C.

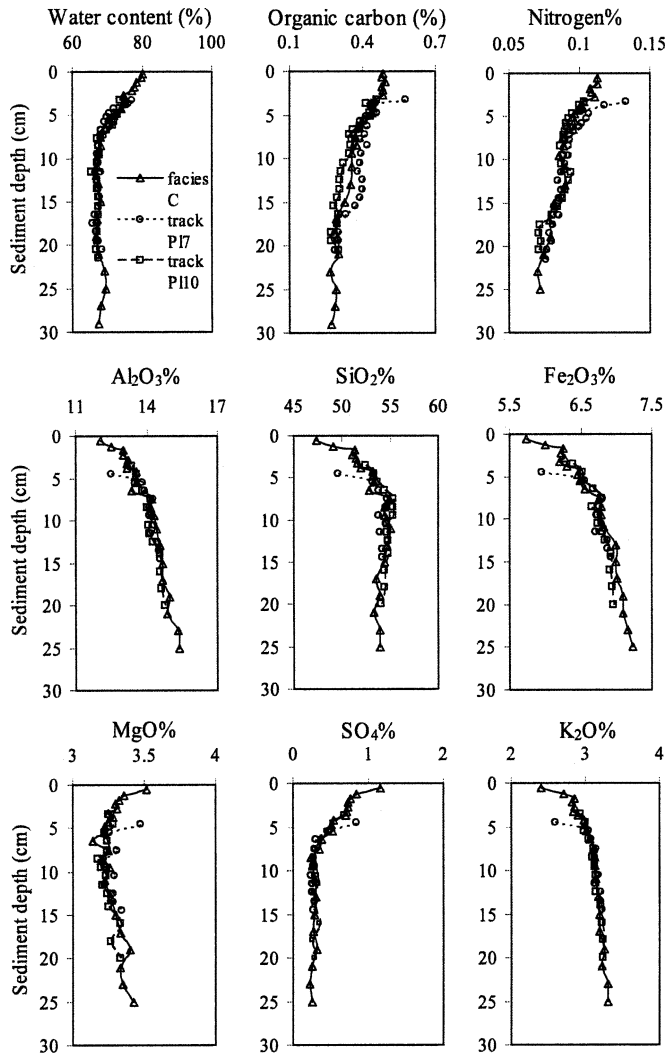


Fig. 4. Elemental composition of the sediment in facies C and in the track. The values of the track cores are shifted 3.5 cm for pl 7 and 4 cm for pl 10.

an excess of  $^{210}\text{Pb}$  only in the upper sediment that would suggest slow rates of mixing. The labile organic matter is deposited on the seafloor and rapidly is consumed by the benthic community at the sediment–water interface. Organic-carbon content decreases sharply after this homogeneous slice, perhaps because of the labile carbon consumption by the benthic organisms living in this surface slice or a change of sedimentation rate 5,000 yr ago.

As a consequence of being deeper than CCD and the fast carbonate-skeleton dissolution, the very low concentration of inorganic carbon (as carbonate) in the sediment leads to undetectable calcium concentrations, except at the upper surface of the sediment from facies C between 0 and 0.5-cm depth (0.05%). This result indicates that the Ca measured in the sediments (0.80% at the surface to 0.74% at 30-cm depth) was not as  $\text{CaCO}_3$ , but probably as  $\text{CaSO}_4$ .

Like the organic carbon, total nitrogen decreased with increased depth in the sediment (Fig. 4). A high organic C:N ratio (3:4.5) is typical of Pacific deep-sea sediments (Harada and Shibamoto 1997), in which ammonia ad-

sorbed on clays represents a significant fraction of total nitrogen (Müller 1977).

The elemental composition of the surface sediment on facies C (Table 2) shows strong similarities with the sediment composition described by Kotlinski and Stoyanova (1998) at the IOM BIE site of the CCFZ. It is dominated by Si (50%), which is the major compound of the clay and also of the radiolarian and diatom tests. Al (12%) is the second most abundant element of the clay, and it increases steadily from the surface down to the end of the core, whereas Si concentration increases only down to 7-cm depth and does not vary within the next 25 cm. Small variations in the Si:Al ratio from the surface to 7-cm depth could be linked to deeper dissolution of the biogenic silicate. Fe and K follow the same profile as the one described for Al. Mg concentration, in contrast, decreases down to 7-cm depth and then increases until the end of the core at 30-cm depth.

*Depth of the track*—The comparison of chemical-element profiles obtained from the undisturbed sediment of facies C with those obtained from two cores taken in the track makes possible the study, with precision, of the sediment thickness removed by the passage of the dredge. The dredge eliminated a sediment layer that does not exceed 4.5 cm in thickness (Fig. 4). A visual estimate had given a greater depth of disturbance because it was influenced by the berm of the sediment deposited by the dredge on the two sides of the track. Subsurface sediment composition (0–0.5 cm) shows great difference between the two samples taken in the track, even though the distance between them was only a few hundred meters. The surface sediment composition of core pl-10 is in agreement with the depth of the dredge's depression and does not indicate any modification of the sediment since the dredge's passage 26 yr ago. Conversely, core pl-7 shows surface sediment more similar to the undisturbed surface sediment of facies C. This difference can be explained by local hydrodynamic resuspension. Our observations show that any mixing processes appear to transport recently deposited material below the water–sediment interface (Pope et al. 1996) and confirm the very weak bioturbation on the track.

Disturbance created by the dredge directly modified the chemical gradient in the superficial sediment for unknown periods of time. The surface of the track has, thus, not changed for 26 yr, and the geochemical structure of the sediment seems not to be restored through diffusive or bioturbation processes. The surface sediment will be able to find its initial state only over a very long time, mainly in relation to the rate of sedimentation and the horizontal transport.

*The oxic zone in the superficial sediment*—Although the chemical element profiles show that the dredge penetrated about 4 cm, we observe an exception for the manganese, whose profile with the 4-cm shift into the track sediment differs distinctly from the reference sediment (Fig. 5). Mn penetration in the track sediment is higher than the predicted depth. Mn, like other metals, is in oxide form in the surface sediment (typical dark-brown color) and can

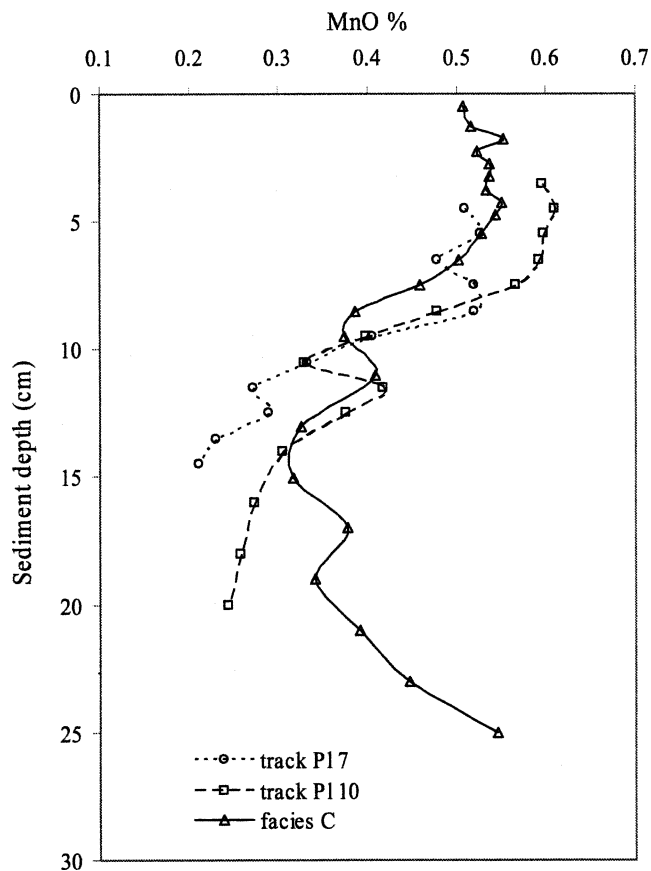


Fig. 5. Profile of MnO in facies C and in the track. The values of the track cores are shifted 3.5 cm for pl 7 and 4 cm for pl 10.

be reduced and dissolved under suboxic conditions. As Froelich et al. (1979) have suggested, the depth at which the dissolution of solid Mn begins corresponds to the sediment depth at which oxygen is exhausted. In the cores, the deeper oxide phase, at the lower limit of the oxide layer, can also be assumed to be the point at which manganese dissolution begins. On our manganese profile, the decrease in Mn was observed at 6-cm depth in the reference (Fig. 5). Between 6 and 8 cm, more than 40% of Mn is reduced and released into the pore water. For Pope et al. (1996), a rapid diffusive mixing allows rapid transport of reactive elements into the deep-sea seabed and may affect a wide range of geochemical processes, including biogenic silica dissolution and oxygen consumption.

In the track, and assuming that the dredge's penetration depth equals 4 cm, the oxygen limit would have been observed at 2-cm depth in the case of constant oxygen diffusion through the sediment over the past 26 yr. However, our results indicate that the dissolution of Mn begins at 5-cm depth in the track and is faster than in facies C: Mn concentration decreases by 50% at only 2-cm depth. Therefore, the oxygen penetration reached the natural limit observed in the surrounding sediment, in agreement with the model developed by König et al. (2001), which predicts that the oxic thickness in disturbed sediment should be restored after a few months.

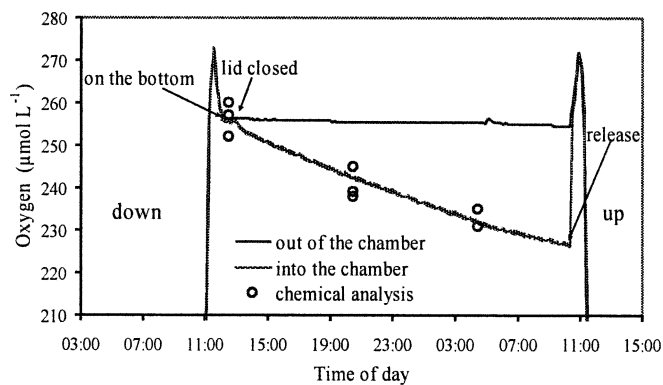


Fig. 6. Test of oxygen optode at 3,000-m depth.

*Oxygen exchange at the water-sediment interface*—Because the Aanderaa electrochemical sensor optode was new (Tengberg et al. 2006), we tested it at 3,000-m depth before we used this equipment in very deep water. First, one sensor was attached outside the chamber in the environmental water to observe its drift over time, and a second sensor was put inside a chamber. Drift of the optode over 21 h was only  $0.1 \mu\text{mol h}^{-1}$  (Fig. 6) and can be neglected in our calculation. The values of oxygen concentration given directly by the optode under the chambers were in agreement with the oxygen concentration obtained with the chemical analysis of the sampled water (Fig. 6). These results justify the great interest in this new equipment when it is used with deep-sea, autonomous landers.

Difference in uptake rates on the track versus the rates in the undisturbed sediment (Fig. 7) is not the result of higher biological activity on the undisturbed sediment, but reveals a difference in penetration of the measuring chambers into the sediment. Greater insertion speed in free fall produced 10-cm penetration in facies C, whereas more deliberate deployment with the submersible resulted in 8-cm penetration and, hence, a different volume of overlying water. When corrected for this volume difference, no difference in oxygen-uptake rate is seen between the two stations (Table 3), and it was, on average, equal to  $0.74 \text{ mmol m}^{-2} \text{ d}^{-1}$ . The variability between the chambers during the two deployments was very low, which indicates a little patchiness of the sediment fauna (Fig. 7). Change in slopes of chamber incubations have been seen in the deep sea (Jahnke and Christiansen 1989; Jahnke et al. 1994) and interpreted as the result of a shift in diagenetic processes in response to the decrease of oxygen.

The results obtained with the RAP2 are in good agreement with previously measured oxygen uptake rates in the northeastern Pacific (Smith et al. 1997) and in the equatorial Pacific (Hammond et al. 1996). However, they were double the measurements made in the North Pacific subtropical gyre and Murray Fracture Zone by Berelson et al. (1990) and Smith et al. (2002). Benthic activity varies from year to year, depending on the quantity and quality of the settling particulate organic matter, and the variation of the oxygen consumption observed in the deep-sea ocean can be attributed to the change in the particulate flux that reaches the bottom. The difference in oxygen consumption

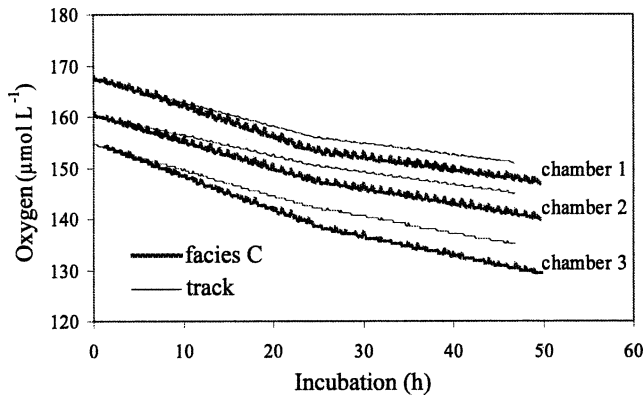


Fig. 7. Optode records during the incubations in the facies C and in the track (the curves are shifted on y axis for a better viewing).

observed in the deep Pacific can be explained by the variations in the organic-carbon input. Our working stations in the CCFZ area were more similar to the equatorial and East Pacific than to the Pacific central gyre.

The dredge skimmed 4 cm of the surface sediment. This depth is more than sufficient to remove or to kill most of the benthic fauna, which is distributed primarily in the first 2 cm of sediment (Menot pers. comm.). If we assume that oxygen consumption is the result of biological metabolism, essentially by the bacteria and very small organisms (Heip et al. 2001; Pfannkuche 1993), we can conclude that the dredge-disturbance effects are imperceptible for the sediment-dwelling fauna. After 26 yr, this benthic fauna seems to have completely recolonized the track sediment. This observation confirms results obtained during physical-disturbance experiments on nodule regions made during the DISCOL program in 1989 (Thiel 2001) and during the IOM program in 1995 (Trueblood and Ozturgut 1997). These authors observed that, after 2 to 7 yr, abundance recoveries of deep-sea fauna were largely complete, however, with some differences in taxonomic composition, which indicates that disturbance effects remained present over several years. For Radziejewska (2002), one of the explanations for different observed effects may be a difference in severity of the disturbance created. Only epifauna living attached on the nodule surface were totally destroyed or exported, and its recolonization is impossible because no nodules were left in place. The absence of metabolism difference between the track and the unperturbed station indicates that epifauna activity is certainly low in comparison with the metabolism of benthic organisms living in the sediment.

**Organic-carbon balance**—The oxygen uptake of  $0.74 \text{ mmol m}^{-2} \text{ d}^{-1}$  is equal to  $7.1 \text{ mg m}^{-2} \text{ d}^{-1}$  of organic carbon mineralized by the biological activity (assuming a respiratory coefficient of 0.85). The particle flux measured with sediment traps by Yamasaki and Kajitani (1999) in the CCFZ area indicates that settling particles sink rapidly to the bottom and shows seasonal variations with a maximum rain rate in April–May. The organic-carbon flux in June was about  $3.5 \text{ mg m}^{-2} \text{ d}^{-1}$  (Harada and Shibamoto 1997), two times smaller than the carbon mineralization measured with the respirometer. This discrepancy is well known in the deep-sea Pacific (Smith et al. 2002), and the reasons are many, including underestimation of the deep-sea energy input by sediment-trap measurements, unknown dissolved organic-carbon flux as a source of food, and lateral transport in the balance of organic matter in the deep sea.

**Nutrients: silicate, nitrate, and phosphate**—We observed a flux of nutrients from the sediments to the overlying water (Fig. 8) in the track and in facies C. By order of flux importance, silicate was higher ( $0.65 \pm 0.06 \text{ mmol m}^{-2} \text{ d}^{-1}$ ) than nitrate ( $0.043 \pm 0.005 \text{ mmol m}^{-2} \text{ d}^{-1}$ ), and the lowest was phosphate ( $0.001 \pm 0.0005 \text{ mmol m}^{-2} \text{ d}^{-1}$ ). The measured nitrate fluxes are very close to this estimate of the N regeneration rate and are comparable to results obtained by Hammond et al. (1996) and Harada and Shibamoto (1997) in the equatorial Pacific.

The measured phosphate flux was very low. Our analytical uncertainties cannot confirm whether the flux is really in or out of the sediment. Hammond et al. (1996) in the Pacific also showed that phosphate fluxes were very weak but usually indicated fluxes out of sediments and sometimes indistinguishable from zero.

A distinctive feature of our sediments is certainly the flux of silicate ( $0.65 \text{ mmol m}^{-2} \text{ d}^{-1}$ ), which was higher than those obtained by Hammond et al. (1996) but was similar to the results of Harada and Shibamoto (1997) in the CCFZ area. The Si solubility is controlled by the opal-rain rate, the sediment-accumulation rate, and the types of solid-phase opal. The lack of information on pore-water profiles of silicate at our stations cannot favor any particular mechanism.

Because nutrient flux did not differ between the track and facies C, we can assume that the nutrient concentration in the track sediment achieved the same profile as the original sediment. Finally, both the nutrient-flux measurements and the oxygen-flux measurements indicate no significant difference between the track and the surrounding sediment. The flux perturbations generated by the dredge now seem completely healed.

Table 3. Oxygen consumption ( $\text{mmol m}^{-2} \text{ d}^{-1}$ ) measured under each chamber by use of chemical analysis and oxygen probes.

	Method	Chamber 1	Chamber 2	Chamber 3	Mean O <sub>2</sub> ( $\text{mmol m}^{-2} \text{ d}^{-1}$ )
Facies C	Chemical	0.75	0.70	0.85	0.76
	Optode	0.705	0.73	0.81	0.75
Track	Chemical	0.76	0.73	0.71	0.73
	Optode	0.70	0.74	0.75	0.73

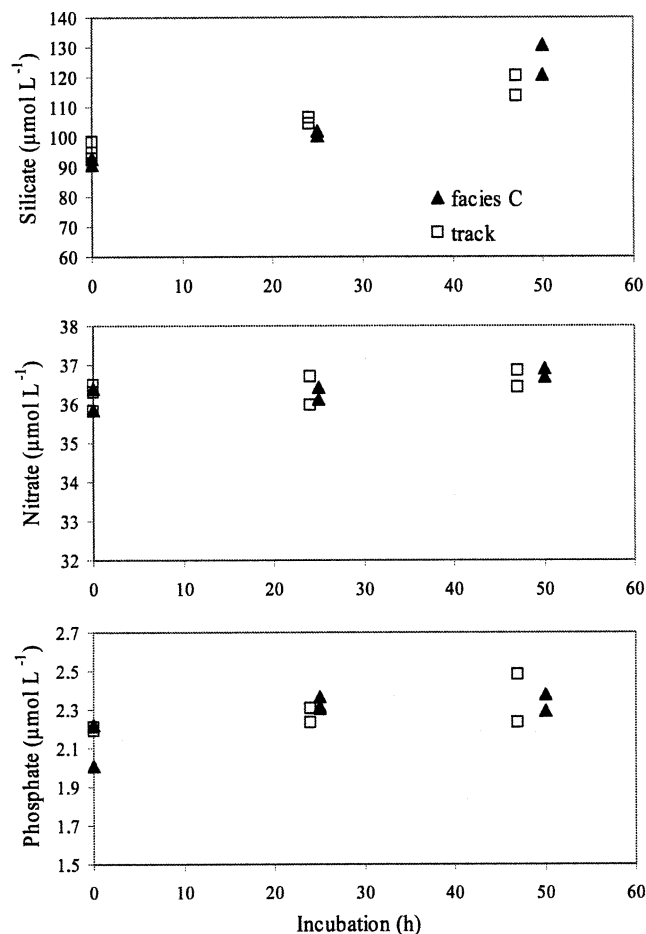


Fig. 8. Variation of nutrient concentration ( $\text{mmol L}^{-1}$ ) during the incubation in facies C and in the track.

In conclusion, our results agree with the evaluation of the environmental consequences of polymetallic-nodule mining proposed by Thiel (2001). The severity of the disturbance, like the change in the superficial sediment and structure, is the major parameter that controls the recolonization of the sediment. The disturbance made by the OMCO consortium dredge appeared weak in comparison with other similar studies because the oxic layer of the sediment was not completely destroyed and the amount of resuspended sediment was low. Whatever sampling tool is used, the sediment surface might be restored only after many years, or even centuries.

## References

- BERELSON, W. M., D. E. HAMMOND, D. O'NEILL, X. XU, C. CHIN, AND J. ZUKIN. 1990. Benthic fluxes and pore water studies from sediments of the central equatorial north Pacific: Nutrient diagenesis. *Geochim. Cosmochim. Acta* **54**: 3001–3012.
- CARRITT, D. E., AND J. H. CARPENTER. 1966. Comparison and evaluation of currently employed modifications of the Winkler method for determining dissolved oxygen in sea water. A NASCO report. *J. Mar. Res.* **24**: 286–318.
- COCHONAT, P., R. LE SUAVÉ, C. CHARLES, B. GREGER, M. HOFFERT, J. P. LENOBLE, J. MEUNIER, AND G. PAUTOT. 1992. First in situ studies of nodule distribution and geotechnical measurements of associated deep-sea clay (Northeastern Pacific Ocean). *Mar. Geol.* **103**: 373–380.
- EL MAGHRAOUI, M., J.-L. JORON, J. ETOUBLEAU, P. CAMBON, AND M. TREUIL. 1998. Determination of forty four major and trace elements in GPMA magmatic rock reference materials using X-ray fluorescence spectrometry (XRF) and instrumental neutron activation analysis (INAA). *Geostandards Newslett.* **23**: 59–68.
- FROELICH, P. N., G. P. KLINKHAMMER, M. L. BENDER, N. A. LUEDTKE, G. R. HEATH, D. CULLEN, P. DAUPHIN, D. HAMMOND, AND OTHERS. 1979. Early diagenesis of organic matter in pelagic sediments of the eastern equatorial Atlantic: Suboxic diagenesis. *Geochim. Cosmochim. Acta* **43**: 1075–1090.
- HAMMOND, D. E., J. MCMANUS, W. M. BERELSON, T. E. KILGORE, AND R. H. POPE. 1996. Early diagenesis of organic material in equatorial Pacific sediments: Stoichiometry and kinetics. *Deep-Sea Res. Part II* **43**: 1365–1412.
- HARADA, K., AND Y. SHIBAMOTO. 1997. Chemical characteristics of sediment in the JET site, p. 303–310. *In* T. Yamazaki, K. Aso, Y. Okano, and K. Tsurusaki [eds.], *Proceedings of International Symposium on Environmental Studies for Deep-Sea Mining*. Tokyo, Japan.
- HEIP, C. H. R., G. DUINEVELD, E. FLACH, G. GRAF, W. HELDER, P. M. J. HERMAN, M. LAVALEYE, J. J. MIDDELBURG, AND OTHERS. 2001. The role of the benthic biota in sedimentary metabolism and sediment-water exchange processes in the Goban Spur area (NE Atlantic). *Deep-Sea Res. II* **48**: 3223–3245.
- JAHNKE, R. A., AND M. B. CHRISTIANSEN. 1989. A free-vehicle benthic chamber instrument for sea floor studies. *Deep-Sea Res.* **36**: 625–637.
- , D. B. CRAVEN, AND J.-F. GAILLARD. 1994. The influence of organic matter diagenesis on  $\text{CaCO}_3$  dissolution at the deep-sea floor. *Geochim. Cosmochim. Acta* **58**: 2799–2809.
- , S. R. EMERSON, J. K. COCHRAN, AND D. J. HIRSCHBERG. 1986. Fine scale distributions of porosity and particulate excess  $^{210}\text{Pb}$ , organic carbon and  $\text{CaCO}_3$  in surface sediments of the deep equatorial Pacific. *Earth Planet. Sci. Lett.* **77**: 59–69.
- JUMARS, P. 1981. Limits in predicting and detecting community responses to manganese nodule mining. *Mar. Min.* **3**: 213–229.
- KÖNIG, I., M. HAECKEL, A. LOUGEAR, E. SUESS, AND A. X. TRAUTWEIN. 2001. A geochemical model of the Peru Basin deep-sea floor—and the response of the system to technical impacts. *Deep-Sea Res. II* **48**: 3737–3756.
- KOTLINSKI, R., AND V. STOYANOVA. 1998. Physical, chemical and geological changes of marine environment caused by the benthic impact experiment at the IOM BIE site, p. 277–281. *In* J. S. Chung, M. Olagnon, C. H. Kim, and W. Koterayama [eds.], *Proceeding of the 8th ISOPE Conference*.
- MÜLLER, P. J. 1977. C:N ratios in Pacific deep-sea sediments: Effect of inorganic ammonium and organic nitrogen compounds sorbed by clays. *Geochim. Cosmochim. Acta* **41**: 765–776.
- PFANNKUCHE, O. 1993. Benthic response to the sedimentation of particulate organic matter at the BIOTRANS station,  $47^\circ\text{N}$ ,  $20^\circ\text{W}$ . *Deep-Sea Res.* **40**: 135–149.
- POPE, R. H., D. J. DEMASTER, C. R. SMITH, AND H. SELTMANN, JR. 1996. Rapid bioturbation in equatorial Pacific sediments: Evidence from excess  $^{234}\text{Th}$  measurements. *Deep-Sea Res. II* **43**: 1339–1364.

- RADZIEJEWSKA, T. 2002. Responses of deep-sea meiobenthic communities to sediment disturbance simulating effects of polymetallic nodule mining. *Int. Rev. Hydrobiol.* **87**: 457–477.
- SANTSCHI, P. H., R. F. ANDERSSON, M. Q. FLEISHER, AND W. BOWLES. 1991. Measurements of diffusive sublayer thickness in the ocean by alabaster dissolution, and their implications for the measurements of benthic fluxes. *J. Geophys. Res.* **96**: 10641–10657.
- SMITH, JR., K. L., R. J. BALDWIN, D. M. KARL, AND A. BOETIUS. 2002. Benthic community responses to pulses in pelagic food supply: North Pacific subtropical gyre. *Deep-Sea Res. I* **49**: 971–990.
- , R. C. GLATTS, R. J. BALDWIN, S. E. BEAULIEU, A. H. UHLMAN, R. C. HORN, AND C. E. REIMERS. 1997. An autonomous, bottom-transecting vehicle for making long time-series measurements of sediment community oxygen consumption to abyssal depths. *Limnol. Oceanogr.* **42**: 1601–1612.
- STRICKLAND, J. D., AND T. R. PARSONS. 1972. A practical handbook of seawater analysis, 2nd ed. Fisheries Research Board of Canada.
- TENGBERG, A., P. HALL, U. ANDERSSON, B. LINDÉN, O. STYRENIUS, G. BOLAND, F. DE BOVEE, B. CARLSSON, AND OTHERS. 2005. Intercalibration of benthic flux chambers II. Hydrodynamic characterization and flux comparisons of 14 different designs. *Mar. Chem.* **94**: 147–173.
- , J. HOVDENES, J. H. ANDERSSON, O. BROCANDEL, R. DIAZ, D. HEBERT, T. ARNERICH, C. HUBER, A. KÖRTZINGER, AND OTHERS. 2006. Evaluation of a lifetime-based optode to measure oxygen in aquatic systems. *Limnol. Oceanogr. Methods* **4**: 7–17.
- THIEL, H. 2001. Evaluation of the environmental consequences of polymetallic nodule mining based on the results of the TUSCH Research Association. *Deep-Sea Res. II* **48**: 3433–3452.
- TRUEBLOOD, D. D., AND E. OZTURGUT. 1997. The benthic impact experiment: A study of the ecological impacts of deep seabed mining on abyssal benthic communities, p. 481–487. *In* J. S. Chung, B. M. Das, T. Matsui, and H. Tiel [eds.], *Proceedings of the 7th ISOPE Conference*. Honolulu, Hawaii.
- WEBER, M. E., U. VON STACKELBERG, V. MARCHIG, M. WIEDICKE, AND B. GRUPE. 2000. Variability of surface sediments in the Peru Basin: Dependence on water depth, productivity, bottom water flow and seafloor topography. *Mar. Geol.* **163**: 169–184.
- YAMASAKI, T., AND Y. KAJITANI. 1999. Deep-sea environment and impact experiment to it, p. 374–381. *In* J. S. Chung, T. Matsui, and W. Koterayama [eds.], *Ninth International Offshore and Polar Engineering Conference*. Tokyo, Japan.

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