Hydraulic control of pore water geochemistry within the oxic-suboxic zone of a permeable sediment

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Abstract

The geochemical behavior of the top 70 cm of permeable reef flat sediments on Checker Reef, Oahu, Hawai‘i was examined using spatial and temporal changes in pore water O2, NO2, NO3, NH4, and N2O concentrations. The shallow depth of the sediment-water interface relative to the height of waves propagating across the reef creates an environment in which pore water mixing and transport are dominated by wave-induced mechanisms. Dissolved oxygen penetrated 15–50 cm in the four sites studied. The depth-integrated concentration of dissolved oxygen was greater under larger wave conditions and in more permeable sediments, which suggests that dissolved oxygen may be a good indicator of the relationship between sediment metabolism and the physical nature of the sediment environment. The absence of any subsurface N2O maxima, limited temporal variability in pore water N2O concentrations, and vertically coherent profiles of O2, NO2, NO3, and N2O suggest that suboxic processes are typically restricted to spatial scales that are smaller than for oxic processes in these sediments. The geochemical response of the sediments to a natural perturbation was monitored by examining the composition of pore waters immediately following a large wave event and for several weeks thereafter. Significant changes in the depth-integrated concentrations of O2, NO2, NO3, and NH4 were observed following the perturbation; however, only changes in NO3 lasted for several weeks after the event, whereas most other species returned to previous conditions within two weeks or less.

Sediments can be defined as being hydraulically driven when in situ hydrodynamic forces induce the bulk flow of interstitial water, and possibly the movement of particles, within a permeable sediment bed. The hydraulically driven transport of pore water can result from the interaction of bottom topography with flow fields overlying the sediment-water interface, such as when bottom currents pass over rippled sediment beds (Thibodeaux and Boyle 1987; Huettel and Gust 1992), mounds constructed by infauna (Ziebis et al. 1996), or the benthic fauna themselves (Huettel and Gust 1992). This interaction creates spatial pressure gradients within the sediment bed that drive the advective exchange of fluid between sediment interstices and the overlying water column. Hydraulically driven material transport can also result when surface gravity waves pass across a permeable sediment bed (Putnam 1949; Sorensen 1997). The dynamic pressure field created by these gravity waves can induce bottom currents that, in turn, drive pore water exchange via the interaction of wave-driven currents with the uneven morphology of the sediment surface (Webb and Theodor 1972; Shum 1992, 1993). The wave-induced dynamic pressure field can also penetrate the permeable sediment bed itself, driving pore water flows that have elliptical trajectories (Shum 1992, 1993). This particular mechanism has been described as more of a dispersive, rather than an advective, process analogous to eddy diffusion (Riedl et al. 1972; Harrison et al. 1983; Webster and Taylor 1992; Haberstroh 1994) and may dominate in relatively shallow waters. Solute transport rates within hydraulically driven sediments can be orders of magnitude greater than molecular diffusion but depend on the strength of in situ pressure gradients and the permeability of the sediment bed (Vanderborght and Wollast 1977; Harrison et al. 1983; Huettel and Gust 1992; Shum 1993; Haberstroh 1994; Lohse et al. 1996).

The spatial structure of sediment redox state results from a balance between the metabolic demand of sediment biota oxidizing organic matter and the delivery rate of viable electron acceptors to the sites of oxidation (e.g., Froelich et al. 1979). Consequently, the redox structure of hydraulically driven sediments should be controlled by the mechanics of material transport within a permeable sediment bed. These mechanisms, in turn, depend on the hydrological characteristics of the sediment and the nature of the surrounding hydrodynamic environment.

The efficiency by which sediments recycle carbon, nitrogen, phosphorus, and trace metals is strongly dependent on reactions that are sensitive to sediment redox conditions (e.g., nitrification, denitrification, phosphate sorption and co-precipitation with iron hydroxides, iron and manganese precipitation and dissolution, and aerobic organic carbon oxidation). Many of these reactions occur primarily within the oxic-suboxic transition zone, or the region of sediment bounded by oxygenated conditions near the sediment-water interface and the depth at which sulfate reduction occurs within the bulk pore water. Reactions occurring within the oxic-suboxic transition zone should also be more heavily

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Fig. 1. Locations of Sta. C and Sta. S on Checker Reef, Oahu, Hawai’i (21°26.5’N, 157°47.5’W). Locations of the fore and back reef are shown.

coupled with hydraulically driven transport processes than would anaerobic reactions occurring deeper in the sediment, since the hydrodynamic forces driving the exchange of materials between the sediments and the overlying water column attenuate with distance from the sediment-water interface (Huettel and Gust 1992; Shum 1992, 1993; Haberstroh 1994; Huettel et al. 1996).

The hydraulically driven transport of materials has already been demonstrated within the upper decimeters of sediments in sandy coastal environments (Riedl et al. 1972; Harrison et al. 1983; Huettel and Gust 1992; Webster and Taylor 1992; Haberstroh 1994; Ziebis et al. 1996; Haberstroh and Sansone, in press) and within the upper centimeters of shelf sediments as deep as 58 m in the North Sea (Lohse et al. 1996). Hydraulically driven sediments may be a common, rather than uncommon, feature of the continental shelf, since the dominant sediment type on the shelf is sands (Kennet 1982; Shum and Sundby 1996). These sand beds may be permeable enough to be hydraulically driven by wind-induced, wave-induced, and tidally induced currents reaching the benthos (Davies 1993; VanWeering et al. 1993; Huettel et al. 1996). Consequently, much of the organic matter remineralization occurring on the continental shelves may be hydraulically driven.

We present measurements of O$_2$, NO$_3^-$, NO$_2^-$, N$_2$O, and NH$_4^+$ concentrations in pore waters from the oxic to anoxic zones within a wave-driven, permeable sediment. The purpose of the study was to examine the behavior of these species and their relationship to sediment redox structure under varying physical conditions.

Methods and study site—Our study site, Checker Reef, is a patch reef in Kaneohe Bay on the northeast side of the island of Oahu, Hawai’i (Fig. 1). The reef is described in detail by Tribble et al. (1992) and has been extensively studied; however, this is the first time that information on pore water composition and redox state of this kind has been reported from the surface meter of sediments. The upper meter of the reef consists almost entirely of unlithified, biogenic calcareous sediments (Sansone et al. 1990) whose particle sizes range from fine sand to broken pieces of dead coral tens of centimeters in dimension (Haberstroh 1994). Trade-winds, waves and currents move across the reef in a north-easterly direction from the forereef to the backreef during most of the year. Wave-induced exchange of pore water in Checker Reef is thought to occur due to the shallow depth of the reef (0.7 m) relative to surface-wave heights (up to 0.5 m) (Tribble et al. 1992; this study). Measurement of sediment metabolism made by Sansone et al. (1990) indicate that oxic sediments from the surface meter of Checker Reef are capable of becoming anoxic within several hours upon incubation in the absence of pore water–seawater exchange.

Well points were fabricated from 1/8 in. diameter schedule 80 PVC pipe and used to sample pore water at depths of 7, 15, 25, 35, 50, and 70 cm in the reef. The well points were driven into the reef framework with the aid of a stainless steel installation tool (Falter 1998; Falter and Sansone in press). A set of wells for sampling each of these depths defined an array (Fig. 2). The arrangement of wells within a single array was designed to minimize the degree of lateral separation of any two wells within an array while preventing the pore water volume extracted from one well point from overlapping or interfering with the volume extracted from an adjacent well. The sampling volume was estimated to be a sphere ~6 cm in radius, based upon a total extraction...
volume of ~250 ml per sampling and an estimated sediment porosity of ~0.3. The porosity of modern aragonitic sands is typically ~0.45 (Morse and Mackenzie 1990); however, a more conservative estimate of porosity is used for Checker Reef sediments due to the presence of the larger pieces of broken coral rubble.

Pore water samples were extracted from the sediment using a battery-powered peristaltic pump. An amount in excess of the dead volume in the tubing that connected the well point to the pump (~270 ml) was collected and discarded before taking each 250-ml pore water sample to ensure a pure pore water sample (Falter 1998; Falter and Sansone in press). The mixing of pore water during its passage through the tubing acted to homogenize the samples; however, samples collected from individual well points on and after 1 March 1997 were homogenized in a glass flask free of any head space to ensure uniformity between subsamples intended for different chemical analyses. There did not appear to be any significant change in the relative distribution of pore water species once this deliberate homogenization step was employed. An additional experiment was performed to determine how much pore water composition would change with the volume of water extracted. Four 60-ml pore water samples were sequentially taken from 7-, 25-, and 50-cm well points at each station using 60-ml syringes attached directly to the well points (without using the pump and tubing). These samples showed that NO and NH concentrations did not change significantly with the amount of pore water extracted, even for the 7-cm well points (data not shown), suggesting that there was no enhanced movement of pore water along the sides of the well points.

Two arrays ~1.5 m apart were installed at varying distances from the fore reef (Sta. S and Sta. C, Fig. 1) and sampled over a 9-month period. At no point was there a freshwater flow into the bay large enough to effect surface salinities over the reef (data not shown). Nutrient samples were collected from all arrays starting on 7 October 1996. Dissolved gas samples were collected from arrays CA and SA starting on 5 December 1996 and from arrays CD and SB starting on 1 March 1997. N,O samples were not collected from array CA due to its very shallow dissolved O₂ penetration. All sampling of arrays CA and SA was concluded on 22 April 1997, and all sampling of arrays CD and SB was concluded on 3 July 1997. Sampling intervals thus ranged from 2 weeks to 2 months. Samples for the determination of dissolved NO₃⁻ (~0.05 μM), NO₂⁻ (~5 nM), and NH₄⁺ (~0.2 μM) were filtered through 0.7-μm glass fiber filters and analyzed using standard colorimetric techniques. Dissolved oxygen (~5 μM ±1%) was measured in the field using an Orion model 820 dissolved oxygen meter equipped with a Clark-type electrode. Pore water N,O concentrations were measured (~0.5 nM) following the method of Pierotti and Rasmussen (1980) with only minor modifications.

Sediment hydraulic conductivity was estimated for each of the well points using a falling-head permeameter (Falter 1998). These estimates assumed that the sediments were homogeneous and extended infinitely around a given well point. These assumptions were made to simplify the required calculations; however, the sensitivity of the calculations to these assumptions at distances greater than 7 cm away from the well point was very small (<5%). Wave heights, measured from trough to crest (~5 cm), were estimated by watching waves pass an upright meter stick.

Pore water composition and redox structure—An example of the distribution of NO₃⁻, NO₂⁻, NH₄⁺, N₂O, and O₂ concentrations in Checker Reef pore waters is shown by data taken from array SA (Fig. 3). The solid lines represent profiles of median concentrations, whereas the individual profiles and data points are provided to show the range in the distribution of pore water constituents. Dissolved O₂ penetration was typically 50-cm deep in this array. Ammonium (NH₄⁺) concentrations were less than 0.5 μM within the shallowest depths but rose sharply where dissolved O₂ became depleted. Nitrate (NO₃⁻) and nitrite (NO₂⁻) typically reached their maximum concentrations where dissolved O₂ was still abundant before becoming depleted at the same depths as dissolved O₂. Nitrous oxide (N₂O) concentrations showed the least variable behavior and were typically very close to that of the overlying seawater at the shallowest depths (7 and 15 cm), then decreased with depth to a minimum value of ~2 nM as dissolved O₂ became depleted. The depth of dissolved oxygen penetration was ~35 cm in arrays CD and SB, but was only ~15 cm in array CA (Fig. 4). Concentrations of NO₃⁻, NO₂⁻, N₂O, and NH₄⁺ in arrays CA, CD, and SB (data not shown) showed vertical distributions relative to their respective dissolved oxygen distributions, which were similar to that of array SA (Fig. 3).

The frequent presence of a subsurface O₂ maxima near 15
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The observed O2 maxima would be the prefaces for the entire reef in the same temporal manner. A more likely mechanism whose permeability had otherwise been increased by preferential transport of water through infaunal burrows or sediment...  

Fig. 4. Pore water and overlying seawater concentrations of dissolved O2 at arrays CA, CD, and SB. See text for sampling period. The open circles and dashed lines denote individual profiles. The heavy solid lines denote median concentrations. Values plotted at zero depth represent concentrations in the overlying seawater.

cm within arrays CD, SA, and SB, as well as an O2 maxima at 50 cm in array CD on two occasions, indicate that there may have been an increase in the exchange of water with sediments below 7–15 cm in depth. One possible explanation is that the subsurface O2 maxima is the lateral subsurface advection of pore water driven by tidally induced pressure gradients. However, estimates of pressure gradients occurring on tidal cycles are much smaller than the dynamic pressure gradients created by propagating surface waves (Dean and Dalrymple 1991; Symonds et al. 1995). Tribble et al. (1992) found that field observations and theoretical calculations do not indicate significant hydraulic exchange between surface and interstitial water at 1-m depth. This conclusion should be even more valid for shallower sediment depths where wave-driven pressure gradients are even higher. Furthermore, the observed subsurface O2 maxima were not consistent between the arrays in either space or time. Presumably, tidally induced pressure gradients would effect the entire reef in the same temporal manner. A more likely explanation of the observed O2 maxima would be the preferential transport of water through infaunal burrows or sediments whose permeability had otherwise been increased by infaunal mechanisms. Mounds and burrows resulting from the activity of worms and shrimp were observed throughout the study and were separated, on average, by a distance of ~10–30 cm. The transport of water along such preferential vertical channels could lead to greater pore water–seawater exchange rates below a less hydraulically communicative layer. The time-variant nature of infaunal activity (e.g., burrow creation and destruction, sediment reworking) could also explain the fact that the subsurface O2 maxima were not always present when each of the arrays were sampled. 

Diagenetic theory predicts that maxima in the profiles of dissolved inorganic nitrogen (DIN) compounds of intermediate redox state (e.g., NO2 and N2O) should occur below the NO3 maximum in order of decreasing oxidation potential (Froelich et al. 1979). Such predicted vertical separation between NO3 and NO2 profiles has been observed in diffusively driven sediments offshore of Tokyo Bay; however, profiles of NO2 and N2O within the same sediments had very similar shapes with no apparent vertical separation (Koike and Terauchi 1996). Both N2O and NO3 are intermediates in sediment nitrogen redox transformations and are typically found at relatively low concentrations in sediments (Koke and Terauchi 1996; this study). Nitrite is an intermediate in nitrification and denitrification, whereas N2O is an obligate intermediate only in denitrification (Knowles 1982). Nitrous oxide is also produced as a low-yield byproduct in nitrification but not as an obligate intermediate (Naqvi 1991). There does not appear to be any significant vertical separation between maxima in the Checker Reef profiles of N2O, NO2, and NO3. Furthermore, at no time was there a significant elevation of pore water N2O concentrations above ambient seawater values in any of the arrays. 

Maxima in NO3, NO2, and N2O concentrations roughly overlap at depths where dissolved O2 concentrations are high enough to preclude suboxic respiration of oxidized DIN species (Seitzenger 1988). Brandes and Devol (1995) showed that the inclusion of microzones within a diagenetic model could explain the vertically coherent distributions of dissolved O2 in sediments from the Northeast Pacific continental shelf. Previous studies of pore waters deeper in Checker Reef (1-m sediment depth) have shown elevated levels of methane existing in the presence of sulfate concentrations close to that of ambient seawater (Tribble et al. 1990; Sansone et al. 1990, 1993), which indicates the potential presence of microzones in these sediments. Furthermore, the data presented here are able to resolve elevated dissolved O2 concentrations within the bulk pore water that could support aerobic respiration to depths of up to 50 cm, whereas evidence for exclusively suboxic conditions (elevated NO3 and N2O concentrations in the presence of low dissolved O2 and relatively low NO3 concentrations) could not be resolved by the pore water data. These results, along with the results from previous studies, support the idea that suboxic respiration within Checker Reef sediments is typically restricted to spatial scales smaller than that of aerobic respiration, most likely microzones. The exact metabolic importance of suboxic environments within these sediments will, however, require more explicit knowledge of in situ reaction rates. 

Physical controls on pore water geochemistry—If the spatial distribution of dissolved pore water species is a function of both their net reaction and transport rates, then changes in the hydrodynamic forces driving pore water transport rates should influence pore water composition. Therefore, it would be expected that pore water composition should vary with changes in the height of waves propagating across Checker Reef. Figure 5 shows the relationship between the depth-integrated dissolved O2 concentration and maximum observed wave height using data taken over a 7-month period. These results show that, with the exception of array CA, there is a strong relationship between wave height and sediment-dissolved oxygen content (note that no particular significance is suggested for the numerical relationship used to fit the data in Fig. 5). These results suggest that oxygen delivery rates, along with pore water transport rates, increased relative to sediment metabolism under increasing hydrodynamic forcing. The apparent outlier for array SA taken on 16 March 1997 occurred following a large wave event...
Fig. 5. Depth-integrated concentration of dissolved O$_2$ ($\Sigma$O$_2$) in all arrays versus maximum observed wave heights on Checker Reef. Each array was sampled for dissolved O$_2$ over a 5-month period. Line shown is $y = mx^n$ with $m = 5.25$; $n = 0.6$, and $r^2 = 0.86$.

Fig. 6. Depth-integrated concentration of dissolved NO$_3^-$ ($\Sigma$NO$_3^-$) in all arrays versus maximum observed wave heights on Checker Reef. Each array was sampled for NO$_3^-$ over a 9-month period.

The absence of a positive relationship between dissolved oxygen content and observed wave height for array CA (Fig. 5) remains somewhat of an enigma given that array CA was situated only $\sim$1.5 m from array CD. However, array CA showed the shallowest dissolved oxygen penetration of all the arrays (15 cm) on all days sampled. Although sediments at CA did appear to have a much lower average hydraulic conductivity than sediments surrounding the other three arrays, this fact alone could not explain the lack of a response to changing wave conditions. One explanation is that large pieces of dead coral inhabited with feathery macroalgae situated 30 to 100 cm apart on the surface at Sta. C could have led to the net upward advection of anoxic pore water in the sediments surrounding array CA through a current-induced mechanism (Thibodeaux and Boyle 1987; Huettel and Gust 1992). However, currents interacting with the macroalgal stands should have led to the net advection of anoxic pore water underneath the macroalgal stands (Thibodeaux and Boyle 1987; Huettel and Gust 1992), not in array CA, which was approximately a meter behind the nearest macroalgal stand in the direction of predominant flow. Current-induced advection, however, cannot be ruled out, and could have partially counteracted the wave-induced transport of dissolved oxygen into the sediments. Another possibility is that there was some sort of conductive restriction choking the flow of pore water near the surface (10–20 cm). However, the average concentration of NH$_4^+$ within the top 35 cm at array CA increased 32% over a 3-week period in response to the large wave event, which suggests that these sediments might not have been hydraulically isolated from the overlying seawater. More information will be required before the geochemical behavior of array CA can be resolved.

In addition to in situ hydrodynamic processes, the physical properties of the sediment itself are also important in controlling pore water transport rates. Figure 7 compares the sediment permeability (depth-averaged over the top 50 cm of sediment) with the depth-integrated concentration of dissolved oxygen in each of the four arrays. Depth-integrated
values were felt to better represent the sediments around the array as a whole than would individual values taken from specific depths. The mean depth-integrated dissolved oxygen concentrations presented in Fig. 7 were calculated as the average of data taken on 3 days over a 2-month period when dissolved oxygen was measured in both arrays at a given station. However, the days from which the data were taken are different for each of the stations.

Sediment-dissolved oxygen content is higher in the more permeable sediments (Fig. 7). This result suggests that oxygen delivery rates, and hence solute transport rates, relative to sediment metabolism were greater in more permeable sediments, although the exact cause and effect nature of the relationship is uncertain. The greater dissolved oxygen content could have resulted from greater pore water transport rates in more permeable sediments exposed to the same wave conditions. However, it is also possible that the more permeable sediments were composed of coarser particles with a lower volume-specific surface area in comparison with the less permeable sediments. Sediments with a lower volume-specific surface area could also have a lower volume-specific organic matter content and therefore have lower sediment respiration rates. Thus, either a lower sediment respiration rate or a higher permeability could lead to higher sediment-dissolved oxygen content.

Although the relationship between pore water geochemistry and the physical characteristics of the sediment environment may appear difficult to assess under more typical wave conditions (with the exception of dissolved oxygen), significant changes in the hydrodynamic conditions to which permeable sediments are exposed can lead to significant changes in the geochemical composition of pore waters within those sediments. We observed an example of such a perturbation-response behavior when one of the largest surface-wave events to occur during the study period hit the northeastern shores of Oahu during the last week of February 1997. Offshore wave heights rose from typical values of ~1 m on 23 February 1997 to a maximum height of just under 4 m on 26 February 1997, then declined rapidly to a height of ~1 m on 1 March 1997. Observed wave heights on Checker Reef of up to 0.45 m on 25 February 1997 and 0.1 m on 1 March 1997 were consistent with this trend (Falter 1998). The non–steady state geochemical response of the sediments to the changing hydrodynamic conditions can be observed from the distribution of NO$_3^-$, NO$_2^-$, NH$_4^+$, and O$_2$ in pore waters at Sta. S before (28 January 1997, Fig. 8A), just after (1 March 1997, Fig. 8B), and 2 weeks following (16 March 1997, Fig. 8C) the large wave event. Surface water temperatures rose only ~2°C during this time period. Depth-integrated concentrations of O$_2$, NO$_3^-$, NO$_2^-$, and NH$_4^+$ are also presented in each of the figures. Concentrations of NH$_4^+$ were depth integrated to only 25 cm so that high concentrations of NH$_4^+$ deeper in the sediment would not obscure changes in NH$_4^+$ concentrations occurring within the oxic-suboxic transition zone.

The geochemical composition of pore water from array SB on 28 January 1997 reflected nearly typical conditions (Fig. 8A) and are thought to be a reasonable proxy for pore water conditions just before the swell event, as evidenced from similar wind and wave conditions observed on 23 February 1997. NO$_3^-$ and NO$_2^-$ concentrations within the array were slightly lower than their median values, whereas NH$_4^+$ concentrations in the upper sediment were very low. Although dissolved oxygen was not measured in array SB on 28 January 1997, elevated dissolved oxygen concentrations measured from array SA on that day (Fig. 8A) indicate that pore water oxygen concentrations in array SB were likely higher than their median values.

A few days after the wave event on 1 March 1997, significant changes in the composition of pore water within the surface sediments at Sta. S became very apparent (Fig. 8B). Pore water NO$_3^-$, NO$_2^-$, and NH$_4^+$ concentrations all increased, with changes in NO$_2^-$ being the most drastic. Pore water dissolved O$_2$ concentrations decreased at all depths, with the largest change occurring at 7 cm in the form of a subsurface O$_2$ minimum. The largest change in pore water NO$_3^-$ concentrations occurred at 7 cm as well, further indicating the likelihood of these shallower sediments being partially decoupled from deeper sediment layers owing to mechanisms described earlier. The depth-integrated concentration of O$_2$ decreased to 8.3 mmol m$^{-2}$, a value significantly lower in comparison with values measured on all other days ($p < 0.005$, mean = 14, SD = 1.9, $n = 5$). The concentration of NH$_4^+$ depth integrated to 25 cm increased to 75 µmol m$^{-2}$, whereas the depth-integrated concentration of NO$_3^-$ increased to 71 µmol m$^{-2}$. Both values were significantly greater than those measured for the same array all other times. (NH$_4^+$: $p < 0.005$, mean = 11, SD = 7.1, $n = 8$. NO$_3^-$: $p < 0.005$, mean = 15, SD = 3.2, $n = 8$.) The depth-integrated concentration of NO$_3^-$ increased to 670 µmol m$^{-2}$ on 1 March 1997, a value significantly greater...
than all measurements made before ($p < 0.005$, mean = 260, SD = 33, $n = 4$) and after 1 March 1997 ($p < 0.025$, mean = 510, SD = 79, $n = 4$). Pore water N$_2$O concentrations were not sampled prior to 1 March 1997 at Sta. S; however, the observed distribution of N$_2$O in array SB on 1 March 1997 was similar to that found in the following months (data not shown). There were no significant changes in the composition of the overlying seawater in comparison to data taken before and after the event.

Two weeks after the wave event, concentrations of O$_2$, NO$_3^-$, and NH$_4^+$ within the top 35 cm had declined to values that were close to those previously observed (Fig. 8C). Over the same time period, concentrations of NO$_2^-$ within the top 35 cm declined to values that were still higher than those observed before the wave event, despite the relatively vigorous wave conditions observed on 16 March 1997, which would be expected to lower NO$_2^-$ concentrations by disper- sive mixing. Although depth-integrated concentrations of O$_2$, NO$_3^-$, and NH$_4^+$ before and after the event were not significantly different, the depth-integrated concentration of NO$_2^-$ was significantly higher after the event in comparison to before the event ($p < 0.005$). A depth-integrated NO$_2^-$ concentration of greater than 400 μmol m$^{-2}$ was observed on 3 July 1997.

One explanation for the simultaneous decrease in sediment-dissolved O$_2$ content and increase in sediment NO$_3^-$, NO$_2^-$, and NH$_4^+$ content is that there was a shift in the overall sediment metabolism relative to pore water transport rates. If increased wave pumping had led to greater injection of organic particles into the sediment, then sediment metabolism would be expected to increase. As wave heights declined in the following days, the lower pore water transport rates relative to higher sediment metabolism could have lead to the observed lower sediment-dissolved O$_2$ content and greater sediment NO$_2^-$ content observed on 1 March 1997. The anomalously high NO$_2^-$ and NH$_4^+$ content within the upper 35 cm observed at the same time may indicate the increased activity of suboxic and anoxic microzones within the more weakly oxic zone, or a greater imbalance between the rates of NH$_4^+$ and NO$_2^-$ oxidation along the nitrification pathway, also resulting from more weakly oxic conditions. The significant increase in sediment NO$_2^-$ content sustained long after the event likely indicates the lasting effects that physical perturbations can have on sediment geochemistry, or more specifically, the dynamic balance between microbially driven redox transformations of DIN species. It is possible that the observed shift in sediment NO$_2^-$ content may have occurred, in part, as the result of seasonal changes in pore water composition. However, it would be fortuitous if such an abrupt shift occurred just after the second largest wave event in the past year. Although the exact mechanisms responsible for the geochemical changes occurring in these sediments following the wave event remain uncertain, the data do attest to the importance that such perturbation events can have on sediment geochemical processes.

Future work—It appears that the biggest uncertainty of our understanding the geochemical behavior of these sediments, and perhaps other hydraulically driven sediments as well, is the loading of organic matter that drives sediment respiration. The large size distribution of the sediments on Checker Reef make quantitative recovery of the solid phase extremely difficult. However, Huettel and coworkers have found that suspended particles penetrate permeable sands to varying depths depending on particle size (Huettel et al. 1996) and that the in situ injection of algal particles into a sand flat occurs via a hydraulically driven mechanism (Huet-
Tel and Rusch 2000). If sediment redox structure is ultimately the result of a balance between pore water transport and organic matter loading, then elucidation of both these processes under in situ conditions is required. Furthermore, the potential role of infauna to influence hydraulically driven pore water and organic particle transport rates should not be overlooked.

References


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