Tidal sands as biogeochemical reactors

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A B S T R A C T

Sandy sediments of continental shelves and most beaches are often thought of as geochemical deserts because they are usually poor in organic matter and other reactive substances. The present study focuses on analyses of dissolved biogenic compounds of surface seawater and pore waters of Aquitanian coastal beach sediments. To quantitatively assess the biogeochemical reactions, we collected pore waters at low tide on tidal cross-shore transects unaffected by freshwater inputs. We recorded temperature, salinity, oxygen saturation state, and nutrient concentrations. These parameters were compared to the values recorded in the seawater entering the interstitial environment during floods. Cross-shore topography and position of piezometric level at low tide were obtained from kinematics GPS records. Residence time of pore waters was estimated by a tracer approach, using dissolved silica concentration and kinetics estimate of quartz dissolution with seawater. Kinetics parameters were based on dissolved silica concentration monitoring during 20-day incubations of sediment with seawater. We found that seawater that entered the sediment during flood tides remained up to seven tidal cycles within the interstitial environment. Oxygen saturation of seawater was close to 100%, whereas it was as low as 80% in pore waters. Concentrations of dissolved nutrients were higher in pore waters than in seawater. These results suggest that aerobic respiration occurred in the sands. We propose that mineralised organic matter originated from planktonic material that infiltrated the sediment with water during flood tides. Therefore, the sandy tidal sediment of the Aquitanian coast is a biogeochemical reactor that promotes or accelerates remineralisation of coastal pelagic primary production. Mass balance calculations suggest that this single process supplies about 37 kmol of nitrate and 1.9 kmol of dissolved inorganic phosphorus (DIP) to the 250-km long Aquitanian coast during each semi-diurnal tidal cycle. It represents about 1.5% of nitrate and 5% of DIP supplied by the nearest estuary.

1. Introduction

We need information about net metabolism of coastal zones in order to better constrain the cycles of carbon, nutrients, or trace metals at the land–ocean transition zone (Jickells and Rae, 1997). Pioneering works showed that filtration through the sands of exposed beaches represented a mechanism that enhanced the decomposition of organic matter in the coastal zone (Riedl and Macmahan, 1969; Riedl and Machan, 1972; Mclachlan et al., 1985; Mclachlan and Turner, 1994). However, sandy sediments of continental shelves and most beaches are often thought of as geochemical deserts because they are usually poor in organic matter and in other reactive substances (see discussion in Boudreau et al., 2001). Based on the belief that the importance of

sedimentary environment is proportional to its own stock of reactants and organic matter, sandy sediments are generally neglected. Recent observations, however, suggest that it is inappropriate to neglect biogeochemical fluxes from sandy sediments (Rusch et al., 2006). One of the major differences between sandy sediments and muddy sediments is the permeability, which controls the transport of pore waters, and consequently, the fluxes inside, and outside the sediment (Wilson et al., 2008). Permeable sediments are subjected to pressure fluctuations generated by currents. Pressure gradients induce transport of pore water (advective flow) and generate dispersive mixing that can dominate diffusion processes (Huettel et al., 1996). Bacon et al. (1994) showed that permeable sediments could trap and decompose organic matter efficiently enough to consume organic matter wholly. Consequently, permeable sediment constitutes a fundamental component to understand the biogeochemical cycles of the biogenic components (Middelburg and Soetaert, 2004). Advective flow enhances circulation of dissolved oxygen in pore waters.

Interactions between mineralisation reactions and advective flow generate complex biogeochemical compartments inside the permeable sediment (e.g., Shum and Sundby, 1996). The advective transport of pore water, which is obvious during ebb and flood tides in sandy sediments of the tidal zone, makes this environment particularly transient in terms of saturation of water. Sediments of the Aquitanian coastal beach are extreme examples of advective transport of pore waters because of significant sediment permeability and exposure to waves and tides.

The intertidal zone represents a key environment of nutrient dynamics (e.g., Billerbeck et al., 2006; Deborde et al., 2008), where sandy sediments have been intensely investigated to study subterranean estuaries and ground water discharge (Charette et al., 2005). Freshwater discharge through coastal sandy sediments has been recognized as a widespread phenomenon (Li and Barry, 1999; Moore, 1996; Taniguchi et al., 2002). Freshwater inputs have effects on the carbon and nutrient cycles (Kroeger and Charette, 2008). But when coastal pore water is mixed with fresh groundwater, it becomes difficult to determine the portion of nutrient input originating from fresh water, and that caused by in situ mineralisation of organic matter. Here we report a survey of dissolved biogenic compounds of surface seawater and permeable sediment pore waters of a section of the Aquitanian tidal zone that is not affected by mixing of fresh groundwater. Thus, the portion of the Aquitanian coast studied enables us estimate the magnitude of benthic biogeochemical processes in sandy tidal sediments, based on an in situ study. The purpose of this study was to observe and quantify these processes.

2. Materials and methods

2.1. Study area

The French Aquitanian coast is a 250-km long straight coast bordered by high aeolian dunes and exposed to high-energy conditions in a meso–macrotidal setting. This coast is located between the Gironde and Adour estuaries, and is interrupted by the Arcachon lagoon tidal inlet that is approximately 5 km wide, and comprises a complex sandbar and channel system (Michel et al., 1995; Cayocca, 2001). The Aquitanian coast commonly displays double bar beaches with very dynamic rhythmic features (Castelle et al., 2007). Since 1998, several field experiments have been conducted at the Truc Vert beach, which is assumed as being representative of the Aquitanian coast beaches that display balanced sedimentary budget.

Truc Vert beach is located a few kilometres north of the Cap Ferret sand spit. The sediment consists of fine to medium quartz sand with mean grain sizes ranging from 300 to 400 μm (Pedreros et al., 1996). The tide is of meso–macro type, with an average tidal range of 3.2 m, extending up to 5 m during spring tides. This beach is also characterised by the presence of ridge and runnel systems (Fig. 1), developed more or less in relation with meteorological conditions (Michel and Howa, 1999; Castelle et al., 2007).

2.2. Sampling

Water samples were collected in winter 2007 during three periods of mean spring tide (January 18th and 25th, and March 8th). Due to prevalence of fair weather conditions, ridge and runnel systems were well developed and the runnels were almost isolated from seawater at low tide. Surface seawater samples were collected at high tide in the intertidal area and at low tide in the supratidal area of the Truc Vert beach, at a depth of 30 cm below the sea surface. To collect interstitial water at low tide, and at the time of each sampling we bored several holes along a cross-shore transect, until the borehole reaching the saturated zone in the intertidal sandy beach. Temperature, salinity and oxygen concentration were immediately recorded in the waters of the bored holes using WTW probes. Sampling sites were identified with a GPS record. Samples were collected at distances between 2 and 65 m away from the low tide shoreline. Interstitial waters were reached close to the surface on the lower beach, and down at depth of 1.2 m on the upper beach. Cross-shore topography and position of piezometric levels at low tide were obtained with kinematics GPS records. The cross-shore profile was made on January 25th 2007. Waters were sampled using a 50 ml syringe and filtered through a 0.45 μm cellulose acetate syringe-membrane. One subsample was acidified with HNO_3 to analyse dissolved inorganic phosphorus (DIP); another subsample was kept refrigerated until analyses of other dissolved nutrients.
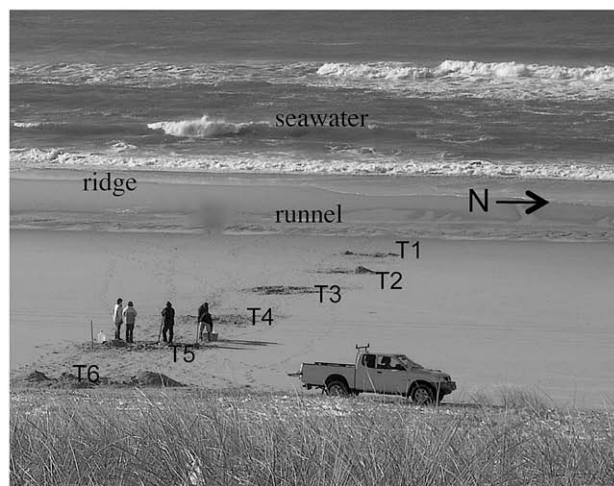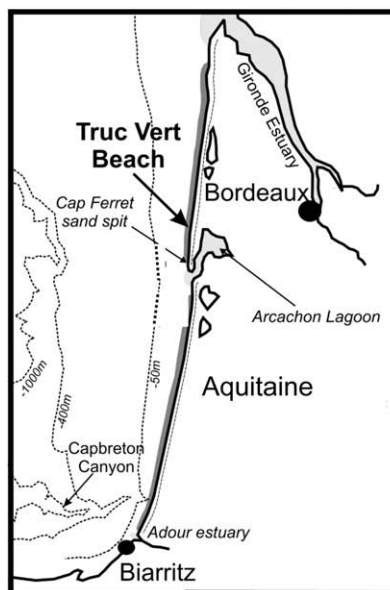

Fig. 1. Map of the south-western part of France and location of the study area. View at low tide of the Truc Vert beach on the Aquitaine coast, and location of pore water sampling sites (T1–T6) on January 25th 2007.

2.3. Experimental setup

Residence time of pore waters was estimated by a tracer approach, using dissolved silica concentration and kinetics of quartz dissolution with seawater. Kinetics parameters were based on two 20-day incubations of seawater collected at high tide with natural sediment from the Truc Vert beach. The sediment consisted of sands with well-sorted grain sizes ranging from 300 to 400 μm. Sand grains contained mostly quartz and less than 2% calcium carbonates. Dissolved silica concentration was monitored. The basic structure consisted of sand and filtered seawater stored in darkness at 20 °C in a polypropylene vial. In the first experiment, 11 50 ml vials were filled with 50 g of sand and 36 ml of seawater. Experimental units were destroyed at the time of each sampling to collect pore water. Sampling time intervals varied between 1 and 3 days. In a second experiment, 60 ml of seawater was circulated at a flow rate of 2 ml min^{-1} through 230 g of sand in a dark and closed system connected to a peristaltic pump. A bypass device enabled collection of aliquots. At the time of each sampling, 1 ml of water was collected with a syringe, and replaced by 1 ml of seawater. Samples were collected once to three times a day.

2.4. Analyses

Dissolved nitrate ($\Sigma NO_3^- = NO_3^- + NO_2^-$) was analysed by flow injection analysis using standard methods (Anderson, 1979). Precision obtained was ±10% for ΣNO_3^-. Dissolved silica, phosphate (DIP), and ammonia were analysed by colorimetric procedures (Mullin and Riley, 1955; Murphy and Riley, 1962; Strickland and Parsons, 1972). The precision of these procedures obtained was ±5%. Free porosity of sand was estimated from the volume of water able to seep out of a known volume of water-saturated sediment placed on a permeable 100-μm mesh grid.

3. Results

3.1. Topography

On January 25th 2007, the tidal range was 3.05 m. The piezometric level was at the surface of the lower beach, and at 1.2 m below the sediment surface in hole T6 located on the upper portion of the intertidal beach (Fig. 2). The water-saturated sediment was detected at 2 m depth in one hole dug higher up on the tidal beach (T7 in Fig. 2), but from which water was not sampled.
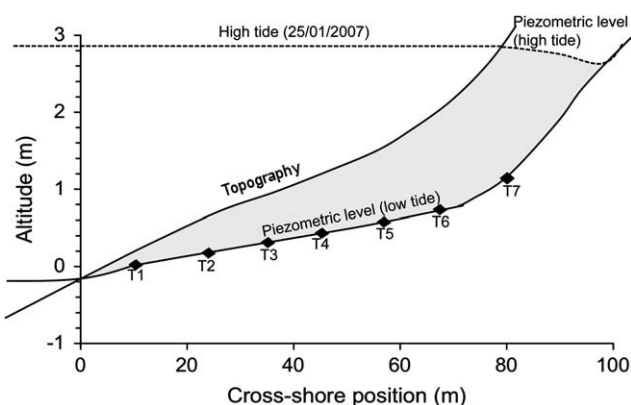

Fig. 2. Cross-shore topography as deduced from kinematics GPS record (January 25th 2007) and the position of the piezometric level at low tide deduced from the depth of water-saturated sediment in holes bored for pore water sampling (T1–T7, see Table 1). The maximum level of the previous high tide is positioned at the top of this profile.

The vertical cross-shore section of unsaturated sediment at low tide, i.e., the surface enclosed in the grey area (Fig. 2) bounded by topography, low tide and high tide piezometric levels, exhibits a surface of 75 m^2, or a volume of 75 m^3 per metre width along the shore (Fig. 2). Therefore, a large volume of sediment porosity fills up successively with water during flood tide, and with air at low tide. During flood tides, waves fill the interstitial environment of the swash zone. Air in the sediment is rapidly replaced by seawater; we observed air bubbles evacuating the sediment during flood. Because of the high permeability of the sand studied, we assumed that no air bubbles were trapped in the interstitial environment at high tide.

3.2. Water chemistry

The temperature of seawater and pore waters was between 12 and 13 °C. Concentrations of the dissolved biogenic compounds measured in free seawater were similar, within ±10%, both at low tide and at high tide. We show here only results obtained in samples collected at low tide. The salinity was 34.1 PSU and oxygen saturation was 101 ± 1%. Nitrate and ammonia concentrations were between 2 and 5 μM; DIP concentrations ranged between 0.09 and 0.19 μM, and dissolved silica ranged between 3.6 and 5.9 μM. In pore waters, salinities were the same as those of free seawater, but oxygen saturation level was lower than 92%. One sample collected on January 25th showed a minimum value of 81%, i.e., 60 μM lower than that of seawater concentration. Dissolved nitrate, silica, and DIP concentrations of interstitial waters generally exceeded significantly those of seawater (Fig. 3, Table 1). Maximum values were 0.5, 15 and 12 μM for DIP, nitrate and silica, respectively. Average values of enrichment of nitrate and DIP relative to seawater concentrations were 5 and 0.25 μM, respectively. Maximum concentrations of dissolved nitrate and silica were recorded in shallow holes of the lower beach, where the water-saturated layer was close to the surface of the sediment. In the pore waters collected on the upper beach at depth of more than 1 m below the surface, nitrate and silica concentrations were between 2 and 6 μM, i.e., close to seawater values. Ammonia concentrations varied between 0 and 4 μM with no clear trend emerging.

3.3. Incubations monitoring

The incubations of seawater carried out with sands from the Truc Vert beach revealed an increase in silica concentration with time. Experiments initially showed a rapid increase. The slope decreased after the first 3 days, and the silica enrichment became linear. In the static incubation experiment for which pore waters were extracted from 11 experimental units, silica concentration rose from 3 μM at the commencement to 6.4 μM after passage of 48 h (Fig. 4). Then, the concentration increased linearly at a rate of 0.23 μM d^{-1}. In the flow-through experiment, silica concentration increased abruptly from 4 to 12.6 μM in the first hour. It reached 22.6 μM after passage of 55 h. Afterwards, the concentration increased linearly by 1.4 μM d^{-1} until the end of the experiment.

Kinetic parameters of sand grain dissolution can be deduced from the linear increase in silica concentration. Kinetics of dissolution must be related to the surface area of grains. Assuming that sand grains can be assimilated to spheres with a diameter R of 400 μm, the volume of each grain is 3.35×10^{-11} m^3. The mass of each grain is 88.8 μg according to the density of quartz. During the first incubation 50 g sand were introduced in experimental units, i.e., 5.63×10^5 grains, corresponding to a surface area $S = 4\pi R^2 \times$ grains number, i.e., 0.283 m^2. The silica concentration increased by 0.23 μM d^{-1}. Therefore, the dissolution of silica in the 36 ml water volume was of 0.96×10^{-13} mol s^{-1}. Considering the
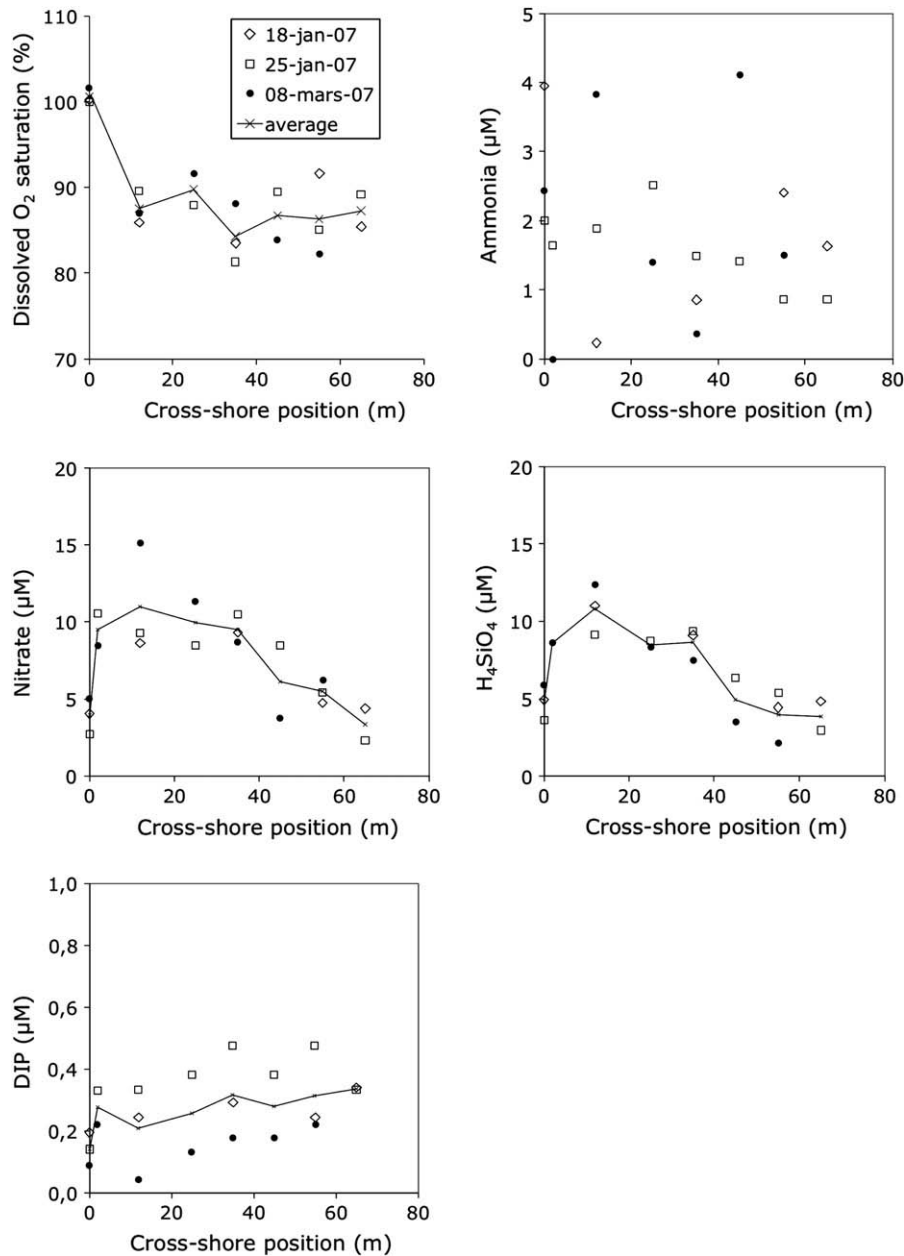
Fig. 3. Concentrations of dissolved O_2, nitrate, DIP, ammonia, and silicic acid in seawater (values on the y-axis) and in pore waters collected on three cross-shore sections of the tidal beach at low tide, in holes at the level of water-saturated sediment. The 0 m position corresponds to the shoreline and to samples collected in seawater. All other samples were collected within the intertidal zone. The high tide level of the previous high tide was at about 75 m.

surface calculated, the dissolution kinetics estimate is 3.28×10^{-13} or $10^{-12.48}$ mol m^{-2} s^{-1}. A value of $10^{-12.59}$ mol m^{-2} s^{-1} is obtained when sand grains are assimilated to spheres with $R = 300$ μm. A similar calculation was done for the flow-through incubation, in which 230 g of sandy sediment (i.e., 1.3 m^2) interacted with 60 ml of seawater and produced an increase in silica concentration of 1.4 μM d^{-1}. The dissolution kinetics estimate ranges between $10^{-12.25}$ and $10^{-12.13}$ mol m^{-2} s^{-1} for 300 and 400 μm grain sizes, respectively.

4. Discussion and conclusions

4.1. Interstitial water dynamics

Intertidal sandy sediments are saturated with water at high tide, and become unsaturated at low tide. Our observations were noted during low tide. The results show that the piezometric level position was located at 1.5 m depth on the upper portion of the intertidal beach, which was immersed in seawater a few hours before. This means that a large interstitial water volume is evacuated seawards during each tidal cycle. High permeability of the sediment studied enables the tidally driven flow. Permeability was estimated at 0.9×10^{-10} m^2 ± 0.4 log unit, according to the empirical relation established by Wilson et al. (2008).

Assuming a mean free porosity of 40%, as measured in the sediment studied, and assuming a vertical cross-shore section of 75 m^2 of unsaturated sediment at low tide (§ 3.1, Fig. 2), the pore space corresponds to a volume of 30 m^3 per metre width (along the shore). This volume includes the volume of water that replaces air during floods, or the volume of interstitial water that moves out of the sediment at each ebb tide. This volume was estimated from the

Table 1
Concentrations of dissolved O_2, nitrate, DIP, ammonia, and silicic acid in seawater and in pore waters collected on cross-shore sections of the intertidal beach at low tide, in boreholes at the level of water-saturated sediment.

Cross-shore position (m)	Hole deepness (cm)	O_2 saturation ($\pm 2\%$)	NO_3 ($\pm 0.5\ \mu M$)	DIP ($\pm 0.05\ \mu M$)	NH_4 ($\pm 0.2\ \mu M$)	H_4SiO_4 ($\pm 0.5\ \mu M$)
January 18th 2007						
Seawater		100	4.0	0.19	4.0	4.9
12		86	8.6	0.24	0.2	11.0
35		84	9.3	0.29	0.9	9.1
55		92	4.7	0.24	2.4	4.4
65		85	4.3	0.34	1.6	4.8
January 25th 2007						
Seawater		100	2.7	0.14	2.0	3.6
2 (runnel)	0		10.6	0.33	1.7	
12 (T1)*	20	90	9.3	0.33	1.9	9.1
25 (T2)	40	88	8.5	0.38	2.5	8.7
35 (T3)	57	81	10.4	0.48	1.5	9.4
45 (T4)	70	90	8.5	0.38	1.4	6.3
55 (T5)	98	85	5.4	0.48	0.9	5.3
65 (T6)	120	89	2.3	0.33	0.9	2.9
March 8th 2007						
Seawater		102	5	0.09	2.4	5.9
2 (runnel)			8.4	0.22	0	8.6
12		87	15.1	0.04	3.8	12.4
25		92	11.3	0.13	1.4	8.3
35		88	8.7	0.18	0.4	7.4
45		84	3.8	0.18	4.1	3.5
55		82	6.2	0.22	1.5	2.1

*Name of sampling holes on January 25th 2007.

data collected on January 25th 2007 on one E–W cross-shore profile. The topographic profile of the beach changes with time and latitude. The volume of interstitial waters evacuated seawards during each falling tide depends on the level reached by the high tide during the day, i.e., on astronomic tidal cycle. During the field experiment, the volume was calculated for a tidal range close to the averaged range of 3.2 m (Castelle et al., 2007). The morphology of the studied coastal zone is similar along the 25 km length of the Cap Ferret coast (Castelle et al., 2007). Therefore, assuming that the section studied is roughly representative in time and space of the Cap Ferret sand spit, the volume of water entering and leaving the sandy sediment in each tide cycle corresponds to $7.5 \times 10^5\ m^3$. At low tide, the water that previously infiltrated the sandy sediment is progressively evacuated down the slope towards the runnel systems and the ocean. When averaged, the flux of pore water to the ocean amounts to about 16.5 $m^3\ s^{-1}$ for the whole Cap Ferret coast (1.9 tidal cycles per day of $7.5 \times 10^5\ m^3$ each). In the following discussion, we will attempt to estimate the residence time of seawater in the porous environment.

4.2. Interstitial water residence time

Salinity measurements show that the cross-section of the Truc Vert beach is not contaminated with fresh groundwater. We also never measured salinities higher than that of seawater, suggesting that evaporation of pore waters was negligible. Therefore, observed changes in pore water chemical composition can be attributed to in situ transformations. The silica concentration of pore water collected at low tide in deeper holes of the upper beach is similar to the composition of free seawater. On the lower beach, however, pore waters that move out of the sediment during ebb are enriched in dissolved silica. The salinity of these waters is similar to that of seawater, which indicates that mixing with continental fresh waters is not the source of additional Si content found here. Therefore, seawater becomes enriched in Si during its transit through sandy sediments. Dissolved silica enrichment is presumably caused by dissolution of quartz by seawater that circulates in
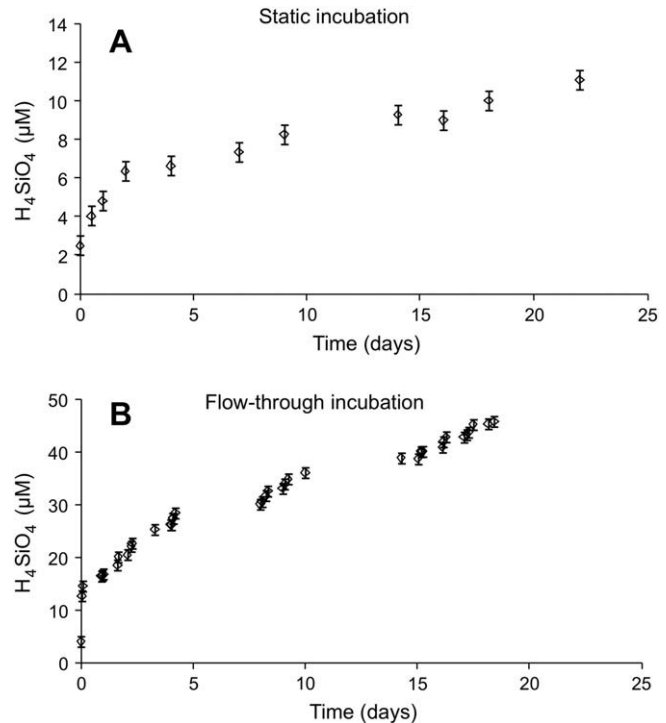

Fig. 4. Evolution of dissolved silicic acid concentration during incubation of sandy sediment of the Truc Vert beach with seawater at 20 °C. (A) Shows the concentration of dissolved silicic acid of 11 experimental units that were sacrificed for pore water sampling at different times between 0 and 22 days. (B) Reports the monitoring of dissolved silicic acid between 0 and 18 days in a flow-through dynamic incubation. Error bars represent the systematic errors in measurement.

the interstitial environment. The silica concentration in interstitial waters may operate as a chronometer from which the residence time of interstitial waters in sand could be estimated, provided we know the kinetics of quartz dissolution in seawater.

Pore waters sampled at low tide in holes of the upper beach have spent at least 5 h in contact with sand grains, because there was at least 5 h interval between the sampling time and the immersion of the upper beach. Dissolved silica concentrations were likewise low in seawater and in pore waters of the upper beach, although both static and dynamic incubation experiments revealed a rise in silica concentration in the first hours. The rapid increase in silica in incubation could be an experimental artefact. Artefacts could be caused by the long storage of sand over several days and its residual pore water in the laboratory before the beginning of the incubations, at which juncture this would have brought about silica desorption.

The rise in silica concentration becomes linear after 3 days in the static and the flow-through experiments. The rate of increase is six times higher in the flow-through experiment. The water/rock ratio is about three times higher in the static experiment (36 ml/50 g) than in the flow-through experiment (60 ml/230 g). When the rate is normalized to the water/rock ratio, the flow-through experiment still shows a rate higher than twice that of the static experiment.

The linear increase in silica concentration can be ascribed to dissolution of quartz when it is exposed to seawater. The concentration of silica increased all through the incubation, because it remains far below that of saturation with respect to quartz (79 μM at 20 °C).

Few experiments that evaluate the dissolution kinetics of quartz in salty matrixes are reported in the literature (Dove, 1994; Tester et al., 1994). Dissolution kinetics depends on temperature. Extrapolating these reported values to the temperature of our incubation,

i.e., 20 °C, the kinetics would be $10^{-11.7} \pm 0.5$ mol m^{-2} s^{-1} (Dove, 1994). Our results, especially of the flow-through experiment, are close to this value, and suggest that our incubations were accurate models for in situ quartz dissolution, and that calculated kinetics enable us to estimate the residence time of interstitial waters in the sandy sediment from the rise in silica concentration.

The water/rock ratio of saturated sediment of the Truc Vert tidal beach is close to the value of the flow-through experiment. Therefore, this incubation probably represents the best estimate of quartz dissolution in the field. During the immersion phase, seawater enters the sandy sediment of the intertidal beach. The high silica concentrations of porewaters at seawater salinity observed in the lower intertidal beach boreholes probably develop after dissolution of quartz during the residence of waters in the porous environment. The linear slope of the flow-through experiment of 1.4 μM d^{-1} enables us to estimate the residence time of water in the sediment. For the three sampling times, the dissolved silica concentration of the lower beach pore waters was about 5 μM higher than the concentration in seawater. About 3.5 days would be needed for the contact of pore waters with quartz grain to attain this enrichment level of dissolved silica at 20 °C. At the in situ temperature (12–13 °C), quartz dissolution is slower than at 20 °C (Dove, 1994), suggesting that the 3.5 days is the minimum time needed. We cannot exclude the possibility that biogenic silica (e.g., from diatom frustules), which has a higher solubility than quartz, may be a source of the silicic acid found in the pore water. However, the occurrence of biogenic silica is probably episodic and patchy, which is not consistent with the constant and regular shape of the cross-shore profiles of dissolved silica obtained for the three sampling times.

To conclude, our data suggest that the mean residence time of water in the sandy sediment of the Truc Vert beach was probably more than seven tidal cycles. Waters that move out of the sediment during ebb and at low tide probably consist of a mixture of seawater that enters the sediment during the flood tide and older seawater enriched in dissolved silica. The residence time probably changes with tidal amplitude, season, or hydrodynamic conditions. Here, we obtained similar overall cross-shore profiles of dissolved silica on three different dates, which suggests that the residence time of pore waters of the tidal beach is always long enough for detecting biogeochemical reactions.

4.3. Sandy tidal sediment as a biogeochemical reactor

The finding that oxygen saturation state in pore waters collected in holes is always lower than that in seawater suggests that oxygen consumption occurs via aerobic respiration activity, and that the Truc Vert beach is a net heterotrophic environment (Smith et al., 1991). Since an oxygen deficit was observed in pore waters of the upper beach, one can assume that respiration occurs as soon as seawater enters the sediment, since upper beach pore waters are young. In the older pore waters of the lower beach, oxygen concentration did not significantly decrease relative to upper beach pore waters. This suggests that either organic matter is rapidly mineralised when seawater enters the sediment during flood or else mineralisation is a continuous process, but oxygen consumption is compensated by diffusion. The consumption of oxygen suggests that there is a reservoir of labile organic matter within the intertidal sediment. We attempted to detect organic carbon in the sandy sediment, but the measured value was found to be lower than the detection limit of 0.01 dry sediment weight %, which agrees with organic carbon contents reported for other exposed sandy beaches (e.g., Incera et al., 2003). Therefore, aerobic respiration is probably not sustained by the stock of sedimentary carbon. This suggests that seawater itself is the main source of organic matter. Advective pore water flows provide a fast pathway for the transport of particles, like

phytoplankton cells, into sandy sediments (Huettel and Rusch, 2000). This food availability may control intertidal biomass (Mclachlan, 1990). The greatest deficit in dissolved O$_2$ relative to seawater for the period studied was 60 μM. It suggests that about 60 μM of organic carbon had been mineralised in this pore water. Such a level of organic carbon concentration is high for coastal waters (Liu et al., 2005), but plausible during bloom periods. The sandy sediment also acts as a filter that may retain and concentrate particulate organic matter (Mclachlan et al., 1985). Organic matter may also be provided by a population of autotrophs, such as benthic cyanobacteria or diatoms, which can be efficient primary producers on exposed beaches (e.g., Spilmont et al., 2005; Hubas et al., 2007). A rapid turnover of this population could explain the low concentrations of particulate organic carbon measured in the sediment.

Respiration of organic matter causes organic N and P to mineralise, and results in a subsequent increase in dissolved nitrate and DIP. Phosphorus and nitrate concentrations in interstitial water exceed seawater values in most of the cases. We attempted to compare the mass balance between the dissolved oxygen consumed with the enrichment of N and P in each sample, with O$_2$/N, O$_2$/P and N/P ratios matching the aerobic mineralisation of a Redfield-type organic matter. However, for most of the cases, ratio calculations were not robust because DIP values were close to the detection limit. Nevertheless, several samples revealed a suitable correspondence between measured O$_2$/N ratios and the Redfield ratio of 138/16. These observations suggest that phosphorus and nitrate enrichments in interstitial waters were presumably caused by oxidation of aerobic organic matter. The cross-shore profiles show a decrease in DIP from the upper beach zone to the shoreline when nitrate remained high in the lower beach pore waters. Therefore, N/P ratio varied significantly. Biogeochemical processes govern benthic DIP behaviour. DIP also interacts with sediment, through adsorption on the particle surface (e.g., Anschutz et al., 1998), which makes DIP geochemistry more complex in the studied environment.

To conclude, pore waters are advected towards seawater during ebb through a process of pumping of tidal pore water. Tidally driven flow supplies products of mineralised organic matter to the pelagic environment of the coastal zone. The results of this study support earlier results (Riedl and Macmahan, 1969; Riedl and Machan, 1972; Mclachlan et al., 1985; Mclachlan and Turner, 1994), which showed that filtration through the sands of exposed beaches enhanced the mineralisation of organic matter. This tidal pump plays probably a major role in the biogeochemistry of the Aquitanian coast. Water mass balance indicates that the discharge volume of pore water is 30 m^3 per metre width along the shore per average tidal cycle. The related flux of nitrate and DIP towards the coastal ocean is of the order of 150 and 7.5 mmol, respectively. The whole of the Aquitanian coast comprises 250 km of sandy beaches, i.e., 10 times the length of the Cap Ferret beach. Truc Vert beach is not representative of the whole the Aquitanian coast, but only of all undisturbed beaches of the Aquitanian coast, that receive sand supply sufficient to balance the sedimentary budget (Castelle et al., 2007). This is the case all along the Cap Ferret sand spit. Coastal sections showing strong erosion or accretion do not present a similar sand reservoir (=porous intertidal sand) such as at the Truc Vert beach. Therefore, an extrapolation of the results done of the Truc Vert beach to the whole of the Aquitanian coast would only provide an order of magnitude of the regional budget of recycled nitrate and DIP. The extrapolated budget represents 3700 moles of nitrate and 190 moles of DIP per tidal cycle for the 25 km length of the Cap Ferret sand spit, and 10 times this value for the 250-km long Aquitanian coast. It corresponds to about 1.5% of nitrate and 5% of phosphorus supplied by the Gironde estuary to the Bay of Biscay (Deborde et al., 2007). The calculated contribution of the tidally driven flux of nitrate and DIP is probably a minimal value because it is based on data collected during

winter. Santos et al. (2009) showed that biogeochemical processes in a Gulf of Mexico subterranean estuary led to higher summertime nutrient input. A better estimate of nitrate and DIP biogeochemistry in tidal beaches of the Aquitanian coast would need a more extensive spatio-temporal investigation. Preliminary sampling done in the northern part of Aquitaine showed that tidal sands pore waters were enriched in dissolved nutrients, but the enrichment was always associated with mixed continental groundwaters. Therefore, it was not possible to determine accurately the portion of nutrient input originating from continental waters and that caused by in situ recycling of biogenic compounds.

The tidal pump represents a diffusive, local and permanent contribution that depends on neither runoff nor currents. Therefore, this could represent a major contribution of recycled nutrients close to the coast. Ehrenhauss and Huettel (2004) had already shown that organic matter was rapidly degraded in subtidal permeable coastal sands, indicating that these sediments were very active sites of nutrient recycling. Gibbes et al. (2008) demonstrated that tidally driven pore water exchange within an offshore sandbank might be capable of delivering bio-available iron across the sediment–water interface. Sandy beaches also act as biogeochemical reactors, in which organic matter supplied by seawater that enters the pore space during flood is trapped long enough to be mineralised. Sandy beaches represent net heterotrophic environments. Because recycled nutrients are efficiently brought back to seawater during ebb through tidally driven flow, the role of sandy beaches in nutrient biogeochemistry should not be overlooked in sandy tidal coasts.

Acknowledgements

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