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The influence of topography on the functional exchange surface of marine soft sediments, assessed from sediment topography measured in situ

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Abstract

We investigated the influence of small-scale topography on the exchange surface between sediment and water in two coastal marine sediments. One site was a sandy silt at Giglio Island, Italy. The sediment was rich in organic material, had a very active fauna, and a rich surface topography. The second site was an estuarine mud in Aarhus Bay, Denmark, which had a less active fauna and less surface topography. The topography at both sites was measured in situ, with a horizontal resolution of ~0.1 mm. The topographic data were used to calculate the area of the three-dimensional exchange surface, which was 12% larger than the projected base area on Giglio and 7% larger in Aarhus Bay. In addition to enlarging the surface area, topography also caused horizontal gradients that were not included in the vertical O_2 flux calculated from the concentration gradient in the diffusive boundary layer. To account for both effects, fluxes calculated from the vertical O_2 gradient in the diffusive boundary layer were corrected by a factor of 1.14 in the estuarine mud, and 1.25 in the nearshore sand. By considering the constraints on exchange surface enlargement and by comparing with previous studies, we argue that it is unlikely to find topographic influences much larger than this range. Topography had an even smaller effect on the area of the oxic–anoxic interface than on the exchange surface between sediment and water. In the nearshore sand, the oxic–anoxic interface was a factor of 1.06 larger than the projected horizontal area, and in the estuarine mud, the enlargement was by a factor of 1.03.

Oxygen consumption can be considered as an integration of both anaerobic and aerobic carbon turnover, which makes the oxygen flux between sediment and water one of the most important parameters in biogeochemistry. To separate different pathways and processes in the redox cycles of cohesive sediments, it is useful to divide the oxygen flux into two parts: the diffusive O_2 uptake through the visible sediment surface, and the fauna-mediated oxygen consumption (FOU), in which oxygen enters the sediment through the burrows of benthic animals. In fine-grained sediments, diffusive O_2 uptake takes place through the diffusive boundary layer (DBL) (Boudreau and Jørgensen 2001). The oxygen gradient in the DBL can be measured with microelectrodes, and the vertical diffusive flux (J_z) is then calculated from Fick's first law of diffusion: $J_z = -D(dC/dz)$, where D is the molecular diffusion coefficient and dC/dz the vertical concentration gradient. The FOU comprises all O_2 consumption associated with ventilated macrofauna burrows. This includes the respiratory oxygen consumption of the animals themselves, the oxygen uptake of burrow walls with the associated microbial community, and the oxygen consumed by oxidation of reduced solutes released from the burrows. Total oxygen consumption is typically calculated from the concentration decrease over time in closed cores, and FOU is assumed to be the difference between total uptake and diffusive uptake. According to Jahnke (2001), FOU is generally insignificant in areas with fluxes below 2.73 mmol m^2 d^{-1}. This is primarily the deep-sea floor. In coastal and estuarine areas, where the fluxes are one order of magnitude higher, FOU typically contributes at least half of the total oxygen uptake (Forster et al. 1999; Jahnke 2001; Meile and Van Cappellen 2003).

Calculation of the diffusive flux from the simple Fick's first law treats the sediment–water interface as an infinitely flat plane with only vertical chemical gradients. However, sediment surfaces are sculptured into elaborate landscapes across a range of scales (Paul et al. 1978; Swift et al. 1985; Briggs 1989; Gundersen and Jørgensen 1990), which leads to an underestimation of the diffusive flux. As pointed out by Wheatcroft (1994), the topography at a given site is dynamic, and temporal variations in topography at a single site might be just as large as variations from site to site.

A number of studies have evaluated the discrepancy between observed topography and the infinitely flat plane (Gundersen and Jørgensen 1990; Jørgensen and Des Marais 1990; de Beer et al. 1994; de Beer and Stoodley 1995; Røy et al. 2002 and references therein). Common to all investigations is the visualization of oxygen concentration fields as isolines or isoplanes. Apart from visualizing the O_2 distribution, the isolines also show the direction of the diffusive flux. Because concentration is constant along these lines, no net diffusion occurs along them and the direction of diffusive transport is perpendicular to the isolines. In other words, an isoline touching the sediment surface at a specific point will define the local exchange surface between sediment and water. Jørgensen and Des Marais (1990) observed that surface

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structures with a characteristic dimension smaller than half the thickness of the DBL are not reflected in the oxygen isolines within the DBL. Thus, isolines of oxygen concentration are smooth lines loosely following the relief of the sediment–water interface (Jørgensen and Revsbech 1983; de Beer et al. 1994; de Beer and Stoodley 1995; Fenchel and Bernard 1995; Glud et al. 1996). The reason for the smoothness is that, at small scales, molecular diffusion levels out any heterogeneity in solute distribution that is not maintained by effective sinks and sources. It is the same diffusion effect that causes microprofiles to be smooth and continuous in one-dimensional representations.

The fact that O_2 isolines resemble a smoothed sediment surface was exploited by Røy et al. (2002) to generate approximated isolines from topographic data with submillimeter resolution. They showed that smoothing the topographic data with a matrix corresponding to the thickness of the effective DBL generated a virtual sediment surface that was practically parallel to the isolines in the DBL. At each point on the mapped surfaces, the area of this exchange surface (A') relative to the projected horizontal surface (A) could then be calculated. The enlarged surface could then be accounted for by simply multiplying J_z by A'/A.

In addition to enlarging the surface area, topography also causes horizontal gradients that are not represented in vertical profiles. The error is related to the angle, α, between the exchange surface and horizontal. Simple geometry implies that the error can be corrected by multiplying the gradient by $1/(\cos \alpha)$ (Jørgensen and Des Marais 1990). Røy et al. (2002) showed that A'/A is equal to $1/(\cos \alpha)$. It follows that a diffusive flux must be multiplied by A'/A twice to account for topographic effects: once to account for increased surface area and once to account for missing representation of the horizontal gradients. Denoting the three-dimensional diffusive flux J', the relation between vertical diffusive flux (J_z) and three-dimensional diffusive flux becomes $J' = J_z \times (A'/A)^2$. In contrast to isolines mapped directly with microsensors, the topographic data necessary to generate the approximated isolines can cover large enough areas to adequately represent the average J'/J_z.

This study builds largely on the arguments and methods presented by Røy et al. (2002). But where the former used a laboratory-contained model system to illustrate correction of J_z on the basis of topographic data, in this study, we apply this principle to topographic data acquired in situ. The aim of this study is to quantify the momentary influence of topography in one-dimensional calculations of diffusive oxygen uptake for actual marine locations and to evaluate how far a one-dimensional view of the oxic zone deviates from reality.

Methods and study sites

Bay of Campese, Isola del Giglio, Italy—Isola del Giglio is a small island in the Mediterranean Sea, 150 km northwest of Rome (42°20′N, 10°52′E). The study site was on the southern side of a small open bay, locally known as the Bay of Campese. Mapping and coring was performed at a 25-m water depth, 200 m seaward from the rocky shore. The sediment was a sandy silt, with a median grain size of 31 μm. Porosity (SE) was 62% (1, $n = 4$), and permeability was 2.95×10^{-13} m^2 (0.53×10^{-13}, $n = 4$). Autumn senescence of *Posidonia* meadows in the shallow regions of the bay and the recent passage of a severe storm had caused accumulation of sea grass debris on the sediment. Consequently, the organic content was relatively high, with 2.24% (0.13, $n = 4$). A diverse and active fauna was observed at this study site, most notably hermit crabs (*Pagurus* and *Paguristes* spp.) and spider crabs (*Inachus* spp.). Large, permanently burrowing animals like the polychaete *Aphrodita aculeata* and brittle stars of the *Ophiouridae* family were also abundant. The mud shrimps *Callianassa truncata,* which form conspicuous landscapes of cones and funnels in the shallower regions of the bay (Ziebis et al. 1996), was not observed at the study site. The Giglio measurements were performed in October 2001. The water column was unstratified down to at least 30 m, with a temperature of 22°C and oxygen concentration close to saturation.

Aarhus Bay, Denmark—Aarhus Bay is a semienclosed bay on the Baltic Sea–North Sea transition. The central regions of the bay, where the study site was located (56°09.1′N, 10°19.2′E), is a plane of sandy clay ~50 km^2, where depth varies little from 15 m. The site has been used intensively for scientific studies of early diagenesis (for an overview, *see* Jørgensen 1996). The benthic fauna consists of a typical *Abra* community, dominated by *Abra alba, Mysella bindentata, Corbula gibba, Pectinaria koreni,* and *Nephtys* spp. The most conspicuous animals on the sediment surface are the brittle star *Ophiura albida.* During the measurements in December 2001, the water column was unstratified, with a temperature of 5.7°C, and oxygen concentration was close to saturation. Both sites have little tidal amplitude and experience mainly low wind-driven currents.

Microsensor analysis—Sediment cores from each study site were recovered in polycarbonate tubes with 50-mm inner diameters. The cores were brought to the laboratory and preincubated submerged in seawater for 2 to 3 days under dim light. During preincubation and subsequent profiling, the water above the sediment was stirred by blowing air gently along the water surface. The strength of the air jet was adjusted to produce a DBL thickness similar to that measured in situ in similar environments (Glud et al. 2003; Røy et al. 2004). Temperature and water column oxygen concentration were held at in situ conditions. Oxygen microprofiles were measured in the cores with the use of Clark-type O_2 microelectrodes with internal reference and guard cathodes (Revsbech 1989). Tip diameters were 15–25 μm, stirring sensitivity was <1%, and response time was ~1 s. The electrodes were calibrated between the O_2 concentration in the mixed water column, determined by Winkler titration, and the anoxic sediment. Vertical diffusive oxygen flux was calculated from the concentration gradient in the DBL.

Topographic mapping—The microtopography at the study sites was determined optically with an in situ version of the instrument described by Røy et al. (2002). A line-generating laser diode module (Lasiris LAS 670 5 with LAS 20 line) was positioned on a moving sledge at ~15 cm distance from the seafloor. A digital video camera (SONY DX-1000 in Amphibico UW housing) was fixed relative to the laser, imaging the vertically projected laser line from an angle of 45°. The translation mechanism of the sledge was fitted with a magnetic position sensor, with optical output that changed state for every 0.1 mm of translation. The output of the position sensor was made visible to the camera by coupling the signal into the field of view through an optical fiber. On Giglio, the instrument was placed and operated by scuba divers, whereas in Aarhus Bay, the instrument was lowered from the ship and operated remotely (Glud et al. 2003).

One frame was extracted from the continuous video recording for each 0.1 mm of translation. The images of the projected line were then used to determine the relative heights of the sediment surface. Resolution in the direction of translation is given by the distance translated between the extracted images (i.e., 0.10 mm). Along the laser line, the resolution depended on the magnification factor of the camera, and therefore on range-, zoom-, and focus settings. For the settings used, the horizontal resolution was 0.10×0.10 mm^2 for the Giglio data and 0.13×0.10 mm^2 for the data recorded in Aarhus Bay.

The image quality produced by extraction from the digital video did not match the quality that can be obtained by a digital still image camera (Røy et al. 2002). Pixel-to-pixel noise in the images translates directly to point-to-point noise in the determination of surface heights from the images. Without smoothing, such random peaks and valleys cause an overestimation of the surface area. After application of the 0.6×0.6 mm^2 smoothing kernel from which the exchange surface can be derived (Røy et al. 2002), however, each point on the surface was based on ~30 individual determinations. This procedure effectively filters out point-to-point noise. Although the topographic data contain a random variation on the individual data points at full resolution, the noise is insignificant at the resolution at which the information leading to A' is derived.

Each topographic map was smoothed by convoluting with flat matrices of a range of sizes. For each map and matrix size, the ratio between total surface area (A') and projected horizontal area (A) was calculated following the procedure of Røy et al. (2002).

Finally, artificial sediment images were generated from the measured data by simulation of a distant light source illuminating an isometric topographic model from a 40° angle (Surfer 6, Golden).

Results

For both sites, the oxygen distribution within the sediment followed the parabolic profile typical for impermeable sediments (Fig. 1). Diffusive oxygen flux (SE) along the vertical axis (J_z) was 34 mmol m^{-2} d^{-1} (1.9, $n = 5$) in the Giglio sediment and 12 mmol m^{-2} d^{-1} (3.5, $n = 6$) in Aarhus Bay.

The microtopography of the Giglio sediment was a mosaic of overlapping sediment mounds (Fig. 2A). *Posidonia* leaf fragments lying on top of the actual sediment, as for example at (10, 30) in Fig. 2A, added further topographic variation.

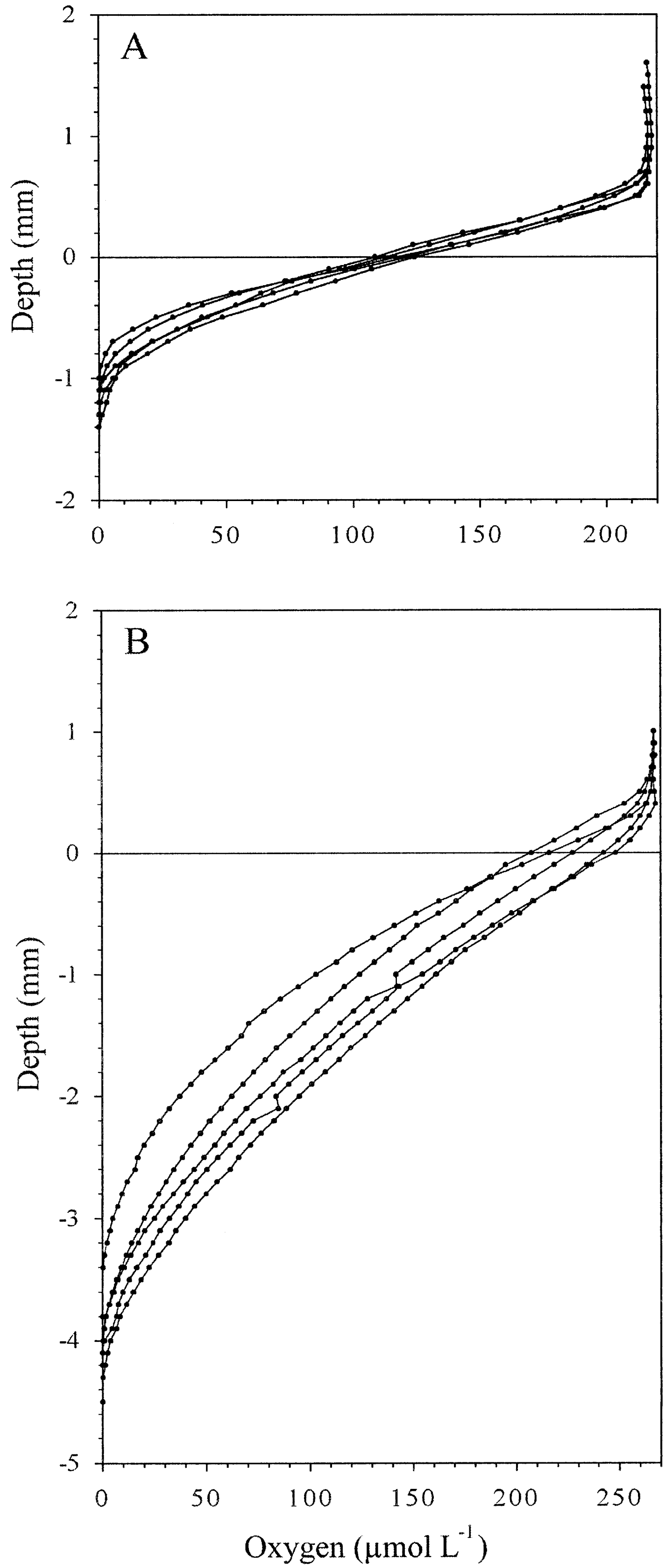

Fig. 1. O_2 microprofiles across the sediment–water interface measured ex situ in cores. (A) Giglio and (B) Aarhus Bay.

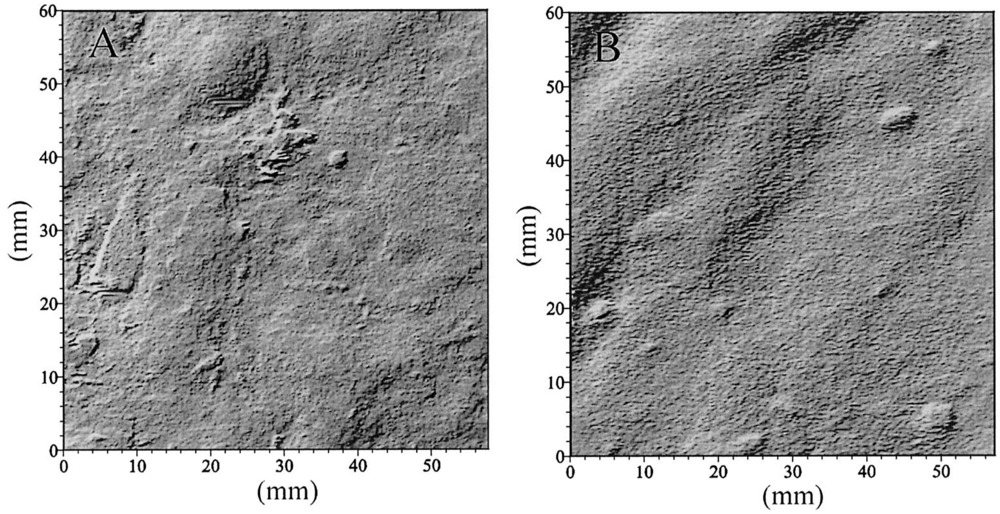

Fig. 2. Topography measured in situ, presented as shaded relief. The images are generated by simulation of a distant light source illuminating the topography from a 40° angle. Examples measured in (A) the Bay of Campese, Giglio, and (B) Aarhus Bay.

According to Røy et al. (2002), the surface calculated by smoothing the topography with a $0.6 \times 0.6\ mm^2$ kernel closely resembles the DBL. Figure 3 shows a subsection of such approximated isolines calculated from a map measured at Giglio. Figure 4A shows the ratio between the smoothed surface area (A') and the projected area (A) for all Giglio maps after application of a range of smoothing kernels. Multiplying $(A'/A)^2 = 1.25$ derived by smoothing with the $0.6 \times 0.6\ mm^2$ kernel with the vertical diffusive flux results in a total diffusive flux of 38 mmol $m^{-2}\ d^{-1}$.

Compared with Giglio, the sediment mapped in Aarhus Bay appeared as a smooth rolling landscape with well-separated biogenic structures such as tracks and fecal mounds (Fig. 2B). Following the same procedure as above, $(A'/A)^2 = 1.14$, resulting in a total diffusive flux of 14 mmol $m^{-2}\ d^{-1}$.

Discussion

As seen in Fig. 4, the surface area increase caused by topography is quite moderate in both examples. The discrepancy between a conceptual model accounting only for vertical gradients and the more complex model taking topography into account thereby is equally small. This is not caused by exceptionally smooth sediment surfaces at the two sites, but the smoothing effect of molecular diffusion. The latter causes the DBL to loosely follow the relief, with isolines aligned at mostly small angles relative to horizontal (α). The relation between α and the area increase is not linear. Below ~20°, the surface slope has little influence on the surface area, and the areas with angles above 20° are too rare to have a large effect on the average surface area. The average surface slope from the Giglio sediment is illustrated by the line marked "A′ DBL" in Fig. 5. At first glance, it appears that the topographic influence of such steep slopes must be significant. However, because the influence is related to the relative length of A' and A, the effect is moderate.

Table 1 shows a short compilation of other studies that quantified the difference between vertical diffusive flux and three-dimensional diffusive flux caused by surface topography. The biofilms and photosynthetic mats, which contain large amounts of exopolymers, have quite large differences between vertical diffusive flux and three-dimensional diffusive flux. In an extreme example presented by de Beer and Stoodley (1995), the influence was linked to the vertical sides of clusters and channels in the biofilm structure. But with DBL thickness >200 μm, the structures were completely submerged in the DBL, which caused the diffusive flux to occur almost perfectly vertical. So even if a marine sediment has a surface as complex as this biofilm, the influence of structures as small as 100–300 μm would be negligible. The mat described by Jørgensen and Des Marais (1990) was structured by tufts and clusters of cyanobacteria and diatoms, with size scales of a few millimeters. The exopolymers in the mat allowed steep structures of a size that could be partly followed by the DBL under high flow velocities. Under lower velocities, the thicker DBL again dominated the effect of topography, causing the vertical flux to contain most of the diffusive exchange. The study of Jørgensen and Des Marais (1990) demonstrates that for sediments with large amounts of exopolymers, a large topographical influence is possible. But the sizes of the structures responsible for the increased exchange surface are large enough to be easily recognized. The studies of Jørgensen and Des Marais (1990) and Gundersen and Jørgensen (1990) were examples brought forward to show that horizontal gradients in the DBL *could* be an important factor. Their data cover <1 cm^2 combined, and their results were not intended to be extrapolated to the marine environment in general.

As illustrated, the relatively low effect of topography inferred from our data is in agreement with the previously published studies, even though those studies stressed high potential effects from topography. Because the low effect of topography is linked to physical and mathematical con-

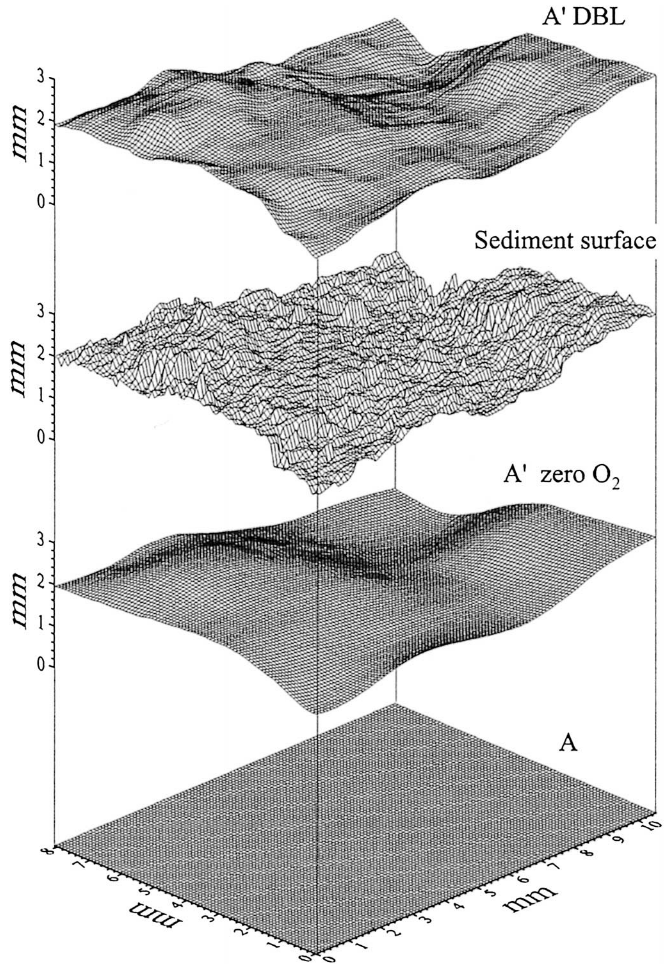

Fig. 3. Cutout of three interfaces around the sediment surface measured at the Giglio site. The DBL forms the interface between sediment and water. It has been approximated by smoothing the measured sediment surface with a matrix of the same size as the DBL thickness (0.6 mm). Likewise, the zero isoline is approximated by smoothing with a kernel with the same dimension as the distance from the top of the DBL to the penetration depth of O_2. The surface areas marked by A' are used to calculate surface enlargements relative to the projected horizontal area A (*see text for details*).

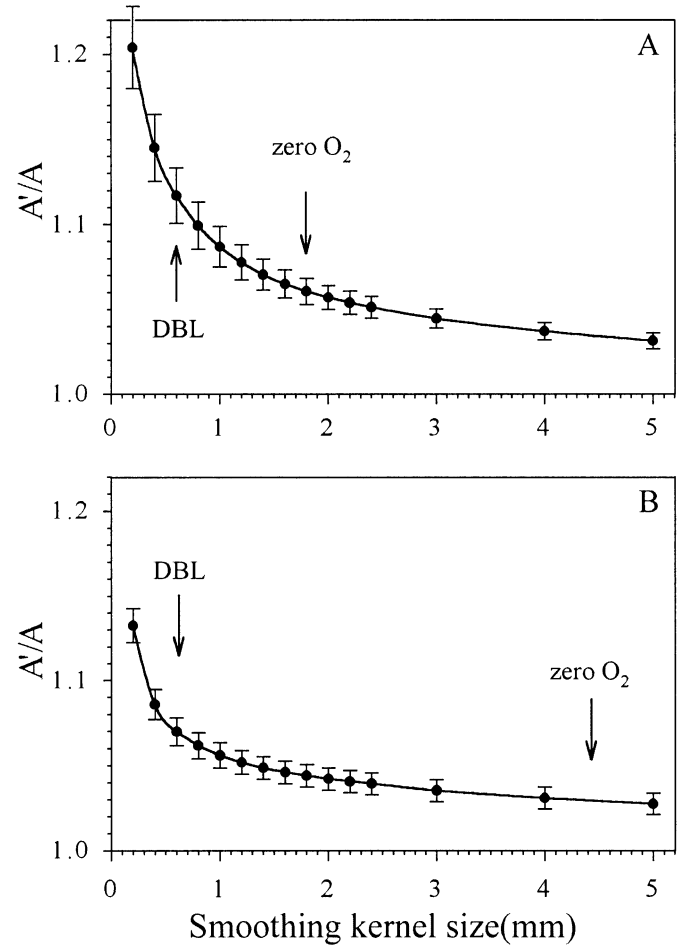

Fig. 4. The surface area calculated after different degrees of smoothing relative to the projected horizontal area. (A) Generated from the surface topography measurements from Giglio (Fig. 2 and 13 similar maps) and (B) with the measurements from Aarhus (Fig. 2 and another 17 maps). Error bars are 95% confidence intervals.

Table 1. Previous studies comparing the vertical diffusive flux to total diffusive flux.

Study	J'/J_z
A biofilm with complex surface structure, in which roughness was submerged in the DBL (de Beer and Stoodley 1995).	1.00
A model benthic community in a laboratory flume, in which the topography consisted of annelid fecal mounts on a more or less flat background (Røy et al. 2002).	1.08
Estuarine mud measured in Aarhus Bay (this study).	1.14
Organic-rich sandy silt littered with seagrass fragments measured in Giglio Island, Italy (this study).	1.25
A gelatinous microbial mat from a hypersaline environment. The mat was structured by tufts and clusters of cyanobacteria and diatoms, with a size scale in the same range as the thickness of the DBL. The original J'/J_z of 1.49 was recalculated by Røy et al. (2002) to 1.3–1.4. (Original reference: Jørgensen and Des Marais [1990])	1.3–1.49
A heavily bioturbated sediment from a shallow estuarine lagoon stabilized by diatoms. The original J'/J_z of 2.5 was calculated according to the procedure of Jørgensen and Des Marais (1990) and is therefore probably an overestimation (Røy et al. 2002). Recalculating along the same lines, as for Jørgensen and Des Marais (1990), gives a J'/J_z of 1.8. (Original reference; Gundersen and Jørgensen [1990])	1.8–2.5
A biofilm with complex surface structure, in which a 50-μm thin DBL wrapped around the surface elements (de Beer and Stoodley 1995).	2–2.5

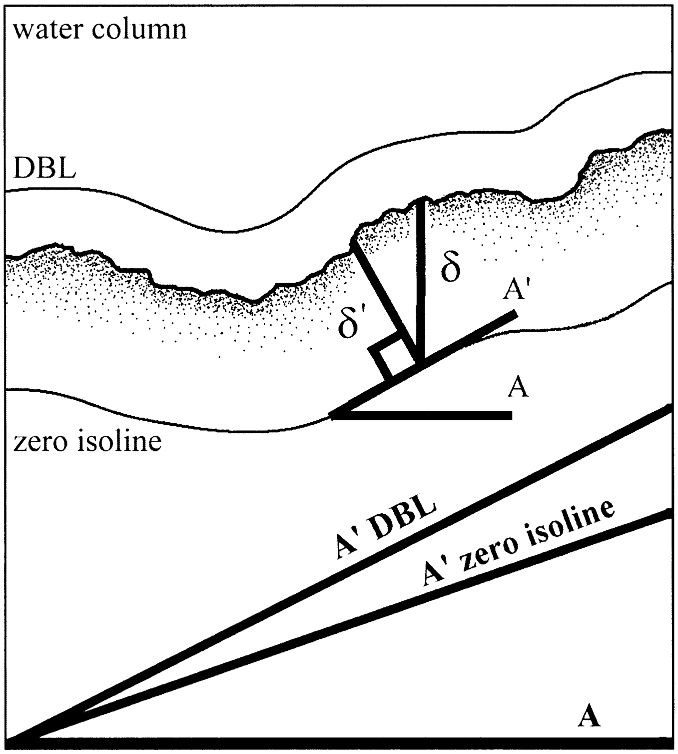

Fig. 5. Geometric representation of the relation between the vertical flux and the diffusive exchanges across a sculptured sediment–water interface. The small triangles demonstrate one point on the sediment surface, whereas the thick lines at the bottom of the figure represent the calculated average sediment slope for the Giglio sediment. The sediment mapped in Aarhus bay was significantly smoother.

straints as discussed previously, we should expect this to be a general feature of marine sediments. The correction factor of 1.25 measured in Giglio was connected to an active fauna and to seagrass litter on the sediment surface. A factor close to 1.1 between J_z and J', as measured in Aarhus Bay, might be more common for marine soft sediments.

The exchange surface toward the water column is not the only part of the sediment that is influenced by the surface topography. Underneath the DBL, O_2 penetrates into the sediment, forming a thin oxic zone. The average O_2 penetration in fine-grained coastal and estuarine sediments is generally only a few millimeters (Revsbech et al. 1979; Cai and Sayles 1996). Under diffusive control, the thickness of the oxic zone is mainly determined by the oxygen concentration in the water column and the volume-specific oxygen consumption rate (Glud et al. 2003). Local hot spots in oxygen consumption rate associated with fecal mounds thus are reflected in locally reduced oxygen penetration depth (Glud et al. 1996; Huettel et al. 2003). Oxygen profiles from silty coastal sediments closely resemble the parabolas that are characteristic for zero-order kinetics (Rasmussen and Jørgensen 1992; Cai and Sayles 1996). Assuming zero-order kinetics, a fourfold increase in rate is necessary to decrease the penetration depth by 50%. Therefore, multiple measurements of oxygen penetration depth are often remarkably similar (Fig. 1). Furthermore, the edges of the hot spot are smoothed by lateral diffusion, causing a gradual disturbance in the zero isoline. The zero isoline therefore is almost parallel to the DBL, even when the activity distribution in the sediment surface layer is uneven. This can be seen directly in two-dimensional oxygen distributions from coastal and estuarine sediments (e.g., Glud et al. 1996, Glud et al. 2001). Thus, Glud et al. (2003) assumed that the measured A'/A of the DBL accounted for the enlargement of the entire oxic zone. Thereby, they could use A'/A to assess the overestimation of the thickness of the oxic skin caused by oblique penetration of the oxic layer (Fig 5). There is, however, no reason to assume that topographic variation much smaller than the thickness of the oxic layer should be reflected in the oxygen penetration depth. The situation is similar to the smoothing out of smaller variations in isolines around the sediment surface, the only difference being that the isoline now under consideration is the zero line. To approximate the area of the oxic–anoxic interface, we should therefore smooth with a kernel with the characteristic size of the diffusive distance between the zero isoline and the mixed water column (i.e., the DBL thickness plus the oxygen penetration depth; Fig. 3). According to this argumentation, it should be possible to predict the variation in oxygen penetration depth from the differences between the measured sediment surface heights and the simulated zero isoline. The measured oxygen penetrations for Giglio fall within 0.4 mm, which compares well with the standard deviation of the difference of 0.19 mm. The different area increases of the exchange surface between sediment and water, and of the oxic–anoxic interface, are shown in Figs. 4 and 5.

When measuring oxygen penetration into the sediment with a microelectrode, an oblique penetration of the oxic zone increases the apparent oxygen penetration depth, as illustrated by δ and δ' in Fig. 5. The vertical scale should therefore be compressed by $\delta/\delta' = A'/A$ before profile interpretation. Because this compression causes the volume of the oxic zone to be underestimated, we must enlarge the area by the same factor that the vertical scale is compressed in order to calculate the correct oxic volume.

If the appearance of the sediment from other locations is comparable to the images in Fig. 2, Fig. 4 can be used to indicate in which range we should expect to find A'/A for the oxic–anoxic interface. Instead of reading at the left arrow, where A'/A associated with the DBL is found, A'/A for the oxic–anoxic boundary should be read at the O_2 penetration depth. An argument similar to that made for the oxic skin can be applied to other processes constrained by diffusion (e.g., when calculating the volume of the zone where denitrification occurs). The common principle is that the deeper the respective layer is situated, the smaller the influence of surface topography.

We have shown that two marine sediments were relatively flat with respect to diffusive exchange, even though both sediments had considerable surface sculpturing. Because the lack of the effect of topography was linked to mathematical and physical constraints, we argue that the flatness is likely a general feature of muddy marine sediments.

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