A biogeochemical survey of the anoxic basin Golfo Dulce, Costa Rica

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Abstract: The waters and surface sediments of a 200 m deep tropical fjord were investigated with respect to chemical zonation, rates of respiratory processes, and benthic fluxes. Oxygen was found to ca. 100 m water depth, but only the upper part of the oxycline was associated with the pycnocline, which was situated above the sill located at 60 m. Nitrate-rich water entered the bay at sill depth, and denitrification was indicated at anoxic depths. Hydrogen sulfide was only found in low concentrations near the bottom, and nitrate was a possible oxidant for the hydrogen sulfide. The observations reproduced those of a survey in 1969 to a large extent. This suggests that water exchange is frequent enough to prevent the development of strongly reducing conditions in the bottom water. High rates of dark oxygen uptake indicated intense carbon cycling within the euphotic zone. The rates decreased rapidly with depth, and at anoxic depths, rates of denitrification and sulfate reduction were more than 100-fold lower than the surface oxygen uptake. The chemical zonation as well as x-radiographs indicated that sediments underlying oxic bottom water were strongly irrigated and bioturbated while anoxic sediments were laminated and composed of turbidites. The rates of carbon oxidation were 5-10 times higher in the sediments underlying oxic bottom water than in those at the bottom of the basin. Sulfate reduction was a dominating process, accounting for about 50% and 100% of the carbon oxidation at the oxic and anoxic sites respectively. Even at the anoxic sites, hydrogen sulfide did not accumulate in the pore water and a high sedimentation of reactive iron phases is suggested as a contributing cause.

Key words: Water column, sediment, microbial processes, carbon cycling, denitrification, sulfate reduction.

The supply of oxygen to the oceanic water masses is generally large enough to prevent degradative processes from causing the development of anoxia, but permanently anoxic waters are found in a number of basins with restricted circulation. The vertical chemical zonation of anoxic water columns provides a basis for general studies of chemical and microbiological processes under different redox conditions, and at redox boundaries such as the oxic/anoxic interface. Both the temporal stability of the zonation, and its extension over depth scales of decimetres or metres, facilitates such investigations in comparison to studies of the analogous redox zonation in sediments, that is restricted to millimetres or centimetres. Many biogeochemical studies have been carried out in anoxic basins at temperate latitudes such as the Black Sea, Framvaren Fjord, Norway, and Saanich Inlet, British Columbia (e.g. Richards 1965, Skei 1988, Murray et al. 1989).

In the absence of oxygen, the bacterial degradation of organic matter reduces the alternative oxidants nitrate, oxides of manganese and iron, and sulfate, releasing dissolved inorganic carbon, nutrients, and inorganic metabolites according to the general reaction (e.g. Froehlich et al. 1979):

$$\text{Organic matter} + \text{NO}_3^- / \text{MnO}_2 / \text{FeOOH} / \text{SO}_4^{2-} \rightarrow$$
$$\text{CO}_2 + \text{NH}_4^+ + \text{PO}_4^{3-} + \text{N}_2 / \text{Mn}^{2+} / \text{Fe}^{2+} / \text{H}_2\text{S}.$$
oxic/anoxic interface due to low inputs, and sulfate reduction dominates in the anoxic bottom water leading to the build-up of hydrogen sulfide (e.g., Lewis and Landing 1991). A main characteristic of anoxic basins is, thus, the $O_2/H_2S$ interface (Anderson and Devol 1987).

Golfo Dulce is one of only five anoxic basins described from the tropics. The others are the Cariaco Trench and Golfo de Cariaco, Venezuela, Kau Bay, Indonesia, and Darwin Bay, Galapagos Islands (Richards 1960, Richards and Broenkow 1971, Middelburg et al. 1988). The hydrography of Golfo Dulce was first described by Richards et al. (1971) based on two visits in March 1969. At that time, a pycnocline was centred well above the sill-depth of ca. 60 m and $O_2$ was found to about 150 m in the 200 m deep basin. The bottom water was sulfidic but the $H_2S$ concentration only reached a few $\mu$mol L$^{-1}$. Based on a rise in the pycnocline, and changes in water column chemistry in the bay between the two visits, Richards and coworkers (1971) suggested that the basin was maintained at a relatively oxidized state through frequent flushing associated with upwelling events along the Pacific coast (see also Anderson and Devol 1987).

A brief description of the sediments has been given by Nichols-Driscoll (1976) who studied the faunal distribution in relation to bottom water $O_2$ concentrations. She found an organic carbon content of about 2% throughout the basin and observed large leaves and coconuts on the sediment surface of the inner basin. Infauna was found to 100 m depth which corresponded to approx. 40 $\mu$mol L$^{-1} O_2$ in the bottom water.

We here summarize the results of the biogeochemical investigations carried out during the second leg of the Costa Rica Expedition of RV Victor Hensen, January 1994. In view of the limited information published on the basin, the study was designed as a general biogeochemical survey. We focused on the degradative part of the carbon cycle, identifying and quantifying pathways of carbon mineralization in relation to the chemical zonation of the water column and sediments. In a parallel study, microbiological and molecular ecological analyses of the bacterial community were performed which are presented in a separate paper (Kuever et al. 1996). The investigations included:
- a description of the physical and chemical zonation of the water column through the bay
- direct determination of aerobic and anaerobic planktonic respiration rates
- analysis of the chemical zonation in the sediment pore waters and solids along a transect from oxic to anoxic bottom water
- quantification of rates of carbon mineralization in the sediments and of the rates of solute exchange between sediments and water column.

**MATERIAL AND METHODS**

**Stations:** Sampling took place 6 - 12 January 1994 at the positions given in Table 1. The hydrographical survey was carried out along the central axis of the bay with CTD casts at all stations and water-column chemistry at stations GD1, 2, 3, 89, 11, and 12 (Fig. 1; stations of Nichols-Driscoll 1976). Rates of respiration were measured in the water column at station GD1. Sediments were studied along a transect perpendicular to the coast from GD30 to GD1.

**TABLE I**

<table>
<thead>
<tr>
<th>Station</th>
<th>Position</th>
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<tbody>
<tr>
<td>GD1</td>
<td>8°41.7'N 83°23.7'W</td>
<td>205</td>
</tr>
<tr>
<td>GD9a</td>
<td>8°40.0'N 83°21.9'W</td>
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</tr>
<tr>
<td>GD2</td>
<td>8°36.6'N 83°18.0'W</td>
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<tr>
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<td>200</td>
</tr>
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<tr>
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<td>8°31.5'N 83°13.0'W</td>
<td>101</td>
</tr>
<tr>
<td>GD11</td>
<td>8°27.2'N 83°13.0'W</td>
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<tr>
<td>GD11a</td>
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<td>205</td>
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<tr>
<td>GD30</td>
<td>8°39.0'N 83°25.5'W</td>
<td>53</td>
</tr>
<tr>
<td>GD9</td>
<td>8°39.9'N 83°25.1'W</td>
<td>196</td>
</tr>
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</table>

**Water column:** Salinity and temperature were measured with a CTD (ME-Meerechnik-Elektronik, Kiel, Germany). Light was measured at 10 m intervals from the surface with a spherical quantum sensor (Licor, Lincoln, Nebraska). Water samples were obtained in 5 L Go-Flo and Niskin bottles and expressed anoxically by applying a slight $N_2$ overpressure. For $O_2$ determinations, water was subsampled in Winkler-bottles under a $N_2$ atmosphere and analyzed by the Winkler method using reagents degassed with $N_2$. For samples from the deep, expectedly anoxic and sulfidic zone, the method of Ingvorsen and Jørgensen (1979) was used.
Samples for NO$_3^-$ + NO$_2^-$ and NH$_4^+$ were stored frozen and analyzed with an autoanalyzer (APHA 1992). As NO$_2$ concentrations were expected to be negligible compared to NO$_3^-$, the NO$_3^-$ + NO$_2^-$ measurements will be referred to as NO$_3^-$(see also Córdoba and Vargas 1996). Samples for H$_2$S were preserved with Zn$^{2+}$ and analyzed with the methylene blue technique (Cline 1969). For analysis of dissolved and particulate Mn and Fe, water was filtered through N$_2$-flushed glassfiber filters (Whatman GF/F) and the filtrate was immediately acidified. Particulate Mn and Fe on the filters was extracted by dithionite-citrate-acetic acid extraction (Lord 1980). Manganese in filtrates and extracts was analyzed by flame atomic absorption spectroscopy (Perkin Elmer, Norwalk, Connecticut), and Fe was analyzed spectrophotometrically with Ferrozine (Stookey 1970). Phosphate was analyzed in the filtered, acidified samples by the phosphomolybdate blue method (APHA 1992).

Oxygen consumption was measured on water collected at 20 m intervals from the surface by incubation in Winkler bottles in the dark at in situ temperature. Incubation time was 12 h at 1 and 20 m and otherwise 24 or 36 h. Denitrification was measured in similar incubations of samples taken at 20 m intervals from 60 m depth. Quantification was by the isotope pairing technique with addition of $^{15}$NO$_3^-$ and mass spectrometric analysis of the N$_2$ produced (Nielsen 1992). The detection limit was estimated from the standard deviation of the mass spectrometric analyses of blanks. Likewise, SO$_4^{2-}$ reduction was measured by addition of $^{35}$SO$_4^{2-}$ to the water samples from 200 and 205 m depth with 6 h incubation (Jørgensen 1978, Jørgensen et al. 1991). The production of reduced $^{35}$S was quantified with the acidic Cr$^{3+}$distillation method (Fossing and Jørgensen 1989) and SO$_4^{2-}$ was determined by non-suppressed anion chromatography (Fossing and Jørgensen 1990). The detection limit for SO$_4^{2-}$ reduction was estimated from the background of the scintillation counting procedure.

**Sediments:** Sediments were obtained with a 50 x 50 cm box corer using only those deployments where the sediment surface appeared undisturbed. The box cores were subcored into acrylic tubes. For flux determinations and O$_2$ microelectrode measurements, cores were incubated with bottom water at in situ temperature and O$_2$ concentration, as described by Rasmussen and Jørgensen (1992). Fluxes were determined from concentration changes in the overlying water during incubations of 4 - 6 h at GD30 and GD9, and 28 h at GD1. The same setup was used for determination of denitrification rates, that were quantified by the isotope pairing technique (Nielsen 1992). Fine-scale profiles of pore-water NO$_3^-$ were obtained by whole-core squeezing (Bender et al. 1987) with quantification by reduction to NO$_3^-$ with spongy cadmium and spectrophotometric detection (Jones 1984).

Rates of $\Sigma$CO$_2$ and NH$_4^+$ production as well as SO$_4^{2-}$ reduction were determined as described by Canfield et al. (1993a). In brief, sediment was sectioned in discrete depth intervals and incubated anoxically at in situ temperature in gas tight plastic bags. The sediment was sampled under N$_2$ five times during an incubation of approx. 30 h, and pore water for $\Sigma$CO$_2$, NH$_4^+$, Mn$^{2+}$, Fe$^{2+}$, H$_2$S, and SO$_4^{2-}$ analysis was obtained by centrifugation. The initial $T_0$ sample from the incubations provided our initial pore water and solid phase data. Rates of SO$_4^{2-}$ reduction were determined in subsamples twice during the incubations using $^{35}$SO$_4^{2-}$ with quantification as in the water-column samples.

Additional pore-water distributions of $\Sigma$CO$_2$ and NH$_4^+$ to 30 cm depth were obtained by sectioning and centrifugation of a separate core. Rates of SO$_4^{2-}$ reduction were also deter-
mined in intact sediment cores by the whole-core $^{35}\text{SO}_2^-\text{O}_4$ injection method (Jørgensen 1978).

In the pore waters, $\Sigma\text{CO}_2$ and $\text{NH}_4^+$ were determined by flow injection analysis with gas exchange and conductivity detection (Hall and Aller 1992), with rates of accumulation during the bag incubations determined by linear regression. Organic C and total N in the sediments were determined on an elemental analyzer (Carlo Erba). Particulate Mn oxides were extracted as described for the water column and, additionally, poorly crystalline Fe(III) and easily extractable Fe(II) were extracted with an oxalate extraction assay (Canfield et al. 1993a). Pore waters $\text{SO}_2^-\text{O}_4$, $\text{H}_2\text{S}$, $\text{Mn}^{2+}$, $\text{Fe}^{2+}$, and Mn and Fe in extracts were analyzed as in the water column. X-radiographs were obtained of sediment sampled in 3.5 x 30 cm acrylic boxes, 20 cm high using 2 min exposure at 80 kV and 2 mA.

RESULTS

Hydrography: The hydrographical survey along the central axis of the bay revealed steep gradients in both temperature and salinity below a shallow mixed surface layer, to about 60 m depth (Fig. 2). At station GD12 outside the bay, the pycnocline was centered at 40 - 50 m, roughly 10 - 20 m above the sill depth of 60 m, and the isopycnic surfaces were tilted slightly, rising about 10 m through the bay from GD12 to station GD1 at the head. Below the pycnocline at GD12, the potential density anomaly, $\sigma_t$, increased from 25.33 at 80 m to 26.52 at 200 m, whereas it only increased to 25.88 inside the basin. Thus, from 80 m, the water outside the bay was denser than the basin water at the same depth. The bottom water in the basin was only about 0.05% less saline and 1 °C warmer than in March 1969 (Richards et al. 1971).

The photic zone extended to 30 - 40 m depth, determined as the depth where the incoming light was attenuated to 1% of the surface value at both GD1 and GD3. Surface $\text{O}_2$ concentrations were 190 - 200 μmol L$^{-1}$ (9 - 11 AM) and a strong oxycline was associated with the pycnocline at all stations (Fig. 2). Outside the bay, the $\text{O}_2$ concentration dropped to 25 μmol L$^{-1}$ at 200 m, but inside, $\text{O}_2$ was not detectable (< 3 μmol L$^{-1}$) below 100 m depth. Parallel to the decrease in $\text{O}_2$, $\text{NO}_3^-$ increased at GD12 reaching 30 μmol L$^{-1}$ at 200 m (Fig. 2). In the Golfo Dulce basin (GD1 - 3), however, $\text{NO}_3^-$ increased with depth from the deple-

Fig. 2. Physical and chemical data from the water column at the head (GD1, 7 January 1994) and mouth (GD12, 9 January 1994) of Golfo Dulce. Far left: CTD data, fat lines GD1, thin lines GD12. Center left: Oxygen concentrations at GD1 and GD12. Center right: Nitrate-nitrite concentrations at GD1 and GD12, and soluble reactive P at GD1 (note separate scale). Far right: Dissolved and particulate Mn at GD1 (note separate scales).
Sediments were investigated near the head of the bay along a peninsula. Close to the shore, the sediment contained much coarse sand, pebbles, and shell and coral debris, and the station GD30 at 42 m was chosen as the shallowest site with a fine-grained texture suitable for our incubation techniques. The sediment there was silty with some sand and gravel-sized particles, and the bottom water contained 54 μmol O₂ L⁻¹. Live snails were observed at the surface, and burrows evidenced the activity of infauna. The sediment at the slightly deeper GD9, with 22 μmol O₂ L⁻¹ in the bottom water, appeared similar to GD30. Burrows were present, but no living organisms were observed. At the anoxic GD160, a 1 - 2 cm thick brown-black fluff-layer covered the very fine-grained sediment. At the surface, 0.5 cm long bacterial filaments of the genus Beggiatoa were observed. Immediately below the fluff, the sediment was black, and below this, there was a sequence of horizons varying in color between light brown and black, and in thicknesses of 1 - 5 cm. Around 17 cm depth a prominent pink layer was observed. The sediment at the deepest station GD1 was covered by 2 - 4 cm fluff. Apart from one black band below the fluff layer and another about 15 cm depth, the sediment here was light brown. At all stations, pieces of coconuts, large leaves, and wood could be found both on and within the sediments.

Observations of sediment structure were corroborated by x-radiographs of the sediments (Fig. 3). Whereas the sediments at GD30 and GD9 (not shown) appeared uniformly mixed and contained worm burrows in the upper 5 cm, the differently colored horizons observed at GD160 were paralleled by changes in sediment density revealed by the x-radiographs. Below the fluff at GD1, a 12 cm thick layer was observed, with only slight laminations but grading from low to high density from top to bottom. At the base of this, a very dense, approx. 1 cm thick layer followed, abruptly succeeded by a more x-ray-transparent zone similar to that near the sediment surface. This observation is in good agreement with the results from long cores, which showed that the basin floor is comprised of a series of turbidites, each grading from fines at the top to a sand horizon at the bottom (Hebbeln 1994). From the x-radiographs the youngest turbidite is estimated to be about 13 cm thick, not including the surface fluff. It seems probable that the visible black band at 15 cm depth is a relict from the previous surface similar to the black band observed under the fluff layer, and that the thinner graded laminations on the slope station GD160 may represent a sequence of turbidite depositions of which the bulk deposited at the bottom of the basin.

Sediments, physical characteristics: Sediments were investigated near the head of the bay along a SW - NE transect from the Osa peninsula. Close to the shore, the sediment contained much coarse sand, pebbles, and shell and coral debris, and the station GD30 at 42 m was chosen as the shallowest site with a fine-grained texture suitable for our incubation techniques. The sediment there was silty with some sand and gravel-sized particles, and the bottom water contained 54 μmol O₂ L⁻¹. Live snails were observed at the surface, and burrows evidenced the activity of infauna. The sediment at the slightly deeper GD9, with 22 μmol O₂ L⁻¹ in the bottom water, appeared similar to GD30. Burrows were present, but no living organisms were observed. At the anoxic GD160, a 1 - 2 cm thick brown-black fluff-layer covered the very fine-grained sediment. At the surface, 0.5 cm long bacterial filaments of the genus Beggiatoa were observed. Immediately below the fluff, the sediment was black, and below this, there was a sequence of horizons varying in color between light brown and black, and in thicknesses of 1 - 5 cm. Around 17 cm depth a prominent pink layer was observed. The sediment at the deepest station GD1 was covered by 2 - 4 cm fluff. Apart from one black band below the fluff layer and another about 15 cm depth, the sediment here was light brown. At all stations, pieces of coconuts, large leaves, and wood could be found both on and within the sediments.

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Sediment chemistry: At both GD30 and GD9, the organic carbon content was about 2.4 % by
Fig. 3. Representative sections of sediment x-radiographs. Darker areas represent higher x-ray transparency, i.e. zones of higher porosity. P: plant debris (tentative identification); C: crack in the sediment surface created during coring; T: worm burrows; S: shell debris. The contrast of the images has been digitally enhanced after recording.

weight and varied little with depth to 15 cm, whereas at GD1, $C_{org}$ decreased from 2.8% in the fluff layer to 1.9% below (Fig. 4). Due to the strong decrease in porosity from the fluff layer to the sediment below at GD1, however, the volume-based $C_{org}$ content actually increased with depth from 0.35 to 0.65 mmol cm$^{-2}$ between 0 - 0.5 and 8 - 10 cm. Similarly, the total $C_{org}$ pool from 0 - 10 cm depth was 55, 128, and 124 mol m$^{-2}$ at GD1, -9, and -30, respectively. The lowest $C_{org}$/N ratio (mole/mole) was observed at GD1, where it increased from 9.2 at the surface to 13.0 at 8 - 10 cm (Fig. 4). At both GD9 and GD30 the $N$ content decreased markedly with depth leading to increases in $C_{org}$/N from 11-13 near the sediment surface to 15-18 at 8-10 cm depth.

The mineralization of organic matter in the sediments led to a build-up of $\Sigma$CO$_2$ (= H$_2$CO$_3$ + HCO$_3$ + CO$_3^{2-}$) and NH$_4^+$ in the pore waters (Fig. 5). Whereas the concentration profiles at GD1 were convex up reaching high values already near the sediment surface, the distributions at both GD9 and GD30 were concave up with steeper gradients below 10 cm. Also with respect to other aspects of pore-water and solid-phase chemistry stations GD30 and GD9 were quite similar, and hence, only results from GD30 are shown below.

To examine which electron acceptors were available for the oxidation of organic matter, the distribution of the possible oxidants, $O_2$, NO$_3^-$, Mn and Fe oxides, and SO$_4^{2-}$ was determined. Microelectrode measurements showed that $O_2$ was only available in the upper 1 - 2 mm at both GD30 (Fig. 6) and GD9, and the whole-core squeezing indicated that NO$_3^-$ was only present to 5 mm depth or less in the sediment pore water (data not shown). Chemical extractions revealed an enrichment of reactive manganese oxides in the upper 5 mm at these stations (Fig. 6; ct. Aller 1994). At GD1, Mn levels were high and stable with depth (approx. 10 $\mu$mol g$^{-1}$) and most likely represented an unreactive Mn phase as no surface maximum could be discerned. In agreement with these observations, Mn reduction in the upper 1 - 2 cm was indicated by Mn$^{2+}$ maxima at 0 - 0.5 cm depth in the pore waters of GD30 (Fig. 6) and GD9. Conversely, at GD1 pore water Mn$^{2+}$ was stable around 30 $\mu$mol L$^{-1}$, which, together with the bottom water level of 8 $\mu$mol
water concentration of SO$_4^{2-}$ decreased with depth from the bottom water level of 28 mmol L$^{-1}$, reaching 26.0, 24.2, and 8.8 mmol L$^{-1}$ at 30 cm depth at GD30, -9, and -1, respectively. Hydrogen sulfide was only detected in the pore water at GD1, where a small peak of < 10 μmol L$^{-1}$ was observed in the fluff layer (data not shown).

**Benthic fluxes and mineralization rates:** The benthic fluxes of ΣCO$_2$, NH$_4^+$, O$_2$, and NO$_3^-$ measured in our whole-core sediment incubations are given in Table 2. The fluxes of ΣCO$_2$ from the shallow oxic sediments were similar, and 10 times larger than that from the anoxic GD1. The NH$_4^+$ fluxes were small compared to ΣCO$_2$ with C/N mole/mole ratios of 22 and 49 at GD30 and GD9, respectively. The O$_2$ uptake was similar at GD30 and GD9 averaging about 50% of the ΣCO$_2$ efflux, whereas the NO$_3^-$ uptakes were quite small.

The rates of ΣCO$_2$ accumulation in the upper 10 cm of the sediment determined by incubation of sediment after sectioning into discrete depth intervals were about twice the ΣCO$_2$ fluxes from the sediments, but showed a similar decrease from the oxic stations to GD1 as did the benthic fluxes (Table 2). The depth integrated rates of NH$_4^+$ accumulation in the pore water were much higher than the NH$_4^+$ fluxes, and the ratio with which ΣCO$_2$ and NH$_4^+$ accumulated in the incubations was close to 10 at all stations and hence similar to the C$_{org}$/N ratio of the sediments (Fig. 4). Ammonia adsorbs onto sediment particles (Rosenfeld 1979), however, and the measured rates of NH$_4^+$ accumulation, thus, underestimate the actual rates of NH$_4^+$ production from the decomposition of organic matter. Assuming that the adsorption coefficient for NH$_4^+$ in Golfo Dulce sediments was in the range reported from other marine sediments (Mackin and Aller 1984) the rates of NH$_4^+$ production were roughly twice the measured accumulation rates, and the production ratio of ΣCO$_2$ to NH$_4^+$ was accordingly about 5 (assuming no precipitation of ΣCO$_2$; see also Canfield et al. 1993a). Similar values have been reported for mineralization of young organic matter in other coastal marine sediments (e.g., 4 - 6, Kristensen and Blackburn 1987).

Bacterial sulfate reduction was an important pathway of carbon mineralization at all sta-
Fig. 6. Pore-water and solid-phase analyses from Station GD30. Left: Typical O$_2$ microprofile. Middle: Pore-water Mn$^{2+}$ and Fe$^{2+}$. Right: Extractable, poorly crystalline Fe(III), extractable Fe(II), and extractable Mn (note separate scales).

### TABLE 2

<table>
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<tr>
<th></th>
<th>GD30</th>
<th>GD9</th>
<th>GD160</th>
<th>GD1</th>
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<td><strong>Benthic fluxes</strong></td>
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<td>$\Sigma$CO$_2$</td>
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<td>18 $\pm$ 9</td>
<td>n.m.</td>
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<td>NH$_4^+$</td>
<td>0.82 $\pm$ 0.02</td>
<td>0.44 $\pm$ 0.02</td>
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<td>O$_2$</td>
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<td>NO$_3^-$</td>
<td>-0.12 $\pm$ 0.03</td>
<td>-0.60 $\pm$ 0.05</td>
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<td><strong>Rates 0 - 10 cm</strong></td>
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<td>30</td>
<td>38</td>
<td>n.m.</td>
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<td>NH$_4^+$ accumulation</td>
<td>3.1</td>
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<td>n.m.</td>
<td>0.48</td>
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<td>n.m.</td>
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<td>SO$_4^{2-}$ reduction, whole cores</td>
<td>n.m.</td>
<td>4.8</td>
<td>2.4</td>
<td>6.0</td>
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<td>$\Sigma$CO$_2$ production from SO$_4^{2-}$ red., bag incub.</td>
<td>14.0</td>
<td>20</td>
<td>n.m.</td>
<td>9.6</td>
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<td>Denitrification</td>
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<td>0.43 $\pm$ 0.07</td>
<td>n.m.</td>
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*Mean ± SE of 2 - 6 determinations
n.m.: Not measured
DISCUSSION

The hydrographic survey of Golfo Dulce reproduced the observations from the first survey by Richards and coworkers (1971) to a large extent. The centering of the pycnocline above the sill depth and the weak stratification of the waters below facilitates the exchange of water between the basin and the Pacific Ocean. The poor stratification of the sub-sill waters is similar to the other known tropical anoxic basins (Richards 1960, Richards and Broenkow 1971, Middelburg et al. 1988). Water of the same potential density as the densest water in the basin was found at 110 - 120 m depth outside the sill. This situation is similar to the first of the two transects sampled by Richards et al. (1971) in March 1969. In a second transect one week later, they observed a 35 m rise in the pycnocline outside the bay (at GD12) lifting water of similar density as the bottom water to a depth of only 70 - 80 m, i.e., close to the sill depth. Simultaneously, they measured chemical changes in the basin to 160 m depth, which were attributed to the introduction of new O2-poor, NO3-rich water over the sill. Seasonal upwelling was suggested as a driving force in the flushing of Golfo Dulce which maintains it in an intermediate stage between oxic and strongly sulfidic conditions.

Although 26 years had passed since the visit of Richards and coworkers (1971), the water column chemistry showed only minor differences from those reported then. Whether this reflects true stability, implying a steady rate of change over the sill, or the similarity was coincidental, can only be determined through a seasonal study.

Richards and coworkers (1971) found that NO3 disappeared at the same depth as, or even slightly above O2 (around 150 m) and inferred that denitrification took place under oxic conditions. In the present study, the depths at which the two oxidants were depleted were clearly separated with anoxia already from 100 m depth and NO3 reaching close to the bottom (Fig. 2). Hence, in the present survey, part of the denitrification occurred under anoxic conditions, either in the water column or in the contacting sediments. Still, the decrease in NO3 concentration in the oxic zone below the pycnocline from the mouth to the head of the bay could be due to denitrification at low O2 levels.
(Fig. 2). The depletion of NO$_3^-$ over the anoxic zone at GD1 could be explained by oxidation of typical organic matter by denitrification according to the equation (Richards 1965):

$$
(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}\text{H}_3\text{PO}_4 + 84.8\text{NO}_3^-
= 106\text{HCO}_3^- + 16\text{NH}_4^+ + \text{HPO}_4^{2-} + 42.4\text{N}_2 + 7.2\text{H}^+
+ 42.4\text{H}_2\text{O}.
$$

(2)

With a decrease in NO$_3^-$ of 5 µmol L$^{-1}$, the predicted increases in PO$_4^{3-}$ (0.06 µmol L$^{-1}$) and NH$_4^+$ (0.9 µmol L$^{-1}$) would not be detectable.

Manganese had not previously been measured in Golfo Dulce, and we found a significant accumulation of dissolved Mn$_2^+$ in the anoxic portion of the water column (Fig. 2). Reduced Mn$_2^+$ is formed by reduction of Mn oxides either in abiotic reactions with, e.g., H$_2$S or Fe$_2^+$, or by dissimilatory bacterial reduction coupled to oxidation of organic matter (Canfield et al. 1993a, Aller 1994). The reduction of Mn could occur as Mn oxide particles sink through the water column, but the Mn$_2^+$ distribution could also be due to a flux from the sediment as predicted by the pore-water distribution of Mn$_{diss}$. Dissimilatory Mn reduction is associated with a release of $\Sigma$CO$_2$ and inorganic nutrients:

$$
(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}\text{H}_3\text{PO}_4 + 212\text{MnO}_2 + 332\text{H}^+
= 106\text{HCO}_3^- + 16\text{NH}_4^+ + \text{HPO}_4^{2-} + 212\text{Mn}^2^+ + 212\text{H}_2\text{O}.
$$

(3)

The accumulation of 8 µmol L$^{-1}$ Mn$_2^+$ at the bottom of the basin is thus equivalent to a slightly smaller carbon mineralization, and associated release of NH$_4^+$ (8/212*16 = 0.6 µmol L$^{-1}$) and PO$_4^{3-}$ to the water column, than that calculated for denitrification.

The depth distribution of Mn$_2^+$ suggested that it was oxidized by O$_2$ and this was supported by a peak of particulate Mn oxides just below theoxic/anoxic interface. In agreement with the findings of Froehlich et al. (1979) in hemipelagic sediments, there were no indications of Mn$_2^+$ oxidation by NO$_3^-$. The Mn oxidation was most likely bacterially catalyzed as this is generally the case in aquatic environments (cf. Thamdrup et al. 1994b). This mode of reaction$^1$ was also suggested for a similar maximum of suspended Mn oxides found at theoxic/anoxic interface in Kau Bay, Indonesia (Middelburg et al. 1988).

Richards and coworkers found low but significant levels of H$_2$S (> 1 µmol L$^{-1}$) below 180 m throughout the basin, whereas we only found such concentrations at GD1 and, more significantly, only at one of two dates. The general absence of H$_2$S as well as the undetectable levels of SO$_4^{2-}$ reduction in the bottom water were in agreement with the deeper penetration of NO$_3^-$ which could both be preferred to SO$_4^{2-}$ as electron acceptor by heterotrophic bacteria, and could serve as an oxidant for any H$_2$S formed (e.g.; Sørensen 1987). Also the PO$_4^{3-}$ concentrations (Fig. 2) were considerably lower than the 3.8 µmol L$^{-1}$ maximum reported from 1969 which is another indication that the bottom water had not developed as far towards reduced conditions as during the 1969 survey. The drop in H$_2$S concentration near the sediment over a week may be explained as the dispersion or oxidation of a local H$_2$S plume which could have developed over a small area with particularly high rates of SO$_4^{2-}$ reduction at the sediment surface. Thus, the maximum bottom-water concentration of 7 µmol L$^{-1}$ was higher than any of the pore water analyses. Conspicuous sulfide-oxidizing bacteria, that might oxidize H$_2$S with NO$_3^-$ were observed in the bottom water (Kuever et al. 1996).

In the traditional description of anoxic marine basins, the existence of a chemocline is assumed where opposed gradients of O$_2$ and H$_2$S meet (Anderson and Devol 1987). The existence in Golfo Dulce of a 100 m deep suboxic (i.e. anoxic and H$_2$S-free; Froehlich et al. 1979) zone containing NO$_3^-$ is paralleled only by the small Darwin Bay in the Galapagos Islands where a similar zonation was found in 1969 (Richards and Broenkow 1971). Both bays are situated in upwelling regions and can thus receive water low in O$_2$ and high in NO$_3^-$. Transient separation of O$_2$ and H$_2$S zones, possibly due to the injection of an intermediate water mass, has been observed in other anoxic basins such as the Black Sea (Murray et al. 1989, Jørgensen et al. 1991). Since a suboxic zone was not identified during the first investigations of Golfo Dulce (Richards et al. 1971), the stability of this phenomenon still needs to be assessed.
The maximum planktonic O\textsubscript{2} respiration rate of 64 \textmu mol L\textsuperscript{-1} d\textsuperscript{-1} measured at the surface was high compared to rates measured in temperate regions which typically have maxima of 10 - 20 \textmu mol L\textsuperscript{-1} d\textsuperscript{-1} (Williams 1984, Kruse 1993). The high rates near the water surface suggested a high degree of internal cycling of carbon in the warm and calm photic zone. Although denitrification was not detectable, a small contribution from this process was still possible when integrating over the entire water column. Richards and coworkers (1971) attributed a NO\textsubscript{3} maximum < 1 \textmu mol L\textsuperscript{-1} near the bottom of the oxic zone to active denitrification but we did not separately analyze NO\textsubscript{2}.

As denitrification and SO\textsubscript{4}\textsuperscript{2-} reduction rates were not detectable in the anoxic water column, we can not accurately determine a turnover time for the bottom water. Division of the mean NO\textsubscript{3} concentration in the anoxic water column (2 \textmu mol L\textsuperscript{-1}; Fig. 2) by the detection limit of the denitrification rate determinations (0.08 \textmu mol L\textsuperscript{-1} d\textsuperscript{-1}) yields a minimum depletion time of 25 days. Thus, disregarding benthic denitrification, the observed NO\textsubscript{3} levels could be maintained with bottom water exchange on the order of once per month.

**Sediments:** The organic carbon contents of the sediments showed only small variations between the stations and were similar to those reported earlier from Golfo Dulce (Nichols-Driscol 1976). The C\textsubscript{org}/N ratios were relatively high but also similar to the earlier report. The high ratios could be due to the input of terrestrial organic matter with a high content of structural N-poor material, such as the leaves and coconut parts observed in the sediments.

The chemical zonation of the sediments at GD30 and GD9 followed the pattern known from coastal sediments at higher latitudes (e.g., Canfield et al. 1993b) with a successive depletion of the oxidants for organic matter in the order O\textsubscript{2} > NO\textsubscript{3} > MnO\textsubscript{2} > FeOOH > SO\textsubscript{4}\textsuperscript{2-}. This sequence represents a decreasing energy yield from carbon oxidation (Froehlich et al. 1979), and is established in part through microbial interactions, where bacteria utilizing energetically more favorable electron acceptors may outcompete other bacterial groups for common substrates (e.g., Lovley and Goodwin 1988). In many marine sediments, however, the competitive exclusion is only partial, and, e.g., SO\textsubscript{4}\textsuperscript{2-} reduction has been demonstrated within the oxic zone and within the zone of dissimilatory Fe reduction (Jørgensen and Bak 1991, Canfield and Des Marais 1991, Canfield et al. 1993a). It therefore appears that the redox zonation is just as much maintained through a chain of abiotic or microbially catalyzed oxidations that consume the reduced inorganic mineralization products Mn\textsuperscript{2+}, Fe\textsuperscript{2+}, and H\textsubscript{2}S (Canfield et al. 1993a, Aller 1994). Thus, for example the Fe reduction indicated at 1 - 2 cm depth at GD9 and -30 (Fig. 6) could both represent dissimilatory reduction by heterotrophic bacteria or a reduction coupled to reoxidation of reduced sulfur species.

The benthic rates of two of the pathways of C oxidation, denitrification and SO\textsubscript{4}\textsuperscript{2-} reduction, could be directly determined (Table 2). In view of the relatively high NO\textsubscript{3} concentrations in the bottom water at GD30 and GD9, the rates of denitrification were low compared to other reports from continental margin sediments (e.g. Devol and Christensen 1993). Also when compared to the other rates in Table 2, denitrification contributed little to carbon mineralization at these sites. Bacterial sulfate reduction, on the other hand, proved to be significant at all stations explaining about 50% of the \(\Sigma\text{CO}_2\) accumulation at GD30 and GD9 and all at GD1. This is in good agreement with other coastal sediments with oxic bottom water where SO\textsubscript{4}\textsuperscript{2-} reduction typically accounts for 50% of C mineralization (Jørgensen 1982). The complete dominance of SO\textsubscript{4}\textsuperscript{2-} reduction at GD1 was expected as O\textsubscript{2} was absent, NO\textsubscript{3} was virtually so, and the Mn and Fe pools only indicated slight Mn and Fe reduction near the surface, leaving SO\textsubscript{4}\textsuperscript{2-} as the only available oxidant. At both the anoxic stations, the SO\textsubscript{4}\textsuperscript{2-} reduction rate decreased with depth as would be expected as a gradual depletion of the degradable fraction of the organic matter accompanies burial (Fig. 7). At GD1 the higher reactivity of organic matter in the fluff layer was evident as the (volume-based) C\textsubscript{org} content was actually lower here than in the underlying sediment. Still, the SO\textsubscript{4}\textsuperscript{2-} reduction rates stabilized at much higher levels at GD1 than at GD160. This distribution is explained by the implacement of turbidite at GD1, revealed by the x-radiographs (Fig. 3), and the high rates suggest that the latest tur-
bidite is quite young. The final increase in the $\text{SO}_4^{2-}$ reduction rate at 17 cm depth at GD1 may represent the previous sediment surface as suggested for the black band observed near this depth. To obtain a quantitative dating of the sediment, analysis of the $^{210}\text{Pb}$ distribution is currently being performed.

At GD9, the increase in $\text{SO}_4^{2-}$ reduction rate from the surface to 4 - 5 cm depth (Fig. 7) was not related to obvious changes in $C_{\text{org}}$ (Fig. 4), which suggested that $\text{SO}_4^{2-}$ reduction near the surface was partially inhibited by competition from other respiratory pathways (cf. Sørensen and Jørgensen 1987). Oxygen, NO$_3^-$, and Mn oxides were only available for respiration very close to the surface, so the only electron acceptor more favorable than $\text{SO}_4^{2-}$ present to 4 - 5 cm depth was poorly crystalline Fe(III) oxides (Fig. 6), and we, thus, suggest that these oxides are important electron acceptors in the this depth interval. Indeed, recent studies have indicated that in many coastal sediments, dissimilatory reduction of Fe and, in some cases, Mn may be as important in C oxidation as is $\text{SO}_4^{2-}$ reduction (Aller 1990, Canfield et al. 1993a). These studies have shown that bioturbation, the mixing of the sediment by the benthos, is essential in transporting the particulate Fe and Mn oxides into the anoxic sediment and maintaining high turn-over rates of these oxidants. The presence of an active infauna at GD30 and GD9 was evident from the worm burrows and the mixed appearance of the sediments (Fig. 3) as well as from the distribution of $\Sigma\text{CO}_2$ and $\text{NH}_4^+$, the products of the oxidation of organic matter, in the pore-water (Fig. 5). In spite of much higher metabolic rates at these stations than at GD1, a much smaller build-up of the metabolites was seen in the upper 10 cm, but below this depth, as irrigation decreased, concentrations rose.

Although $\text{SO}_4^{2-}$ reduction rates were high at all stations, $\text{H}_2\text{S}$ did not accumulate in the pore waters. This is common for bioturbated sediments, where $\text{H}_2\text{S}$ can react with Fe oxides that are continuously being mixed in (Thamdrup et al. 1994a), but it was surprising that no $\text{H}_2\text{S}$ accumulated to at least 15 cm depth at GD1. In addition to the rate of $\text{SO}_4^{2-}$ reduction, the concentration of $\text{H}_2\text{S}$ in pore waters is regulated by the availability of reactive Fe (Canfield et al. 1992), and the speciation of Fe in the basin sediment is therefore currently under investiga-

A particularly high capacity for sulfide retention in the sediments may also be of significance for the suboxic state of the water column.

The anaerobic respirations Mn, Fe, and $\text{SO}_4^{2-}$ reduction produce Mn$^{2+}$, Fe$^{2+}$, and $\text{H}_2\text{S}$. However, the burial of these reduced species, often in precipitated form as, e.g., MnCO$_3$ and FeS$_2$, is typically much slower than the reduction rates in coastal sediments (Jørgensen 1982, Canfield et al. 1993a). Instead they may be transported towards the sediment surface by bioturbation and there be oxidized with $\text{O}_2$ as the final oxidant (Howarth 1984, Thamdrup et al. 1994a). Thus, although sediment accumulation rates are not available for Golfo Dulce, it is most likely that most of the oxygen uptake measured in the sediments was not coupled to oxic respiration of organic matter but rather to the reoxidation of reduced inorganic substances. The imbalance between the $\text{O}_2$ uptake and the $\Sigma\text{CO}_2$ efflux from the sediments implies that the sediments are not at a steady state, and that reduced inorganic compounds are building up in the sediments. If all the reduced species were being reoxidized with $\text{O}_2$ as the final oxidant, the $\text{O}_2$ and $\Sigma\text{CO}_2$ fluxes should be approximately similar. An imbalance like the one observed is expected when bottom-water oxygen concentrations decrease.

The metabolic rates in the sediments showed a similar variation between the shallow and deep sites as did the benthic fluxes, but at all sites the flux of $\Sigma\text{CO}_2$ was only about half of the accumulation rate in the upper 1 cm, and the difference was even larger for $\text{NH}_4^+$ (Table 2). In the oxic sediments, oxidation of $\text{NH}_4^+$ to NO$_3^-$ could be a sink at the sediment surface and thus diminish the flux. However, the small NO$_3^-$ fluxes and rates of denitrification exclude nitrification as a significant sink for $\text{NH}_4^+$ (Table 2). There are no indications, that the processing of the sediment involved in the incubations for $\Sigma\text{CO}_2$ and $\text{NH}_4^+$ accumulation rate determinations affects the rates strongly. Thus, although the $\text{SO}_4^{2-}$ reduction rates determined during these incubations varied from the rates from whole-core incubations, the variation was not systematic (Table 2). We therefore attribute the differences to heterogeneity of the sediments. At the shallow stations, where the largest difference was seen, this could include a spatial and temporal patchiness of the irriga-
tion. At present we have no explanation for the extremely high C/N flux ratios from GD30 and GD9.

Decreases in both amount and quality of the organic matter could influence the decrease in metabolic rates from the shallow to the deep sites. The upper 10 cm of sediment contained less than half as much C$_{org}$ at GD1 than at GD9 and -30, and the strong decrease in respiration rates with depth in the water column indicated that only the more refractory organic matter (including the observed macroscopic plant debris) reached the deep basin. For a recent discussion of other factors that may also affect the rates of decomposition (or, conversely, the extent of carbon preservation) in the sediments see Canfield (1994).

The oxic respiration in the water column of 0.7 mol m$^{-2}$ d$^{-1}$ was about 20 times the sediment $\Sigma$CO$_2$ accumulation rates at the shallow sites (Table 2). Since the water column rate is based on linear interpolation of one measurement at 1 m and one at 20 m depth, it should be regarded as a rough estimate. Still, it suggests that carbon cycling in Golfo Dulce is strongly concentrated above the pycnocline.

Comparison of the detection limit for the depth-integrated denitrification rate in the anoxic water column (11 mmol m$^{-2}$ d$^{-1}$) and the range of benthic carbon mineralization rates measured at the anoxic stations GD1 and GD160 (1.9 - 12 mmol C m$^{-2}$ d$^{-1}$ based on $\Sigma$CO$_2$ flux, $\Sigma$CO$_2$ production, or SO$_4^{2-}$ reduction; Table 2), demonstrates that most carbon oxidation in the anoxic part of the basin probably took place in the sediments. Thus, the benthic exchange may significantly affect the water-column chemistry. Sediment metabolism was dominated by SO$_4^{2-}$ reduction with $\Sigma$CO$_2$, NH$_4^+$, PO$_4^{3-}$, and H$_2$S as the end-products (Eqn. 1). As H$_2$S was to a large extent trapped in the sediment through reaction with Fe minerals, the main effect of the sediment metabolism on the water column should be the release of $\Sigma$CO$_2$, NH$_4^+$, and PO$_4^{3-}$. Of these metabolites, the release of NH$_4^+$ should be most easily observed, as the concentration in the water entering the bay is very low. Oxidation of NH$_4^+$ is not expected under anoxic conditions. If we assume that NH$_4^+$ was not permanently trapped in the sediment but released at a rate equal to its rate of production, then the mean of the different estimates of benthic carbon mineralization rates at GD1 and GD160 (Table 2; mean 6.6 mmol m$^{-2}$ d$^{-1}$) corresponds to an NH$_4^+$ efflux of 1 mmol m$^{-2}$ d$^{-1}$ (cf. Eqn. 1). If the NH$_4^+$ released was distributed over the 100 m of anoxic water column, the accumulation rate there was 0.3 mmol L$^{-1}$ month$^{-1}$. Ammonia concentrations in the anoxic bottom water were generally lower than 1 µM, which implies a turn-over time of less than 3 months. From this rough calculation it is clear that the exchange of bottom water in Golfo Dulce could be quite frequent. Whether such exchange occurs throughout the year or only during winter where upwelling is most intense, as suggested by Richards et al. (1971), remains to be determined. Measurements of water-column parameters at monthly intervals should provide a better quantitative understanding of the hydrographical conditions that appear to maintain the basin in an anoxic, non-sulfidic state.

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RESUMEN

Se investigaron las aguas y los sedimentos más superficiales de un fiordo tropical de 200 m de profundidad en relación a la zonación química, a las tasas de procesos respiratorios y a los flujos béticos. Se encontró oxígeno hasta profundidades de 100 m aproximadamente, si bien solamente la parte superior de la oxiclina se encontraba asociada a la pycnoclina, ésta última localizada por encima del umbral. Aguas ricas en nitritos entraban en la bahía a nivel del umbral (60 m) y se esperaba denitrificación en las aguas anóxicas. Solo se detectaron pequeñas cantidades de ácido sulfhídrico en las cercanías del fondo, de manera que los nitritos aparecen como un posible oxidante del
sulfhídrico. Estas observaciones reproducen en gran medida las de un estudio realizado en 1969, lo cual sugiere que el intercambio de agua es lo suficientemente frecuente como para prevenir el desarrollo de condiciones altamente reductoras en las aguas profundas. Las altas tasas de respiración aeróbica son indicativas de un intenso reciclaje del carbono en la zona eufótica. Estas tasas disminuían rápidamente con la profundidad, y asimismo las tasas de denitrificación y de reducción del sulfato eran 100 veces menores que las de la toma de oxígeno en la superficie. La zonación química, así como las radiografías por rayos X, indican que los sedimentos bajo aguas oxígeno en la superficie prevenir el desarrollo de condiciones altamente reductoras. Las tasas de oxidación del carbono eran de 5 a 10 veces mayores en los sedimentos de aguas óxicas que las de los sedimentos de aguas anóxicas del fondo de la bahía. La reducción del sulfato era un proceso dominante que representaba del 50 al 100 % de la oxidación del carbono en los lugares óxicos y anóxicos, respectivamente. Incluso en los lugares anóxicos no se acumulaba ácido sulfhídrico en las aguas intersticiales, por lo que se sugiere una intensa sedimentación de fases de hierro reactivas.

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